

ژئومکانیک مخازن هیدروکربوری

رفتار سنگ و تنش اطراف چاه

Formation Strength

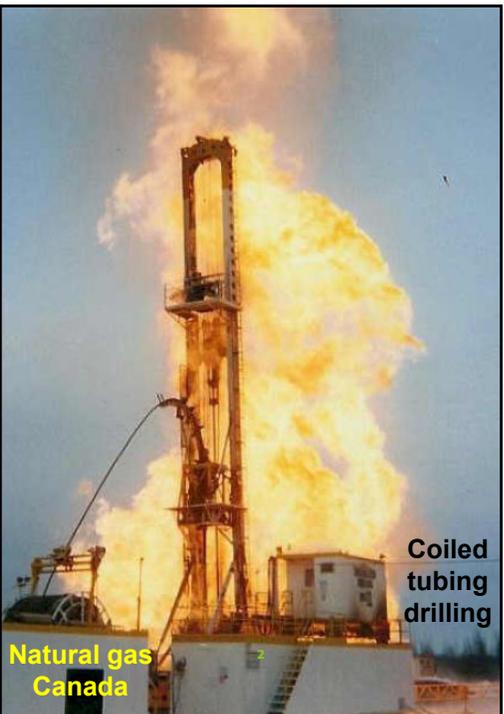
Dr. Hasan Ghasemzadeh

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Petroleum Geomechanics

Bay of Campeche, Mexico

1



## Major Drilling Problems

- ▶ Blowout of fluids under high pressure
- ▶ Lost circulation (often leading to blowouts)
- ▶ Massive shale instability
  - ▶ Chemical reasons – ductile unfractured shales, incompatibility with oil-base mud
  - ▶ Mechanical reasons – highly fractured shale or coal, fissile shale and horizontal wells
  - ▶ Stress reasons – high compressive stress fields
- ▶ Squeeze while drilling salt
- ▶ Induced slip of high angle joints

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Slate displaying fissility

### تانسور تنش

تانسور مرتبه دوم تنش

$$\sigma = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

$\tau_{ij} = \tau_{ji}$  هنگامیکه گشتاورهای جرمی وجود ندارند

این تانسور به صورت یک بردار با شش مولفه نمایش داده می شود:

$$\sigma^T = \{ \sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{yz}, \tau_{zx} \}$$

4

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## تنش های اصلی و مستقل های تنش

$$\sigma = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

مقادیر ویژه تانسور تنش

$$\det(\sigma - \lambda I) = 0$$

$$\lambda^3 - (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})\lambda^2 + (\sigma_{xx}\sigma_{yy} + \sigma_{yy}\sigma_{zz} + \sigma_{zz}\sigma_{xx} - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2)\lambda - (\sigma_{xx}\sigma_{yy}\sigma_{zz} + 2\tau_{xy}\tau_{yz}\tau_{zx} - \sigma_{xx}\tau_{yz}^2 - \sigma_{yy}\tau_{zx}^2 - \sigma_{zz}\tau_{xy}^2) = 0$$

در این وضعیت تنش برشی نداریم

مستقل های تنش به جهت محورها وابسته نیستند

$$J_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} = \sigma_1 + \sigma_2 + \sigma_3$$

$$J_2 = \sigma_{xx}\sigma_{yy} + \sigma_{yy}\sigma_{zz} + \sigma_{zz}\sigma_{xx} - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2 = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1$$

$$J_3 = \sigma_{xx}\sigma_{yy}\sigma_{zz} + 2\tau_{xy}\tau_{yz}\tau_{zx} - \sigma_{xx}\tau_{yz}^2 - \sigma_{yy}\tau_{zx}^2 - \sigma_{zz}\tau_{xy}^2 = \sigma_1\sigma_2\sigma_3$$

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5

## تانسور کرنش

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}$$

تانسور کرنش

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} \quad \frac{1}{2} \gamma_{xy} = \varepsilon_{xy} = \frac{1}{2} \left\{ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right\}$$

$$\varepsilon_{yy} = \frac{\partial v}{\partial y} \quad \frac{1}{2} \gamma_{yz} = \varepsilon_{yz} = \frac{1}{2} \left\{ \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right\}$$

$$\varepsilon_{zz} = \frac{\partial w}{\partial z} \quad \frac{1}{2} \gamma_{zx} = \varepsilon_{zx} = \frac{1}{2} \left\{ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right\}$$

$$\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} \quad \text{تغییر حجم با تقریب برابر مستقل اول کرنش}$$

$$\left\{ \varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yz}, \gamma_{zx} \right\}$$

