Part I Basic principles

1 The tectonic stress field

My goals in writing this book are to establish basic principles, introduce practical experimental techniques and present illustrative examples of how the development of a comprehensive geomechanical model of a reservoir (and overlaying formations) provides a basis for addressing a wide range of problems that are encountered during the *life-cycle* of a hydrocarbon reservoir. These include questions that arise (i) during the exploration and assessment phase of reservoir development such as the prediction of pore pressure, hydrocarbon column heights and fault seal (or leakage) potential; (ii) during the development phase where engineers seek to optimize wellbore stability through determination of optimal well trajectories, casing set points and mud weights and geologists attempt to predict permeability anisotropy in fractured reservoirs; (iii) throughout the production phase of the reservoir that requires selection of optimal completion methodologies, the prediction of changes in reservoir performance during depletion and assessment of techniques, such as repeated hydraulic fracturing, to optimize total recovery; and (iv) during the secondary and tertiary recovery phases of reservoir development by optimizing processes such as water flooding and steam injection. Chapters 1–5 address basic principles related to the components of a comprehensive geomechanical model: the state of stress and pore pressure at depth, the constitutive laws that commonly describe rock deformation and fractures and faults in the formations of interest. Chapters 6–9 address wellbore failure and techniques for using observations of failure to constrain stress orientation and magnitude in wells of any orientation. Chapters 10–12 address case studies that apply the principles of the previous chapters to problems of wellbore stability, flow associated with fractures and faults and the effects of depletion on a reservoir and the surrounding formations.

Why stress is important

The key component of a comprehensive geomechanical model is knowledge of the current state of stress. Wellbore failure occurs because the stress concentrated around the circumference of a well exceeds the strength of a rock (Chapters 6 and 10). A fault will slip when the ratio of shear to effective normal stress resolved on the fault exceeds its frictional strength (Chapters 4, 11 and 12). Depletion causes changes in the stress state of the reservoir that can be beneficial, or detrimental, to production in a number of ways (Chapter 12). As emphasized throughout this book, determination of the state of stress at depth in oil and gas fields is a tractable problem that can be addressed with data that are routinely obtained (or are straightforwardly obtainable) when wells are drilled.

In this chapter, I start with the basic definition of a stress tensor and the physical meaning of principal stresses. These concepts are important to establish a common vocabulary among readers with diverse backgrounds and are essential for understanding how stress fields change around wellbores (Chapters 6 and 8) and in the vicinity of complex structures such as salt domes (as discussed at the end of the chapter). I also introduce a number of fundamental principles about the tectonic stress field at a regional scale in this chapter. These principles are revisited at scales ranging from individual wellbores to lithospheric plates in Chapter 9. While many of these principles were established with data from regions not associated with oil and gas development, they have proven to have broad relevance to problems encountered in the petroleum industry. For example, issues related to global and regional stress patterns are quite useful when working in areas with little pre-existing well control or when attempting to extrapolate knowledge of stress orientation and relative stress magnitudes from one area to another.

Stress in the earth's crust

Compressive stress exists everywhere at depth in the earth. Stress magnitudes depend on depth, pore pressure and active geologic processes that act at a variety of different spatial and temporal scales. There are three fundamental characteristics about the stress field that are of first-order importance throughout this book:

- Knowledge of stress at depth is of fundamental importance for addressing a wide range of practical problems in geomechanics within oil, gas and geothermal reservoirs and in the overlaying formations.
- The *in situ* stress field at depth is remarkably coherent over a variety of scales. These scales become self-evident as data from various sources are analyzed and synthesized.
- It is relatively straightforward to measure, estimate or constrain stress magnitudes at depth using techniques that are practical to implement in oil, gas and geothermal reservoirs. Hence, the state of stress is directly determinable using techniques that will be discussed in the chapters that follow.

In short, the *in situ* stress field in practice is determinable, comprehensible and needed to address a wide range of problems in reservoir geomechanics.

In this chapter I review a number of key points about the state of stress in the upper part of the earth's crust. First, we establish the mathematical terminology that will be used throughout this book and some of the fundamental physical concepts and definitions that make it possible to address many practical problems in subsequent chapters. While there are many excellent texts on elasticity and continuum mechanics that discuss stress at great length, it is useful to set forth a few basics and establish a consistent nomenclature for use throughout this book. Next, the relative magnitudes of *in situ* stresses are discussed in terms of E. M. Anderson's simple, but powerful, classification scheme (Anderson 1951) based on the style of faulting that would be induced by a given stress state. This scheme leads naturally to some general constraints on stress magnitudes as a function of depth and pore pressure. These constraints will be revisited and refined, first in Chapter 4 where we will discuss constraints on stress magnitudes in terms of the strength of the crust and further refined when we incorporate information about the presence (or absence) of wellbore failures (Chapters 7 and 8).

