Stress paths leading to fracture propagation at various stages in the rock cycle: What are the processes for driving stress to failure in caprock seals?

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Brittle failure of rock is commonly defined by one or more criteria, usually denoted by yield surfaces on a plot of stress. A yield surface bounds the permissible stress states within the rock by marking a region beyond which stress can not be supported by the rock. The track that stress follows in moving from one permissible stress state to the next is called the **stress path**. In most environments important to the petroleum industry, the stress path starts at the most stable of stress states, the isotropic stress state which is also called lithostatic stress

$$S_H = S_h = S_v \text{ and } \sigma_1 = \sigma_2 = \sigma_3 \qquad (1)$$

where S_i are components of total stress, σ_i are components of effective stress (i.e., $\sigma_i = S_i - P_p$) and P_p is pore pressure. An isotropic state of stress is found in mud at the seabed and other subaqueous depositional environments (Fig. 1). Almost without exception, stress eventually reaches a failure envelope during the sedimentary-rock cycle that starts at deposition and includes burial, lithification, and a variety of deformational events ending with exhumation and finally denudation. In the petroleum and natural gas environment the rock cycle is closely coupled to the tectonic cycle which often starts with basin subsidence on a passive margin or in a foreland, goes through a stage of tectonic inversion or strong tectonic convergence and ends with an isostatic adjustment causing uplift and exhumation.

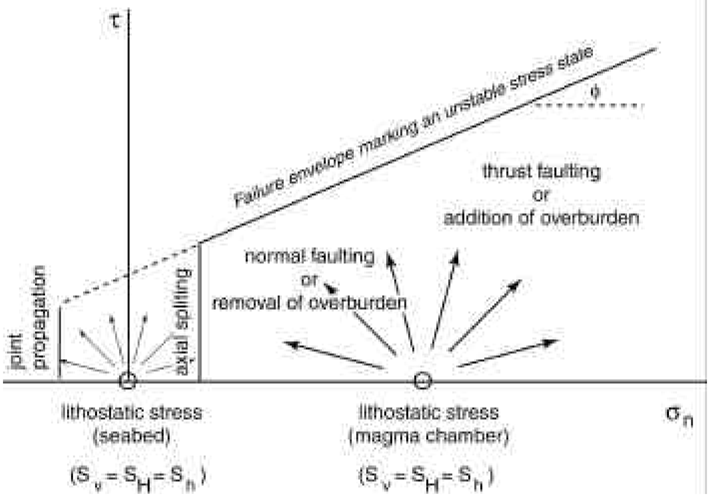

Figure 1. The yield locus in stress space (τ-σ_n) for a potential discontinuity. A Mohr-Coulomb envelope is truncated by two opening critera: axial splitting and joint propagation.

This abstract identifies the various disembarkation points for fracture generation along the path that stress follows in sedimentary rocks of the petroleum and natural gas environment (Table 1). ***Disembarkation*** refers to any one of a number of processes responsible for driving stress to the failure envelope during the history of a sedimentary basin (e.g., Fig 1). By disembarking, the rock leaves its normal (i.e., permissible) stable state and ruptures due to an unstable stress state. Rupture, of course, is one of the most common ways by which seal integrity is lost. It is the purpose of this abstract to provide an understanding of processes that a petroleum geologist might model in developing a quantitative method for predicting whether or not there was failure of seals surrounding his/her fractured reservoir.

Stress paths including those in crystalline rocks as well start from a state of lithostatic stress where the three principal stresses are equal. In sedimentary rocks this is the depositional phase during which the process for disembarkation is shrinkage leading to the propagation of Neptunian joints and mud cracks (Table 1). Drained consolidation follows with principal stresses reflecting a uniaxial strain state. At this stage disembarkation is marked by liquefaction leading to soft sediment structures and clastic dikes. Undrained consolidation is next with pore pressure driven above hydrostatic as a consequence of disequilibrium compaction. Disembarkation is by tectonic compaction (or decompaction) causing early coal cleat and pervasive faults in chalk. Stress is coupled to pore pressure generation during a fourth phase where poroelastic deformation, another disembarkation process, drives the horizontal stress upward. Natural hydraulic fractures are a manifestation of this stage of rapid pore pressure increase. Tectonic stretching, a fifth disembarkation process, arises from a friction-controlled state of stress in sedimentary rocks. Joints such as those found in the hinges of folds are characteristic of this stress state. With the generation of faults under tectonic stress, local process zones are generated by a disembarkation process