جهت سهولت

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6

### رابطه تنش - کرنش

Hooke's Law:

$$\sigma_i = \overline{C}_{ij} \varepsilon_j$$

Where:

$$\overline{C}_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{34} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix}$$

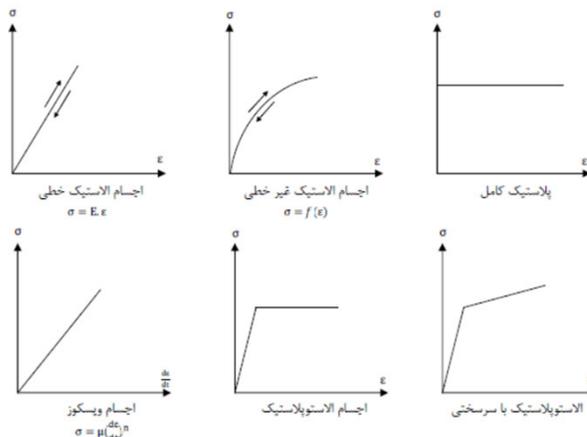
در حالت الاستیک، همگن و همسانگرد تنها دو ضریب مستقل هستند

فرض های بالا برای سنگ همواره صحیح نیست و اثرات تنش های دور گیر حرارت، زمان و نیز ناهمسانگردی ممکن است در نظر گرفته شود

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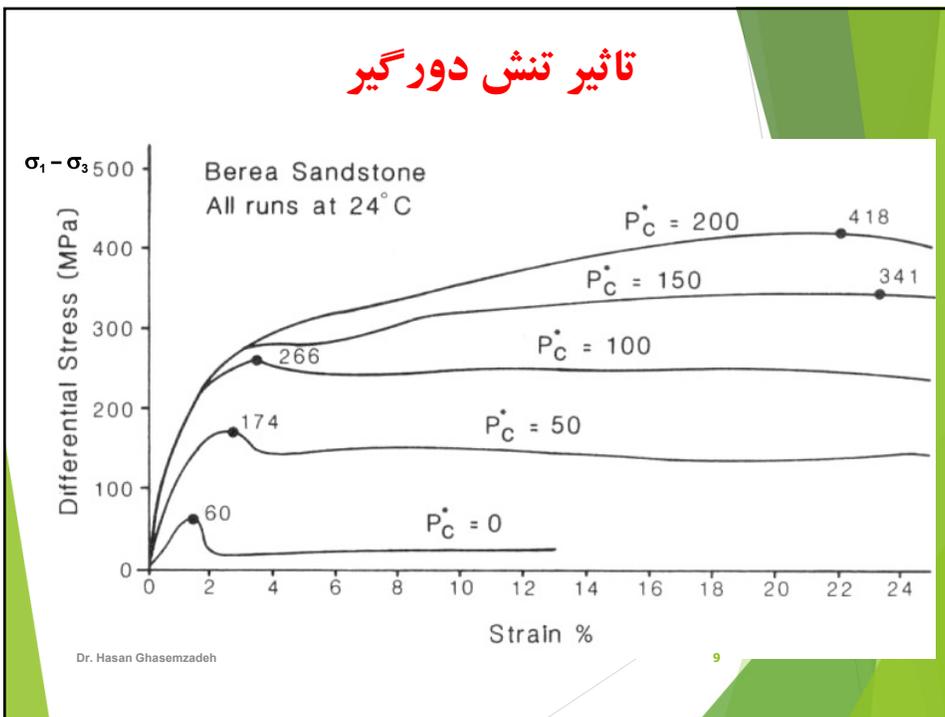
### رابطه تنش - کرنش

فرض های بالا برای سنگ همواره صحیح نیست و اثرات تنش های دور گیر حرارت، زمان و نیز ناهمسانگردی ممکن است در نظر گرفته شود