In the next section of this chapter I briefly review some of the stress indicators that will be discussed at length in subsequent chapters. I do so in order to review synoptically some general principles about the state of stress in the crust that can be derived from compilations of stress information at a variety of scales. The overall coherence of the stress field, even in areas of active tectonic deformation and geologic complexity is now a demonstrable fact, based on thousands of observations from sites around the world (in a wide range of geologic settings). We next briefly review several mechanisms that control crustal stress at regional scale. Finally, we consider the localized rotation of stress in the presence of near frictionless interfaces, such as salt bodies in sedimentary basins such as the Gulf of Mexico.

Basic definitions

In simplest terms, stress is defined as a force acting over a given area. To conform with common practice in the oil and gas industry around the world I utilize throughout the book calculations and field examples using both English units (psi) and SI units (megapascals (MPa), where 1 MPa = 145 psi).

To be more precise, stress is a tensor which describes the density of forces acting on all surfaces passing through a given point. In terms of continuum mechanics, the stresses acting on a homogeneous, isotropic body at depth are describable as a second-rank tensor, with nine components (Figure 1.1, left).

$$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \tag{1.1}$$

The subscripts of the individual stress components refer to the direction that a given force is acting and the face of the unit cube upon which the stress component acts. Thus, any given stress component represents a force acting in a specific direction on a unit area of given orientation. As illustrated in the left side of Figure 1.1, a stress tensor can

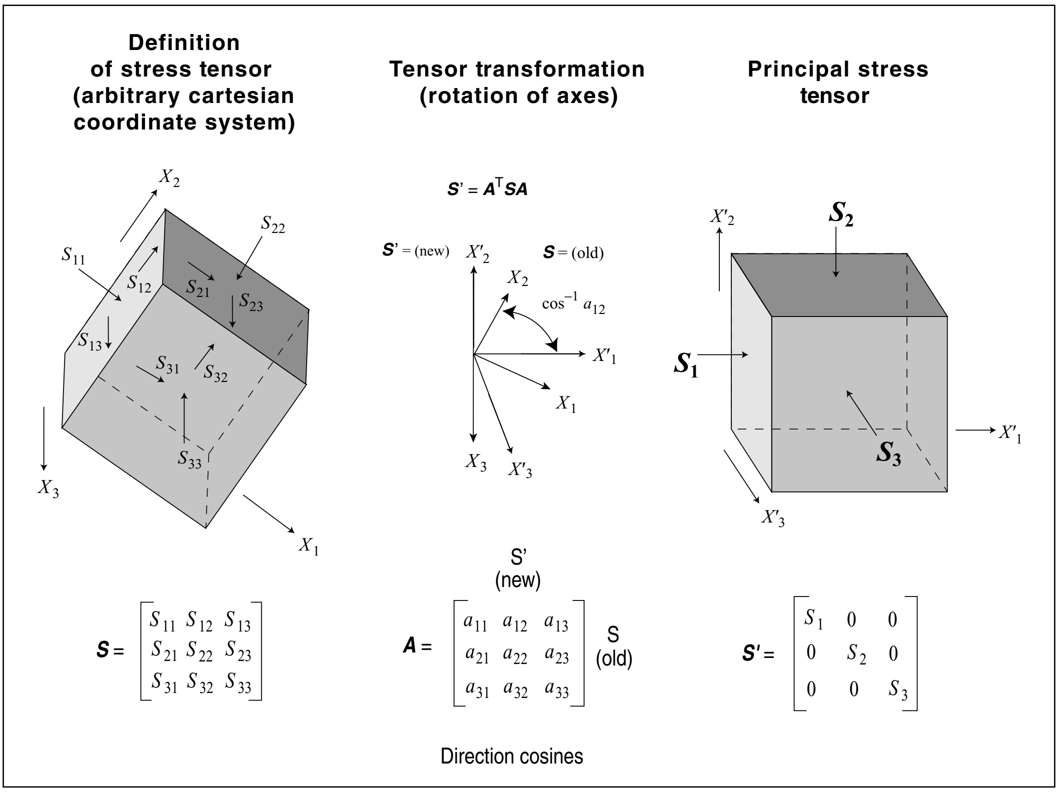

Figure 1.1. Definition of stress tensor in an arbitrary cartesian coordinate system (Engelder and Leftwich 1997), rotation of stress coordinate systems through tensor transformation (center) and principal stresses as defined in a coordinate system in which shear stresses vanish (right).