Table 1. Disembarkation points leading to brittle fracture during the history of a sedimentary basin

Disem-barkation point	Process for disembarkation	Geological process (tectonic setting)	Primary regional stress state	Pore pressure	Sh-Pp Coupling Mechanism	Fracture Type	Name of fractures
1	Shrinkage	deposition	Sv = SH = Sh ~ 0	normal	surface tension	joints	Neptunian joints Mud cracks
2	Liquefaction	drained consolidation (extensional basin)	Sv > SH = Sh	normal	consolidation	joints	Sand dikes
3	Tectonic compaction	undrained consolidation (extensional or foreland basin)	Sv > SH > Sh	abnormal	consolidation	shear fractures	North sea faults
	(or decompaction)		SH > Sv > Sh			joints	Coal cleats
4	Poroelastic deformation	pore pressure generation	(SH > Sv) or	abnormal	poroelasticity	joints	Hydraulic shrinkage cracks (NHF)
			(Sv > SH) > Sh			joints	Veins
5	Tectonic stretching	regional compression (extensional or foreland basin)	SH > Sv > Sh	normal/ abnormal	friction & poroelastcity	joints shear fractures	Fold-related jointing Regional jointing
6	Stress concentration	extension or compression (extensional or foreland basin)	SH > Sh > Sv	normal/ abnormal	friction & poroelasticity	joints shear fractures	Crack-tip stress concentration Fault-related fracturing
7	Exhumation	uplift (isostatic adjustment)	Sv > SH = Sh	normal	poroelasticity	joints	Neotectonic joints
8	Denudation	erosion	Sv = 0; SH = Sh > 0	dry		joints	Axial-splitting cracks Exfoliation fractures

called stress concentration. The final two phases of the rock cycle are found in the form of the stress state as a consequence of disembarkation accompanying exhumation and denudation.

Disembarkation points 3, 4, 5, and 6 are most likely to affect the integrity of seals. As an example of the use of disembarkation points to understand seal integrity, this abstract examines the mechanism leading to the stress path for disembarkation point 4 (Table 1). Seals commonly lead to the development of abnormal fluid pressures. In some instances, a tall hydrocarbon column whose oil-water or gas water contact is at hydrostatic pressure will be overpressured at the top of the column. In other cases a reservoir compartment completely encased in a seal rock like shale can become highly overpressured by a number of mechanisms including compaction disequilibrium, tectonic compaction, aquathermal pressuring, and the generation of hydrocarbons (i.e., Swarbrick, 1998). Hydrocarbon generation is particularly interesting because it is a mechanism that can act to increase P_p without increase in depth of burial or tectonic compaction, provided that burial has taken the rock to the prescribed depth for generation. It alone can affect state of stress through S_h-P_p coupling where a geological stress path , κ, is dictated by change in pore pressure, P_p.

If overburden does not change during hydrocarbon generation in a sealed environment, $R = \frac{S_h}{S_v}$ may be used to track the evolution of stress where S_v remains a constant. We see that, R is driven upward in all tectonic environments characterized by hydrocarbon generation (Fig. 2b). Here κ is a function of the elastic properties of rock according to

$$^{p}k = 1 - k = a_{b}\frac{n}{1-n}\,. \qquad (2)$$

where α_b is the coefficient of poroelasticity or Biot's coefficient and ν is Poisson's ratio. In this case, poroelastic deformation is that mechanism that controls whether or not seals rutpure. If overburden does not change during hydrocarbon generation in a sealed environment, then

$$\Delta S_h = \frac{1-2n}{1-n}a\Delta P_p \qquad (3)$$

as formulated by Anderson (1973). The correlation between increase in stress and pore pressure in deep basin environments suggests that poroelastic deformation is an active S_h-P_p coupling mechanism in several basins (Engelder and Fischer, 1994).

