3
Salt Creep Theory

In this chapter, the theory behind creep and salt creep will be reviewed. Creep plays an important role in salt drilling, and must be clearly understood in order to drill affectively and cost effectively. This chapter gives an overview of deformation along with creep stages.

3.1
Deformation

Strain is an infinitesimal kinematic abstraction defined to represent the deformation state of any material point in a continuum medium. It's an objective quantity useful to describe the mechanical behavior of a particular material. On the other hand, stress is an infinitesimal dynamic abstraction used to define the load level a material point is bearing at a given position. The understanding of how strain and stresses are interrelated leads to the definition of material constitutive models. Examples of constitutive model elements are: elasticity, plasticity and viscoelasticity, among others. These three material behaviors are important in rock mechanics. Elasticity refers to the energy conservative region on the stress-strain curve (σ vs. ε) where a deformed material will return to its original form, fully recovering its strength properties after the removal of a constantly applied load. Elastic isotropic materials may be described by using the constitutive equation from the generalized Hooke's law (Chou et al., 1967), being expressed as

$$\varepsilon_i = \frac{1}{E}\Big[\sigma_i - \upsilon\big(\sigma_j + \sigma_k\big)\Big],$$

(3.1)

where the indicial notation i is any one of x, y or z for three orthogonal directions, and j and k are the other two (Dowling, 1999). The constant elastic parameters E and v are found by performing laboratory experiments on material specimens.

Material	E(kPa)x10^7	ν
Halite	2.040	0.36
Carnallite	0.402	0.36
Tachyhydrite	0.492	0.33
Fine Limestone	3.100	0.30
Cement	2.100	0.25
Casing	21.000	0.28

Figure 3-1: Elastic material constants for rock salt, cement and casing (Costa et al., 2010).

Following the elastic region is the plastic region (), where the deformation becomes irreversible. Viscoelasticity refers to materials that display a viscous behavior within the elastic region, thus having a linear stress-strain relationship. The term visco- indicates a time-dependent response due to shear stresses within the structure, and is accelerated by increasing the load and temperature. Observing the cyclic loading plots in Figure 3-3, an elastic material experiences no change in energy after unloading whereas a viscoelastic material loses energy. The energy loss is represented by the area inside the loading and unloading curves Viscoplasticity describes materials that have a time-dependent response in the plastic regime.
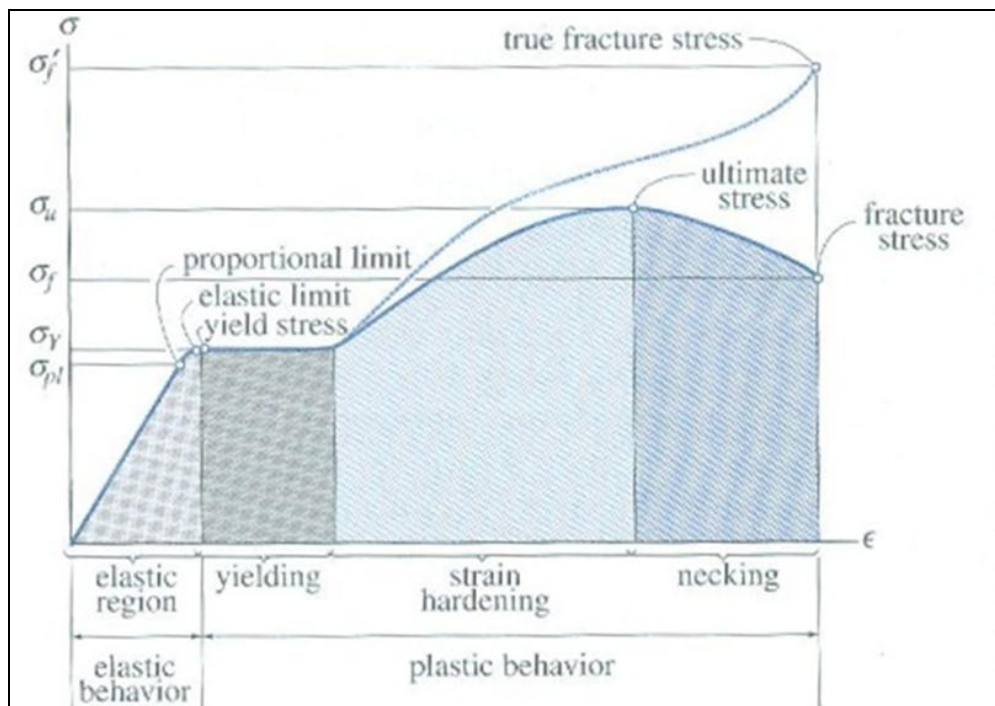

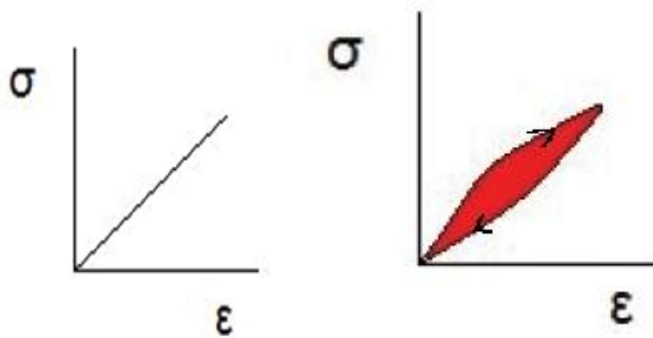Figure 3-2: Typical stress-strain curve for metal (Hibbeler, 2003).

Figure 3-3: Left: Stress-strain plot for an elastic material. Right: Stress-strain plot for a visco-elastic material (Omojuwa et al., 2010 modified). The family of load and unload curves indicates the material sensitivity to load rate.