be defined in terms of any reference system. An arbitrarily oriented cartesian coordinate system is shown. Because of equilibrium conditions

$$\begin{aligned} s_{12} &= s_{21} \\ s_{13} &= s_{31} \\ s_{23} &= s_{32} \end{aligned} \tag{1.2}$$

so that the order of the subscripts is unimportant. In general, to fully describe the state of stress at depth, one must define six stress magnitudes or three stress magnitudes and the three angles that define the orientation of the stress coordinate system with respect to a reference coordinate system (such as geographic coordinates, wellbore coordinates, etc.).

In keeping with the majority of workers in rock mechanics, tectonophysics and structural geology, I utilize the convention that compressive stress is positive because *in situ* stresses at depths greater than a few tens of meters in the earth are *always* compressive. Tensile stresses do not exist at depth in the earth for two fundamental reasons. First, because the tensile strength of rock is generally quite low (see Chapter 4), significant tensile stress cannot be supported in the earth. Second, because there is always a fluid phase saturating the pore space of rock at depth (except at depths shallower than the water table), the pore pressure resulting from this fluid phase would cause the rock to hydraulically fracture should the least compressive stress reach a value close to the value of the pore pressure (Chapter 4).

Once a stress tensor is known in one coordinate system, it is possible to evaluate stresses in any other coordinate system via tensor transformation. To accomplish this transformation, we need to specify the direction cosines (a_{ij}, as illustrated in Figure 1.1) that describe the rotation of the coordinate axes between the old and new coordinate systems. Mathematically, the equation which accomplishes this is

$$\boldsymbol{S}' = \boldsymbol{A}^{\mathrm{T}}\boldsymbol{S}\boldsymbol{A} \tag{1.3}$$

where,

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

There are two reasons why the ability to transform coordinate systems is of fundamental importance here. First, once we know an *in situ* stress field in some coordinate system, we can compute stresses in any other. For example, if we know the stress state in a geographic coordinate system, we will show how it is possible to derive the stress field surrounding a wellbore of arbitrary orientation (Chapter 8) to address problems of stability (Chapter 10), or along a fault plane (Chapter 5) to gauge its proximity to frictional failure and slip (Chapter 11). Another reason why tensor transformation is important is because we can choose to describe the state of stress at depth in terms of the principal stresses (i.e. those acting in the principal coordinate system), making the issue of describing the stress state *in situ* appreciably easier. The principal coordinate system is the one in which shear stresses vanish and three principal stresses, $S_1 \geq S_2 \geq S_3$ fully describe the stress field (as illustrated in the right side of Figure 1.1). In the principal coordinate system we have diagonalized the stress tensor such that the principal stresses correspond to the eigenvalues of the stress tensor and the principal stress directions correspond to its eigenvectors:

$$\boldsymbol{S}' = \begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{bmatrix} \tag{1.4}$$

The reason this concept is so important is that because the earth's surface is in contact with a fluid (either air or water) which cannot support shear tractions, it is a principal stress plane. Thus, one principal stress is generally normal to the earth's surface with the other two principal stresses acting in an approximately horizontal plane. While it is clear that this must be true close to the earth's surface, compilation of earthquake focal mechanism data and other stress indicators (described below) suggest that it is also generally true to the depth of the brittle–ductile transition in the upper crust at about 15–20 km depth (Zoback and Zoback 1980, 1989; Zoback 1992). Assuming this is the case, we must define only four parameters to fully describe the state of stress at depth: three principal stress magnitudes, S_v, the vertical stress, corresponding to the weight of the overburden; S_{Hmax}, the maximum principal horizontal stress; and S_{hmin}, the minimum principal horizontal stress and one stress orientation, usually taken to be the azimuth of the maximum horizontal compression, S_{Hmax}. This obviously helps make stress determination in the crust (as well as description of the *in situ* stress tensor) a much more tractable problem than it might first appear.