To develop a general sense for stress paths when poroelasticity is the S_h-P_p coupling mechanism, we use stress-depth curves for rock well into the oil window at a depth of, say, about 4000m (Fig. 2a). By this time lithification has changed the properties of the rock so that consolidation no longer takes place (Fig 2b). In effect, cementation and other diagenetic effects has moved the yield surface much further into stress space. Hence, the actual state of stress is no longer in contact with the yield surface for consolidation (Fig. 2c). While the pore pressure is increasing, poroelastic deformation causes an increase in S_h as predicted by (3). Consequently, R increases and σ_d decreases (Fig. 2b & c). This effect is similar to the action of tectonic compaction which is illustrated by the reduction of the Mohr circle through the origin in τ-σ_n space to allow contact with the joint-propagation envelope (B in Fig. 2c).

Likewise, the geological stress path enters the negative-mean-effective-stress field in σ_d-σ_m space. Notice, however, that the final state of stress for poroelastic deformation is more likely to remain in the normal fault regime (i.e., A in Fig. 2c) in comparison with tectonic compaction where compression caused a switch to either the strike-slip or thrust fault regime.

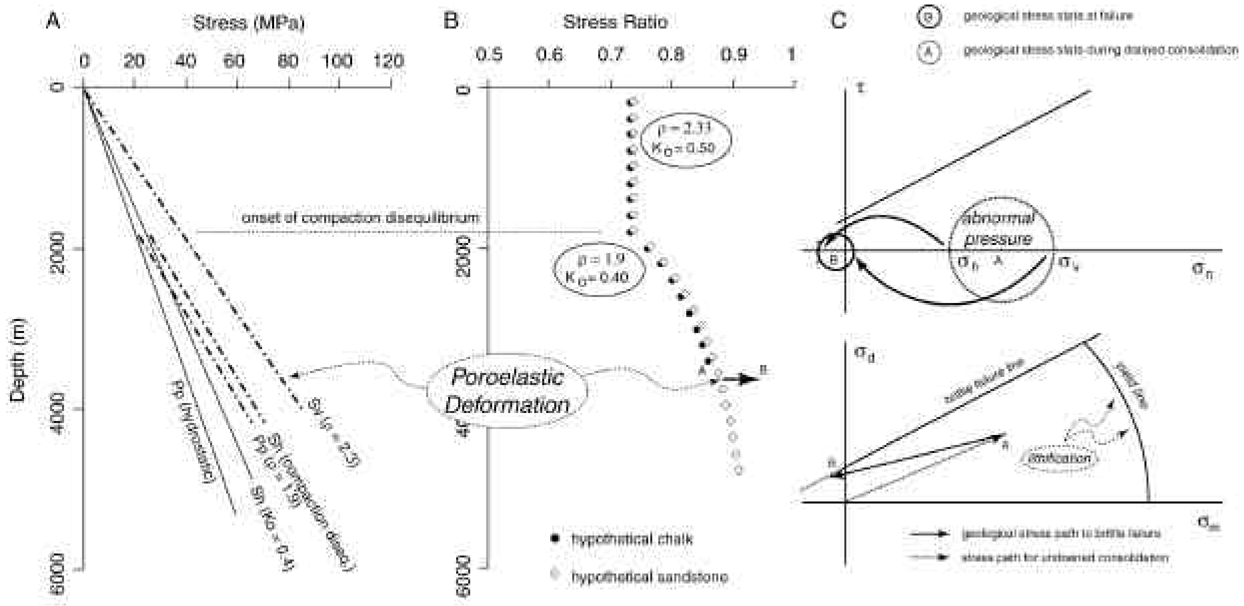

Figure 2. Stress paths at disembarkation point 4: poroelastic deformation. A. Total stress-depth (S_h-z) plot showing trend lines for overburden [S_v ($\rho = 2.3$)], total horizontal stress under hydrostatic (i.e., drained) conditions [S_h(K_o = 0.4)], total horizontal stress under undrained conditions [S_h (compaction diseq.)], hydrostatic pore pressure [P_p (hydrostatic)] and pore pressure under undrained conditions [P_p ($\rho = 1.9$)]. B. R-z plot showing a stress path for a hypothetical chalk and a hypothetical sandstone. C. Yield envelopes for brittle fracture plotted in shear stress vs. effective normal stress (τ-σ_n) space and differential stress vs. effective mean stress (σ_d-σ_m) space. The yield line for consolidation has been driven further into stress space by lithification. Mohr circles and geological stress paths shown as indicated. Capital letters (i.e., A, B, etc.) denote mean stress on both diagrams. Stress axes are not to scale.