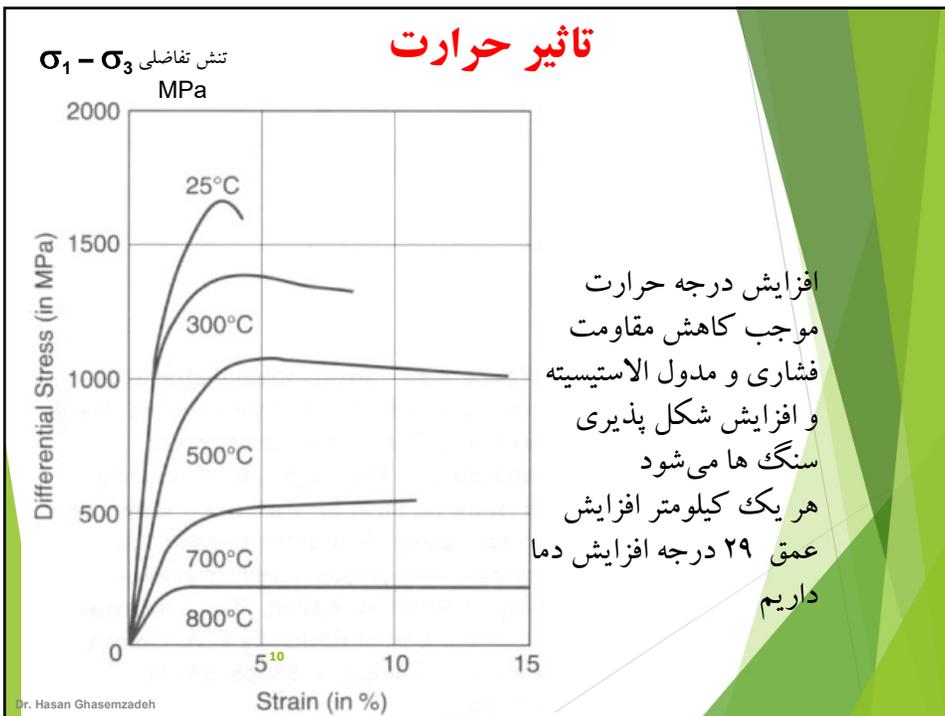


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### تأثير تنش دور گیر



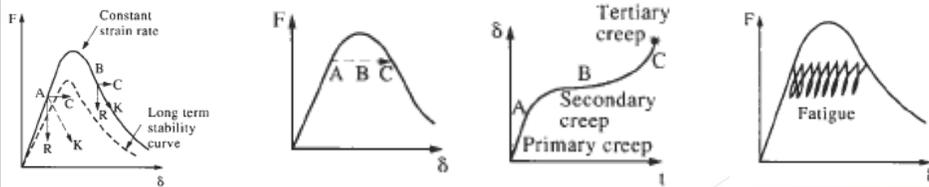
### تأثير حرارت



افزایش درجه حرارت موجب کاهش مقاومت فشاری و مدول الاستیسیته و افزایش شکل پذیری سنگ ها می شود هر یک کیلومتر افزایش عمق ۲۹ درجه افزایش دما داریم

## تأثير زمان

- (a) **strain rate**—the total form of the complete stress–strain curve is a function of the applied strain rate;
- (b) **creep**—a material continues to strain when the applied stress is held constant;
- (c) **relaxation**—there is a decrease in stress within the material when the applied strain is held constant;
- (d) **fatigue**—there is an increase in strain due to cyclical changes in stress.