Relative stress magnitudes and E. M. Anderson's classification scheme

In applying these concepts to the earth's crust, it is helpful to consider the magnitudes of the greatest, intermediate, and least principal stress at depth (S_1, S_2, and S_3) in terms of S_v, S_{Hmax} and S_{hmin} in the manner originally proposed by E. M. Anderson and alluded to above. As illustrated in Figure 1.2 and Table 1.1, the Anderson scheme classifies an area as being characterized by normal, strike-slip or reverse faulting depending on whether (i) the crust is extending and steeply dipping normal faults accommodate movement of the *hanging wall* (the block of rock above the fault) downward with respect to the *footwall* (the block below the fault), (ii) blocks of crust are sliding horizontally past one another along nearly vertical strike-slip faults or (iii) the crust is in compression and relatively shallow-dipping reverse faults are associated with the hanging wall block moving upward with respect to the footwall block. The Anderson classification scheme also defines the horizontal principal stress magnitudes with respect to the vertical stress. The vertical stress, S_v, is the maximum principal stress (S_1) in normal faulting regimes, the intermediate principal stress (S_2) in strike-slip regimes and the least principal stress (S_3) in reverse faulting regimes. The dip and strike of expected normal, strike-slip and reverse faults with respect to the principal stress are discussed in Chapter 4.

Table 1.1. *Relative stress magnitudes and faulting regimes*

Regime	Stress		
	S_1	S_2	S_3
Normal	S_v	S_{Hmax}	S_{hmin}
Strike-slip	S_{Hmax}	S_v	S_{hmin}
Reverse	S_{Hmax}	S_{hmin}	S_v

The magnitude of S_v is equivalent to integration of rock densities from the surface to the depth of interest, z. In other words,

$$S_v = \int_0^z \rho(z) g \mathrm{d}z \approx \overline{\rho} g z \tag{1.5}$$

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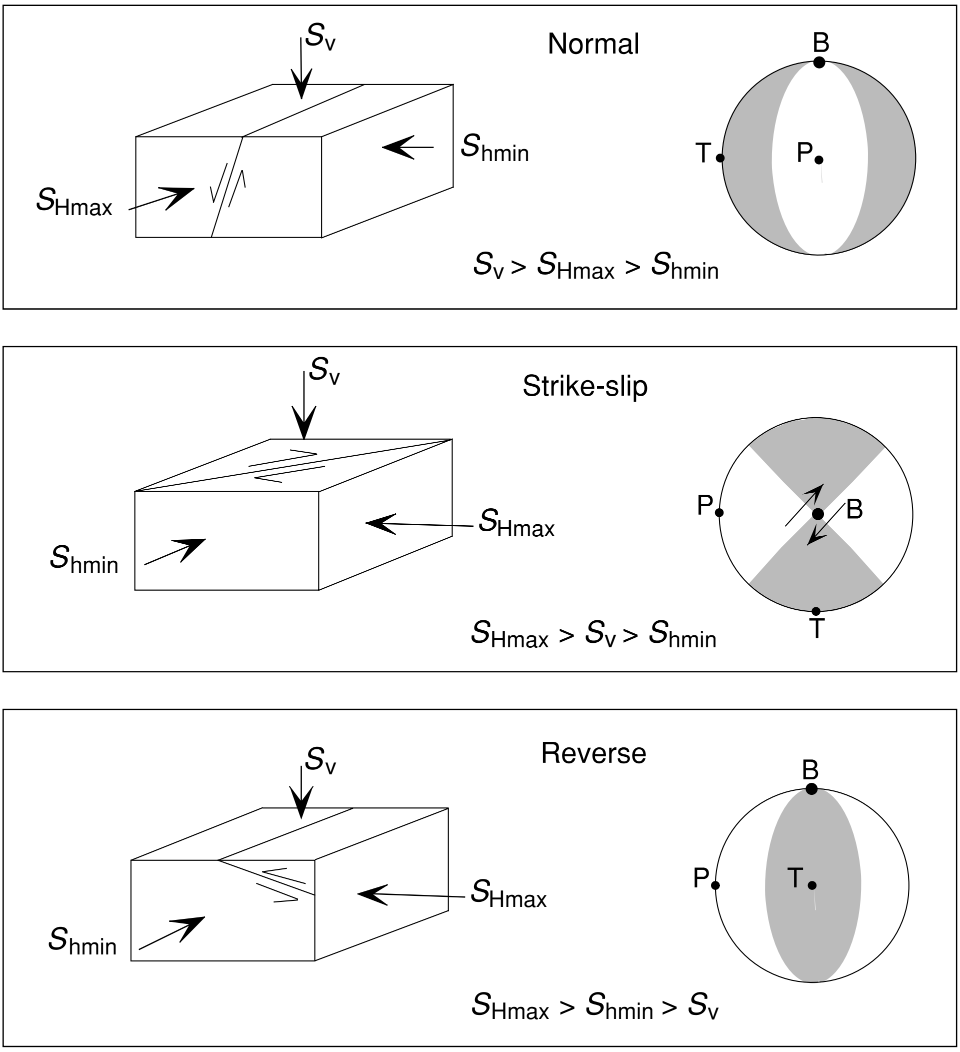