3.2
Creep

Creep and viscoplasticity are sometimes used interchangeably *(*Miravete, 2005), however, creep is a term given for testing permanent deformation in a material subjected to a constant stress whereas viscoelasticity and viscoplasticity are specific creep models. Creep is apparent in metals, polymers, concrete and rocks. Salt has a more noticeable ductile behavior as opposed to other rocks that possess brittle behavior upon conventional laboratory load rates. Some other rocks creep, namely tar sands, compaction shales, granite and limestone and salt rock (Goodman, 1989). Similar to rock salt, tar sands and compaction shales can experience creep by a relatively low deviator stress. In particular, salt has creep behavior because of its microcrystalline structure, where slipping and gliding can occur between its crystal planes.
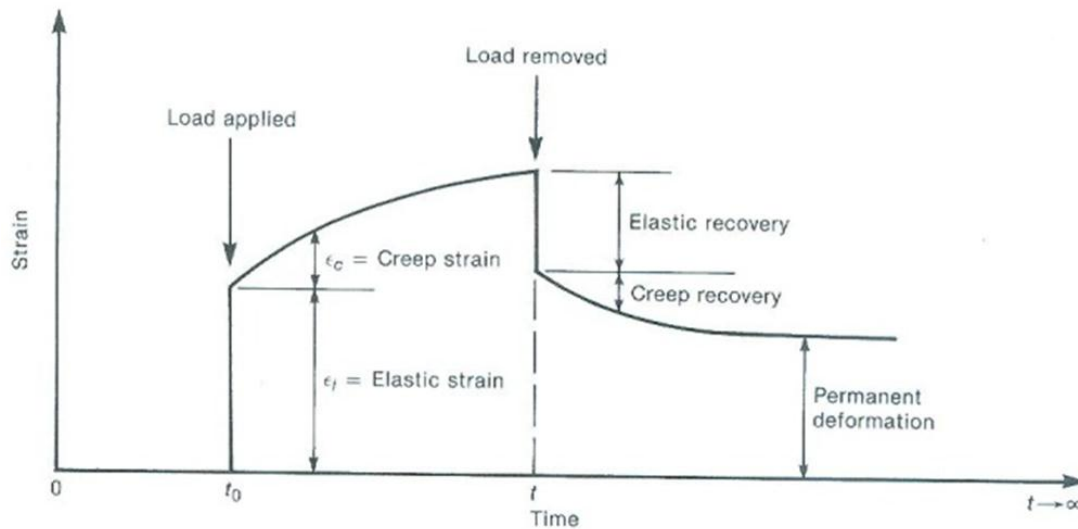
Figure 3-4: Creep strain – time curve (Macgregor et al., 2005).

3.3
Creep Stages

Creep strain can be divided into three distinct stages: primary creep, secondary creep, and tertiary creep. In the primary (or transient) creep stage, there is high deformation in a short period of time, forming a steep curve on a strain-time curve (or creep curve). As the material is subjected to constant loading, the rate of deformation increases at a decreasing rate. This is also referred to as *work hardening* until the curve reaches a steady state (i.e., linear form) of deformation (Munson, 1997). Being the secondary creep stage, the steady state is the longest stage with respect to time and is where the strain rate tends to become constant. The tertiary stage is reached when the rate of deformation increases exponentially until failure is reached. As a result, this final stage causes a volume increase due to microfracturing in the rock and leads to material failure.
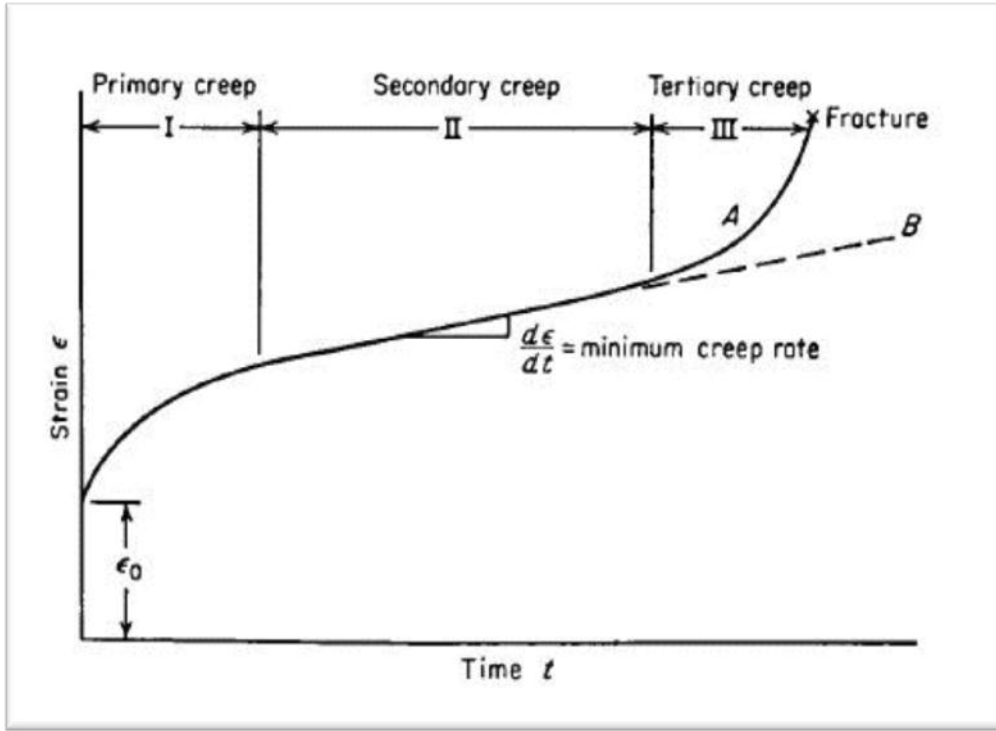
Figure 3-5: Creep Stages (http://ndt-specialist.com/2011/06/conditions-leading-to-defects-and-failures-creep/).

In regard to wellbores in salt formations, however, tertiary creep strain is not of concern. Rupture is unlikely to occur because there is relatively little room for displacement due to the introduction of the cement and casing.

Primary creep strain is the first phase of inelastic flow. Experimental creep test results show that the period of transient creep depends on the loading condition. It also depends on deviatoric stress more than on confining pressure. In general, deviatoric stress s_{ij} is expressed as the difference between the present state of stress σ_{ij} and the hydrostatic stress h_{ij} (i.e., $\sigma_1 = \sigma_2 = \sigma_3$) as shown in eq. (3.2).

$$s_{ij} = \sigma_{ij} - h_{ij} \tag{3.2}$$

$$
\begin{pmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{pmatrix} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix} - \begin{pmatrix} h & 0 & 0 \\ 0 & h & 0 \\ 0 & 0 & h \end{pmatrix}
$$
$$
= \begin{pmatrix} \sigma_{11}-h & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22}-h & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33}-h \end{pmatrix} \tag{3.3}
$$

Recall from mechanics of materials that a measure of the magnitude of the deviatoric stress may be given as

$$\sigma_d = \sigma_1 - \sigma_3 \qquad (3.4)$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively.