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11

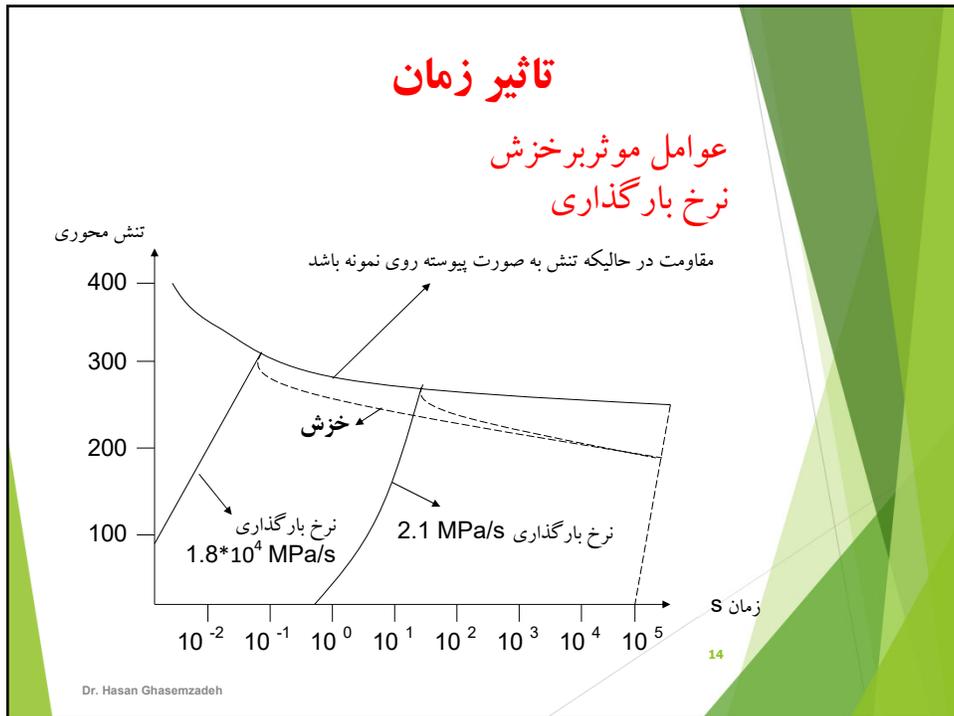
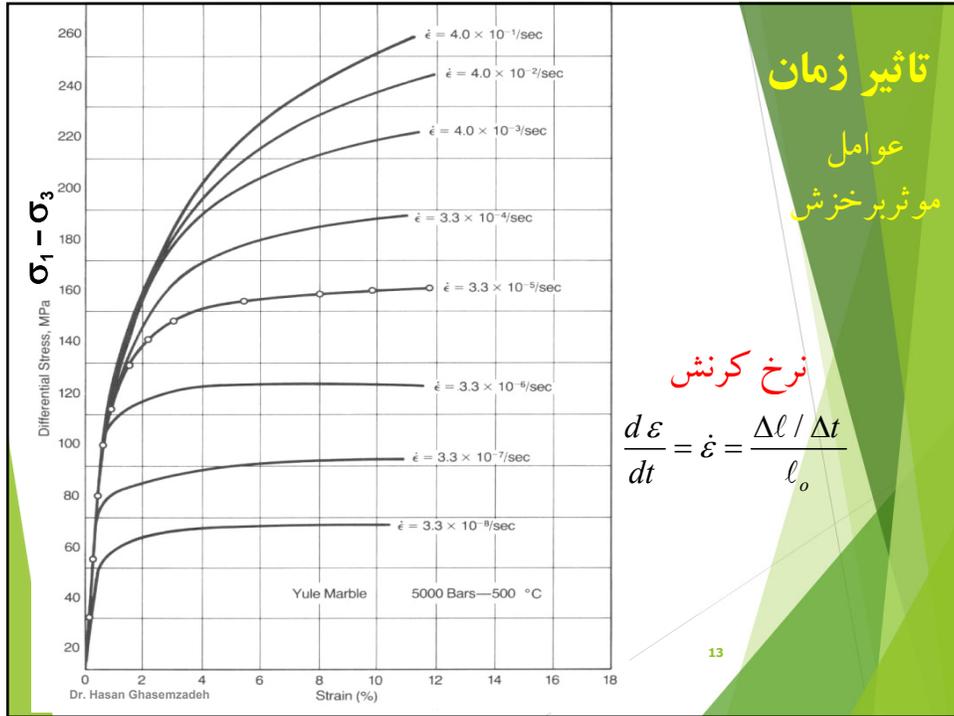
## تأثير زمان