Figure 1.2. E. M. Anderson's classification scheme for relative stress magnitudes in normal, strike-slip and reverse faulting regions. Earthquake focal mechanisms, the *beach balls* on the right, are explained in Chapter 5.

where $\rho(z)$ is the density as a function of depth, g is gravitational acceleration and $\overline{\rho}$ is the mean overburden density (Jaeger and Cook 1971). In offshore areas, we correct for water depth

$$S_v = \rho_w g z_w + \int_{z_w}^{z} \rho(z) g \mathrm{d}z \approx \rho_w g z_w + \overline{\rho} g (z - z_w) \tag{1.6}$$

where ρ_w is the density of water and z_w is the water depth. As $\rho_w \sim 1$ g/cm^3 (1.0 SG), water pressure (hydrostatic pressure) increases at a rate of 10 MPa/km (0.44 psi/ft). Most clastic sedimentary rock has an average density of about 2.3 g/cm^3 which corresponds to a porosity of about 15%. This results in a vertical principal stress that increases with depth at a rate of 23 MPa/km (or conveniently, ~1 psi/ft). Correspondingly, the magnitudes of the two horizontal principal stresses increase with depth. Some of the practical problems associated with the computation of S_v using equations (1.5) and (1.6) relate to the facts that density logs frequently measure anomalously low density when the well is rugose and density is often not measured all the way up to the seafloor when drilling offshore. This is illustrated by the density log in Figure 1.3. The density log (top figure) is somewhat noisy and no data are available between the seafloor (1000 ft below the platform) and 3600 ft. This makes it necessary to extrapolate densities to the seafloor where the density is quite low. Integration of the density log using equation (1.6) yields the overburden stress as a function of depth (middle figure). The rate at which the overburden stress gradient increases with depth is shown in the lower figure. Note that because of the water depth and low densities immediately below the seafloor (or mud line), the overburden stress gradient is only 0.9 psi/ft at a depth of 14,000 ft, even though density exceeds 2.3 g/cm^3 below 8000 ft.

According to the Anderson classification scheme, the horizontal principal stresses may be less than, or greater than, the vertical stress, depending on the geological setting. The relative magnitudes of the principal stresses are simply related to the faulting style currently active in a region. As illustrated in Figure 1.2, the vertical stress dominates in normal faulting regions ($S_1 = S_v$), and fault slip occurs when the least horizontal principal stress (S_{hmin}) reaches a sufficiently low value at any given depth depending on S_v and pore pressure (Chapter 4). Conversely, when both horizontal stresses exceed the vertical stress ($S_3 = S_v$) crustal shortening is accommodated through reverse faulting when the maximum horizontal principal stress (S_{Hmax}) is sufficiently larger than the vertical stress. Strike-slip faulting represents an intermediate stress state ($S_2 = S_v$), where the maximum horizontal stress is greater than the vertical stress and the minimum horizontal stress is less ($S_{Hmax} \geq S_v \geq S_{hmin}$). In this case, faulting occurs when the difference between S_{Hmax} and S_{hmin} is sufficiently large. The angle between the principal stress directions and the strike and dip of active faults is discussed in Chapter 5.

Third, an implicit aspect of Andersonian faulting theory is that the magnitudes of the three principal stresses at any depth are limited by the strength of the crust at depth. An obvious upper limit for stress magnitudes might be the compressive strength of rock. In fact, a more realistic upper limit for the magnitudes of principal stresses *in situ* is the frictional strength of previously faulted rock, as essentially all rocks at depth contain pre-existing fractures and faults (Chapter 4).

Of critical interest in this book is the current state of stress (or perhaps that which existed at the onset of reservoir exploitation) because that is the stress state applicable in the problems of reservoir geomechanics considered in this book. Hence, a point about Figure 1.2 worth emphasizing is that the figure shows the relationship between states of stress and the style of faulting consistent with that stress state. In some parts of the world