For materials that exhibit creep, hydrostatic stress does not provoke yielding but rather deviatoric stress. Hydrostatic stress is also referred to as average normal stress, σ_h:

$$\sigma_h = \frac{\sigma_x + \sigma_y + \sigma_z}{3} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \qquad (3.5)$$

The primary creep strain rate decreases at a constant rate (or "workhardens") until steady-state is reached as shown in Figure 3-6 provided by Yang (1999). It is worth noting that Figure 3-7 does not exhibit failure in comparison to Figure 3-6 because it is subjected to confined pressure just as it would in a salt formation. Confining pressure provokes greater resistance to material failure.
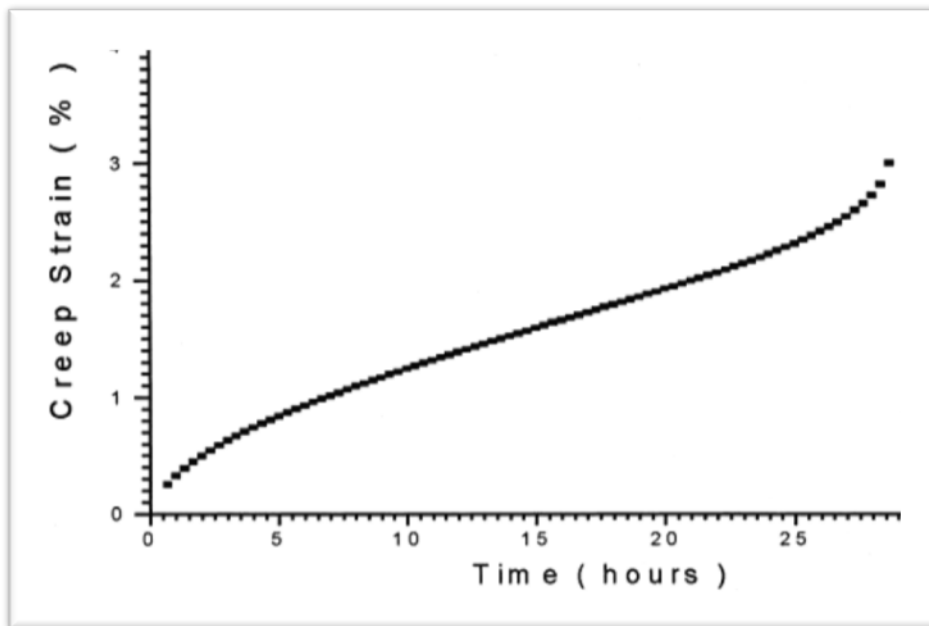

Figure 3-6: Uniaxial creep test result with σ_1 = 21.5 MPa and σ_3 = 0 MPa (Yang, 1999).
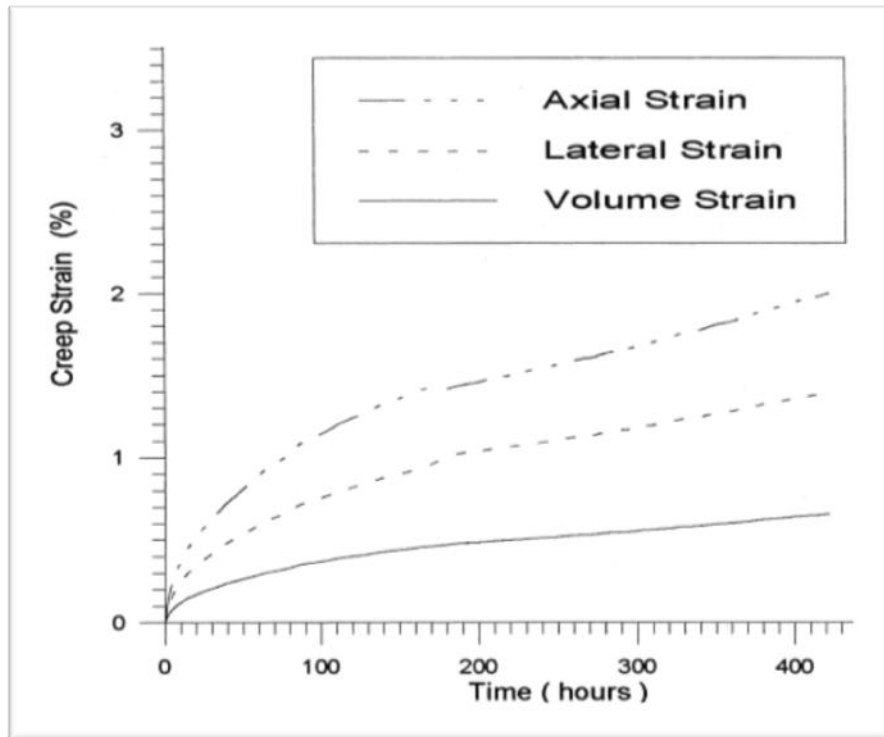
Figure 3-7: Triaxial creep test results with σ_1 = 28.7 MPa and σ_3 = 7.18 MPa (Yang, 1999).

3.3.1
Steady-State Creep Straining

The steady-state stage depicted in Figure 3-7 is of great interest due to its relevance for salt formations, thus being the most understood of the three creep stages. Experts are interested in the effects of well closure not only immediately after drilling, installing the casing and cement but also the rate of closure hours, days or weeks afterwards. Steady-state creep is a function of confining stress and deviatoric stress. Increasing both the deviatoric stress and temperature will result in a greater creep rate.

3.4
Workhardening and Recovery

Through the results of laboratory experiments, Munson (1997) discovered the internal structure of salt can affect the creep curve behavior depending upon the

state of internal equilibrium. If the microstructure of the salt specimen is below the internal equilibrium structure, the material will exhibit workhardening some time within steady state in order to attain equilibrium. Here, the existing defects increase in density, whereas a salt specimen possessing too many defects tends to decrease the density of the existing defects, known as *recovery*. In other words, if the applied stress increases, the material will exhibit a decrease in creep rate, or work hardening, until steady state is reached, whereas a decrease in the applied stress causes the creep rate to recover in order to attain a steady state rate.
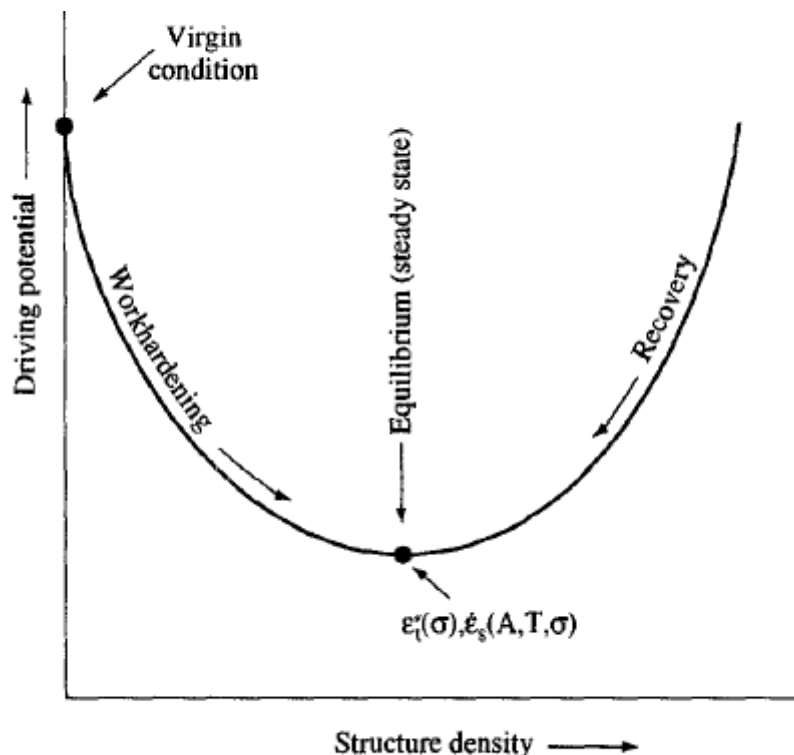

Figure 3-8: Schematic of potential functions for creep (Munson, 1997).

3.5
Constitutive Models for Creep Applications

An interesting fact in spite of constitutive models for creep is the vast number of models that have been developed over the years. The first models were simple and evolved towards more complex models through time. In the early 1990s, the behavior of nuclear waste repositories in the United States were requested to be predictable with "reasonable assurance" prior to licensing (Hambley et al., 1989) and were pursuing constitutive model equations that would approximate better than the existing equations. The models (or laws) that are applicable to salt creep are rheological, empirical and physical models.

3.6
Rheological Models

Creep behavior can be described using a composition of some idealized elements. Springs and dashpots are the most common. Such elements are combined to approximate the true deformation behavior as accurately as possible; these are known as rheological models. *Rheology* is the study of deformation behavior and the plastic flow of materials by using devices (Parker, 1997). The spring element represents the instantaneous elastic response of the material while the dashpot element represents the material's viscous behavior. Once a constant load is removed, the spring recovers instantly from the deformation. The dashpot responds by straining over time and does not return to its original state upon load removal. There also exist two additional components that may be used to further describe material behavior, being the slider and the rupture elements. The slider element models plastic strain. For applicability, it requires that the applied stress be at least equal to the material's yield stress (Yang, 2000). The rupture element models the material's loss of strength or cohesion due to excessive loading or straining. Figure 3-9 displays the symbols and graphs of the four elements. For a further review of rheological models, the following references may be consulted: Flügge (1967), Goodman (1989), Omojuwa (2010), and Yang (2000). Hence, details will be omitted here for brevity.
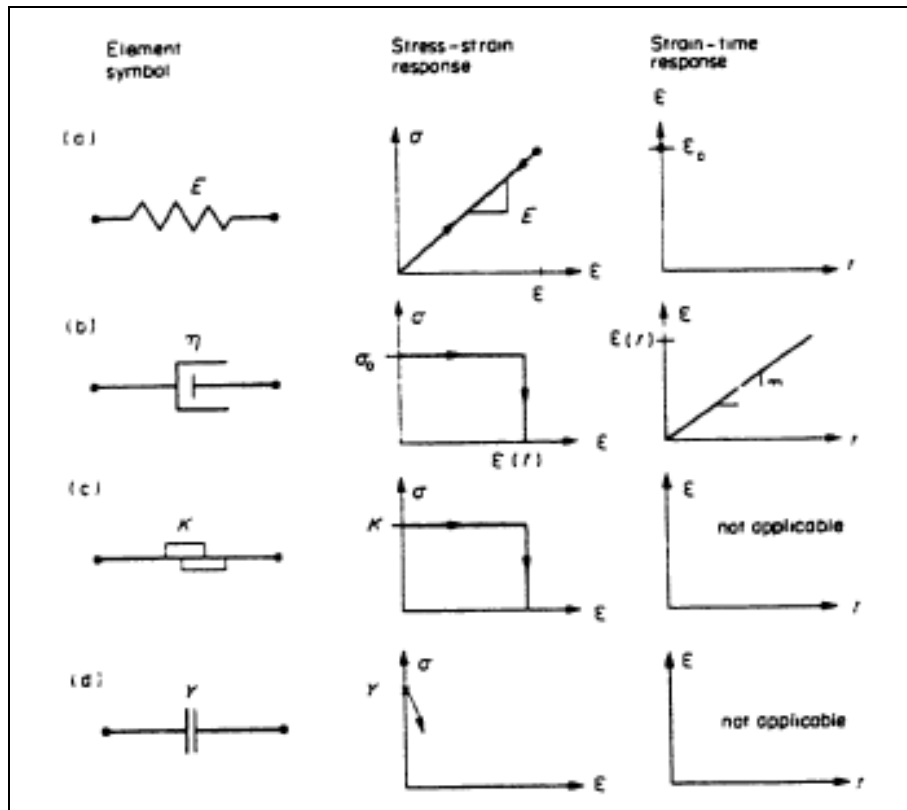
Figure 3-9: Rheological models: (a)spring; (b) dashpot; (c) slider; (d) rupture (Flügge, 1967).

The Maxwell model (Figure 3-10) is used to study the secondary stage of creep, or steady-state creep. It approximates the stress-strain response of a material by the use of a linear viscoelastic model composed of springs and dashpots in series, making it the simplest model for describing creep.

$$\sigma = \eta \cdot \frac{d\varepsilon}{dt} = \eta \cdot \dot{\varepsilon}$$

$$\sigma(t) = k\varepsilon_0 e^{\frac{-kt}{\eta}}$$

$$\varepsilon_{Total} = \varepsilon_K + \varepsilon_\eta$$

$$\varepsilon(t) = \frac{\sigma_0}{k} + \frac{\sigma_0}{\eta}(t)$$

$$\dot{\varepsilon}(t) = \frac{\sigma_0}{k} + \frac{\sigma_0}{\eta} = \varepsilon_k + \varepsilon_\eta$$

Figure 3-10: Maxwell Model Graph (http://quizlet.com/8748869/bmen-301-mechanical-flash-cards, modified).
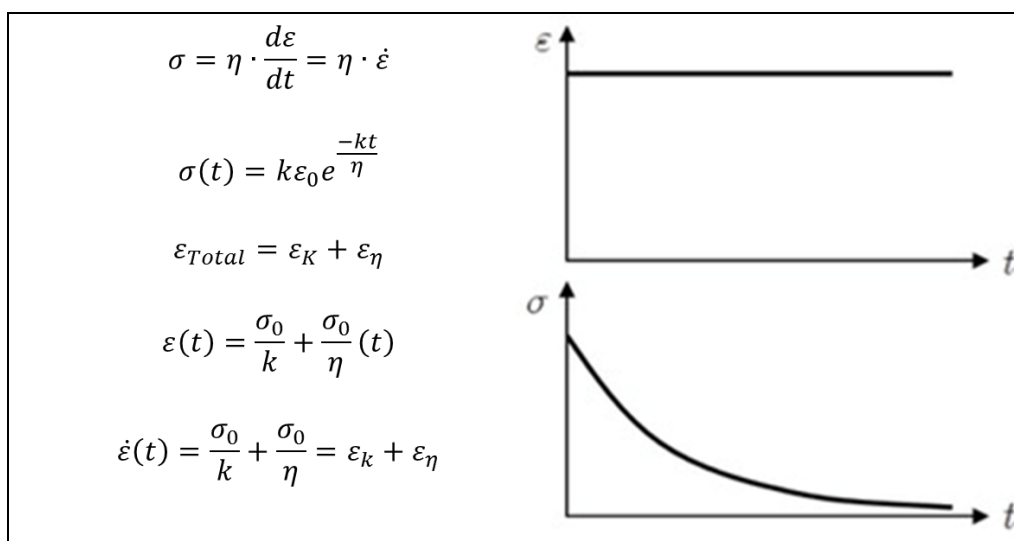
The Kelvin-Voigt model (Figure 3-11) uses the spring and dashpot elements in parallel, representing a creep behavior that consists of an instantaneous shear stress held constant to the specimen while the strain rate decreases at an exponential rate.
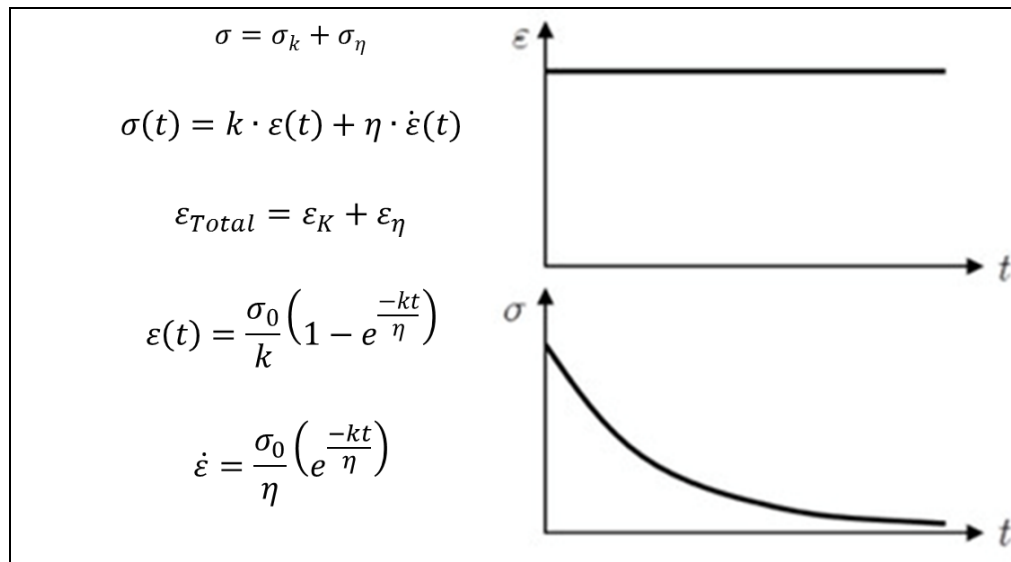

$$\sigma = \sigma_k + \sigma_\eta$$

$$\sigma(t) = k \cdot \varepsilon(t) + \eta \cdot \dot{\varepsilon}(t)$$

$$\varepsilon_{Total} = \varepsilon_K + \varepsilon_\eta$$

$$\varepsilon(t) = \frac{\sigma_0}{k}\left(1 - e^{\frac{-kt}{\eta}}\right)$$

$$\dot{\varepsilon} = \frac{\sigma_0}{\eta}\left(e^{\frac{-kt}{\eta}}\right)$$

Figure 3-11: Kelvin-Voigt model graph (http://quizlet.com/8748869/bmen-301-mechanical-flash-cards, modified).

The Burgers model (Figure 3-12) simply combines the Maxwell steady-state model with the Kelvin-Voigt transient phase model, which is the most general equation. Lab results have demonstrated that the Burgers solid model provides the best representation, but is useful for salt only at stresses less than the yield stress (Ottosen, 1986).
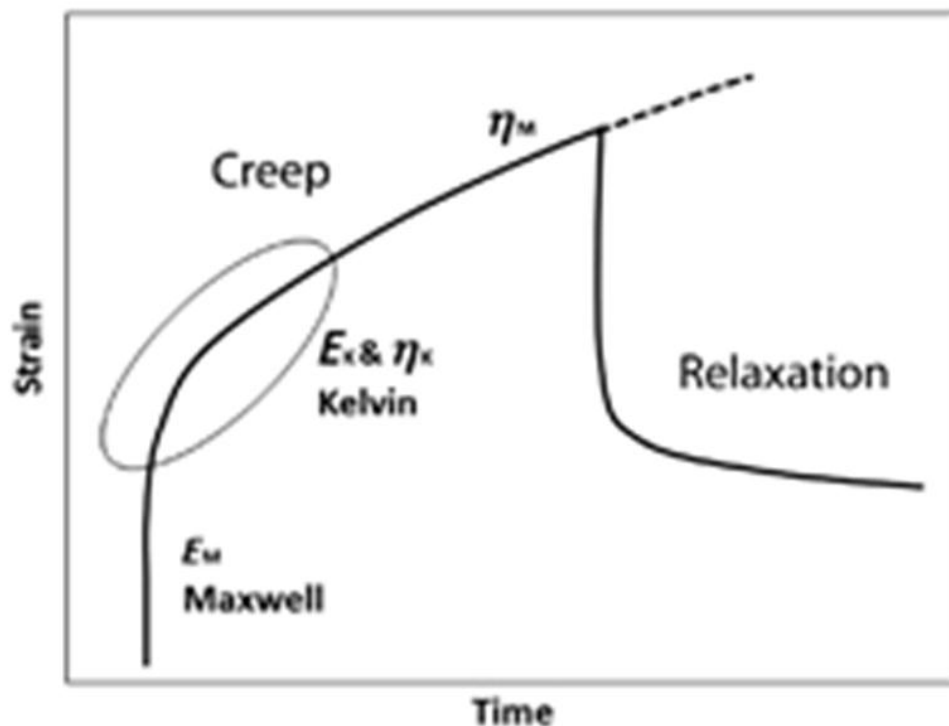
Figure   3-12:   Burgers   model
(http://www.nature.com/pj/journal/v42/n7/images/pj201044f1.jpg).

Rheological models are used to help represent creep behavior and material response. However, they are not commonly used for studying salt creep since they do not exhibit any relation or indication to the physical mechanisms. There exists other constitutive models that provide a more ideal and satisfactory result.
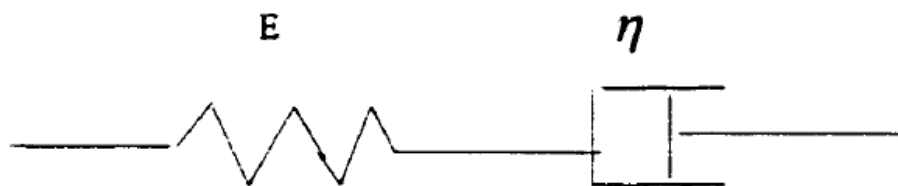

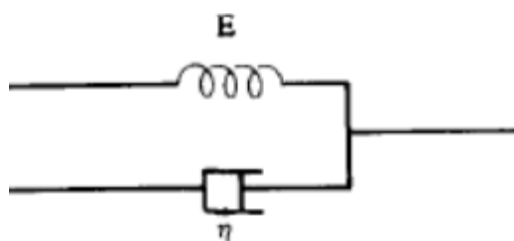Figure 3-13: Maxwell model (Yang, 2000).

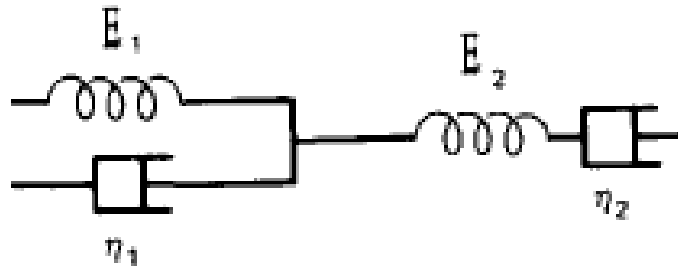Figure 3-14: Kelvin-Voigt model (Goodman, 1989 modified).

Figure 3-15: Burgers model (Goodman, 1989 modified).

3.7
Empirical Laws

By definition, the word *empirical* implies a deduction that is a result of experimental methods such as a trial-and-error approach. Three empirical creep equations have been formulated through strain tests of steel specimens, and since steel does not have the exact same mechanical behavior as salt rock, parameter adjustments are made for better approximation. The equations—or laws—are known as the logarithmic law, the exponential law and the power law.

3.7.1
Logarithmic Creep Law

The logarithmic law is used for describing transient creep at low temperatures. This empirical law describes creep using the logarithmic function given by:

$$\varepsilon = A\sigma^n \ln(t)T^a \tag{3.6}$$

Where

ε = transient creep strain;

σ = deviatoric stress;

t = time; and

T = temperature.

The terms A, a and n are temperature dependent material constants determined by curve fitting. All grain size, moisture content, and mineralogy effects are lumped into the material constants. By considering temperature T and creep deviatoric stress σ as constants, the previous equation can also be simplified to:

$$\varepsilon = A\ln t \tag{3.7}$$

The disadvantage of this law is that as time approaches zero, the transient creep rate becomes asymptotic, approaching infinity (Seni et al., 1984).

3.7.2
Exponential Creep Law

The exponential creep law is used for high temperature creep of metals and salt rock. The exponential creep law for transient creep can be written as:

$$\varepsilon = A\sigma^n t^m e^{\frac{j}{T}}$$

(3.8)

where j represents an additional material constant. According to Botelho (2008), Ludwick in 1909 formulated the following expression for steady-state creep:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left(e^{\frac{\sigma}{\sigma_0}} \right)$$

(3.9)

Where:

$\dot{\varepsilon}_0$ = creep strain rate within the steady-state phase;

σ = deviatoric stress; and

σ_d = deviatoric stress;

3.7.3
Power Creep Law

Suggested as being the most widely used empirical creep law (Shames et al., 1992) and well known for its adjustment capability is the *power creep law*. This creep law is also referred to as the *Bailey-Norton law*, for it was formulated by these two authors in 1929 (Munson, 1991). Its equation can be written as:

$$\varepsilon = A\sigma_d^n t^m$$

(3.10)

Where

ε = transient creep strain;

σ_d= deviatoric stress;

t = time, and

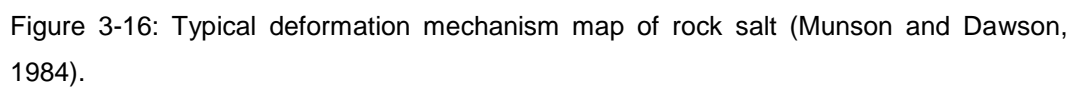A, a, m, n = temperature dependent material constants.

In Eq.(3.10), *A* is the *reciprocal viscosity coefficient* and *n* is referred to as the *stress power* (Shames et al., 1992). Although this equation represents transient creep strain, it can be formulated to represent steady state by manipulating physical mechanisms (Botelho, 2008) as will be discussed in Chapter 3.8.4. Accordingly, this work will focus on this creep law.

Although they provide reliable and adequate results, these empirical equations have the drawback of not taking into account of how the stress and strain states are related.

3.8
Physical Laws

Since the mid 1970s, several studies have been made to help further understand creep in salt rock in order to assure safe disposal of the transuranic radioactive waste generated by the defense programs of the U.S. In recent years, more research has been made in regard to the physical mechanisms of creep due to the contemporary challenges in salt drilling. Darrell E. Munson has made a significant contribution primarily by his development of the deformation mechanisms in salt rock. In some of his work, Munson (1984, 1991) established a deformation-mechanism map for salt shown in Figure 3-16 which illustrates the existence of five deformation mechanisms for secondary creep in salt rock within certain stress and temperature ranges. These five physical mechanisms are: dislocation climb, dislocation glide, undefined mechanism, diffusional creep and defect-less flow. In Figure 3-16, the horizontal axis with the homologous temperature, $\frac{T}{T_m}$, expresses the temperature of the salt as a fraction of its melting point by using the Kelvin scale. The vertical axis shows the normalized stress, $\frac{\sigma}{\mu}$, where μ is the shear modulus. The influence of one mechanism over another strongly depends upon the deviatoric stress and temperature conditions (Cella, 2003). According to Seni et al., (1984), the defect-less flow (regime 1) corresponds to salt with initially no crystal defects, but will experience deformation at the theoretical shear strength. Diffusional creep (regime 4) relates to the spontaneous formation of vacancies

that tend to appear close to the grain boundaries normal to the applied stress (Dowling, 1999) and occurs at relatively high temperatures under low stress. The Nabarro-Herring creep and Coble creep are its two subregimes, the former is where the vacancies move through the crystal lattice while the latter is when they move along grain boundaries (1999).The defect-less flow mechanism takes place in substantially high stresses that are not encountered in salt storage space nor for engineering projects (Seni et al., 1984; Yang, 2000), while diffusional creep is not representative of Brazilian salt formations. Thus, strictly the relevant mechanisms will be discussed. Understanding the salt deformation mechanisms is essential for constructing an appropriate constitutive equation and for engineering applications. Each mechanism has a constitutive equation that specifies the deformation or strain rate as a function of the imposed condition.

Figure 3-16: Typical deformation mechanism map of rock salt (Munson and Dawson, 1984).

3.8.1
Dislocation Climb

This mechanism receives its name due to its climbing deformation behavior. Dislocation climb occurs in salt rock when temperature is within moderate to high range while induced by relatively low differential stress (Botelho, 2008). It is governed by a phenomenon known as thermal activation. Thermal activation occurs when an increase in temperature in a given body causes rapid movement

among the atoms, leading to a molecular redistribution in the material structure and therefore increasing the likelihood of creep occurrence (Medeiros, 1999).

$$\dot{\varepsilon} = A_1 \cdot \left(\frac{\sigma}{G}\right)^{n_1} \cdot e^{\left(\frac{Q_1}{RT}\right)}$$

(3.11)

Where

$\dot{\varepsilon}$ = creep strain rate;

A_1 = material constant;

σ = generalized stress;

G = modulus of rigidity;

Q_1 = activation energy;

R = universal gas constant;

T = absolute temperature (Kelvin);

n_1 = stress exponent.

3.8.2
Dislocation Glide

Also known as dislocation slip, this creep mechanism is provoked by the slipping of adjacent planes in the material when the material is subjected to high levels of stress (Munson, 1989). It is represented by a hyperbolic-sine differential stress level related to thermal activation:

$$\dot{\varepsilon} = H \cdot \left(B_1 \, e^{\frac{Q_1}{RT}} + B_2 e^{\frac{Q_2}{RT}} \right) \sinh\left(\frac{q \cdot (\sigma - \sigma_0)}{G} \right)$$

(3.12)

Where

$\dot{\varepsilon}$ = creep strain rate;

σ = deviatoric stress;

σ_0 = deviatoric referential stress;

H = "Heaviside step function";

Q_1, Q_2 = energy activation;

R = universal gas constant;

T = absolute temperature (Kelvin);

B_1,B_2 = fitting constants.

3.8.3
The Undefined Mechanism

This "undefined" mechanism is given its name for not being based upon any recognized micromechanical model but it can, however, be empirically defined based on lab experiments and presents the same shape as the dislocation climb mechanism. The undefined mechanism controls creep when the evaporite is subjected to both low temperature low and stress. Poiate et al. (2006) states that this mechanism is triggered by creep in contact with salt grains by the dissolution of the salt in function of the increasing solubility while subjected to high pressures that occur in the contacts between grains.

$$\dot{\varepsilon} = A_3 \cdot \left(\frac{\sigma}{G}\right)^{n_3} \cdot e^{\left(\frac{Q_3}{RT}\right)} \tag{3.13}$$

Where

$\dot{\varepsilon}$ = creep strain rate;

A_2 = material constant;

σ = generalized stress;

G = modulus of rigidity;

Q_2 = activation energy;

R = universal gas constant;

T = absolute temperature (Kelvin);

n_2 = stress exponent.

It should be noticed that Eq. (3.13) is identical to Eq. (3.11) and is distinguishable by using its own parameters A_2, Q_2 and n_2 (Cella, 2003). It is worth clarifying that parameters Q_1 and Q_2 in the dislocation glide formula are the same as in the formulas for dislocation climb and the undefined mechanism (2003).

3.8.4
Double Mechanism model

A constitutive model was developed for salt creep by Costa (2005) after conduct-ing experiments on samples from the northeastern state of Sergipe in Brazil. Costa collected samples from the Taquari-Vassouras potash mine mentioned in Chapter 1.3 where, after several analyses, was able to modify Munson's constitutive creep law to represent the creep behavior of Brazilian salt. This was accomplished by incorporating two physical creep laws, namely dislocation glide and the undefined mechanism, into the power creep law (Medeiros, 1999); thus giving the name *double mechanism*. The double mechanism creep law is an elasto/visco-elastic model and currently yields the most suitable approximation for steady-state creep for salt rock primarily in Brazil. In recent years it has been used in the research studies from Costa et al. (2005, 2010) and Poiate et al. (2006), assuming that the mechanical behavior of salts in Taquari-Vassouras are representative of the salts found in both the Campos and Santos Basins. Being the best-fit for the behavior of Brazilian salt rock in the steady-state regime, the double mechanism was se-lected for the analyses in this research. Its constitutive equation is written as

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \cdot \left(\frac{\sigma_{dev}}{\sigma_0} \right)^n \cdot e^{\left(\frac{Q}{RT_0} - \frac{Q}{RT} \right)} \qquad (3.14)$$

Where

$\dot{\varepsilon}$ = Strain rate due to creep at the steady-state condition;

$\dot{\varepsilon}_0$ = Referential strain rate due to creep in steady state;

σ_{dev} = Creep deviatoric stress;

σ_0 = Referential deviatoric stress;

Q = Activation energy (Kcal/mol), Q = 12 kcal/mol;

R = Universal gas constant (kcal/mol.K), R = 1.9858 E-03;

T_0 = Reference temperature (K);

T = Rock temperature (K); and

n = stress exponent.

It should be noted that Tresca—and not von Mises—is the preferred measure of deviatoric stress in the above equation since salt deformation is based on maxi-

mum shear flow potential rather than an octahedral flow potential according to Fredrich et al. (2006, 2007). Further details in regard to Tresca and von Mises will be explained in Chapter 4.

To better understand the derivation of the double mechanism from the power law, Cella (2003) rewrites Eq.(3.14) as

$$\dot{\varepsilon} = \left[\left(\frac{\dot{\varepsilon}_0}{\sigma_0^n} \right) e^{\left(\frac{Q}{RT_0} - \frac{Q}{RT} \right)} \right] \sigma_{dev}^n \qquad (3.15)$$

where the terms inside the brackets in Eq. (3.15) represent the term A in the power law formula:

$$\dot{\varepsilon} = A\sigma_{dev}^n \qquad (3.16)$$

This holds true when the term m in Eq. (3.10) is equal to zero. The deviatoric stress σ_{dev} in the equations above represents the current deviatoric stress (Cella, 2003) while the referential deviatoric stress σ_0 represents the value in which the stress exponent n instantaneously changes. In his work, Costa et al. (2010) uses two values for n in halite, being 3.36 and 7.55, and where the referential deviatoric stress is equal to 10 MPa (see Figure 3-17).
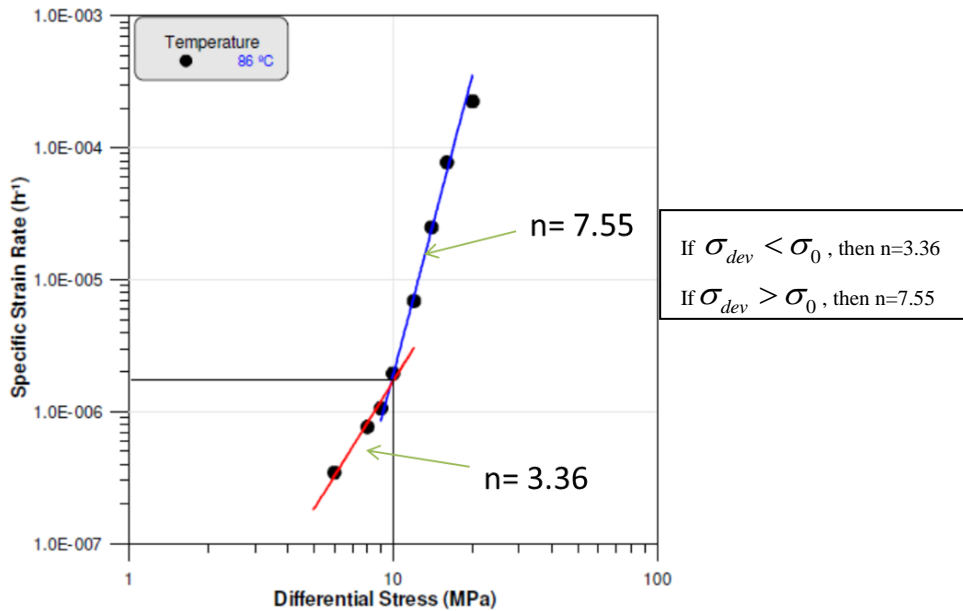

Figure 3-17: Steady-state creep strain vs. differential stress for halite (Costa et al., 2010).

3.8.5
Chapter Summary and Discussion

Salt creep has been observed in drilling within the pre-salt basins off the southeast coast of Brazil and there have been reported problems such as stuck pipe and casing collapse (Poiate et al., 2006). The challenges that salt formations bring have motivated researchers to accurately model its behavior. Rheological, empirical and physical models may be used to simulate salt creep behavior. The empirical and physical models are of interest in this work. To summarize the aforementioned physical models, the dislocation climb mechanism governs at low stress and high temperature; the undefined mechanism governs at low stress and low temperature conditions, whereas the glide mechanism governs at high stress for all temperatures. Both diffusional creep and defect-less flow regime are not applicable to salt creep in Brazilian pre-salt formations. In his work, Munson (1999) states that all of the five mechanisms are thermally activated, showing their temperature dependence. It is worth noting that creep behavior in salt rock has a common mathematical description of the micromechanical constitutive features regardless of the origin of the salt (Munson, 2004). Moreover, non-coherent separate phases of impurities found within salt do not normally create a significant change in the creep parameters (2004). There does exist other models besides the double mechanism such as the M-D model (i.e., Multi-Deformation Model) developed by Munson and Dawson (1984). This model incorporates all of the three mechanisms, having three different constitutive formulations that describe the steady-state creep model while incorporating irreversible work hardening and transient recovery creep (Yang, 2000). In other words, the M-D is an overall creep strain rate model that includes tertiary creep and damage effects. Since tertiary creep and damage effects are not of interest for salt creep drilling in this research, this model includes unnecessary complexities. Due to the fact that it was formulated based on Brazilian salt samples, the double mechanism proposed by Costa et al. (2005, 2010) seems to be the most appropriate constitutive equation representative of the salt rock in the pre-salt basins and will therefore be used in the presented analyses for this research.