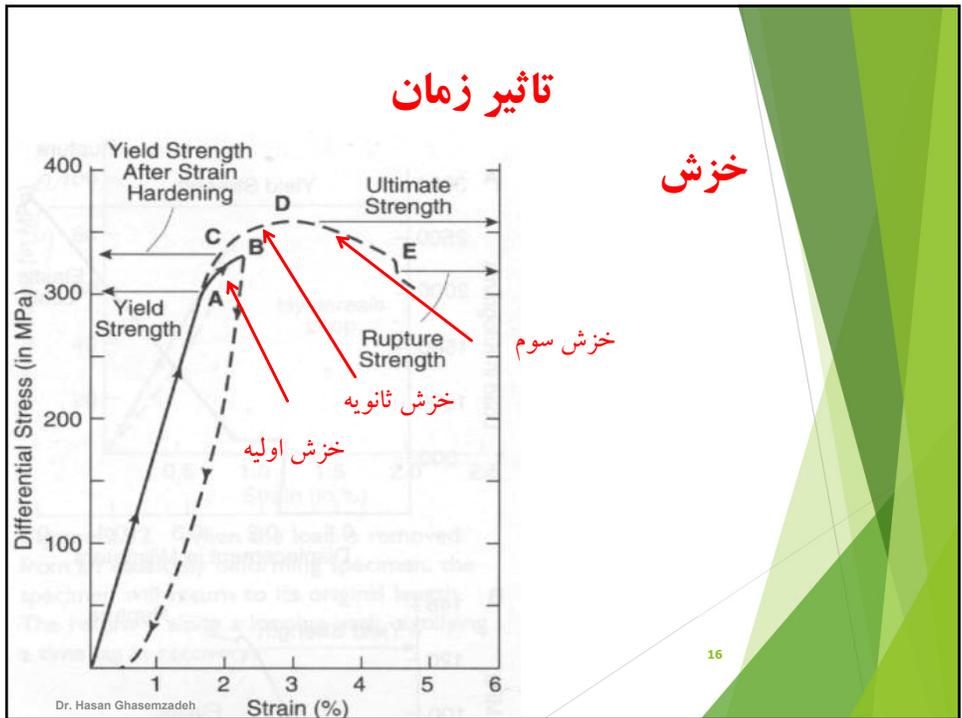
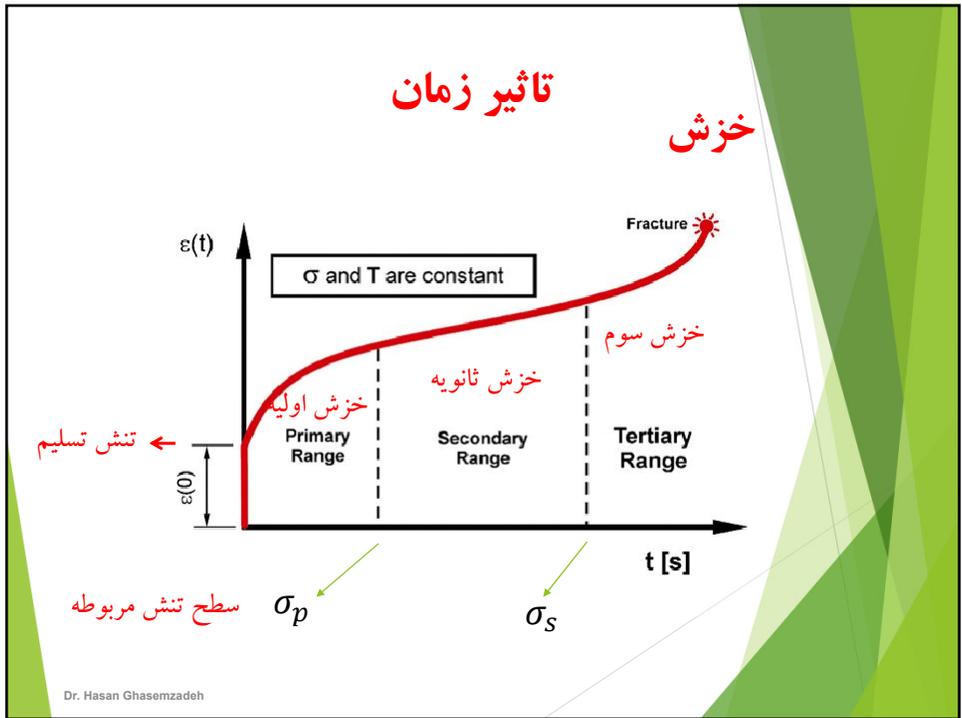
### عوامل موثر بر خزش

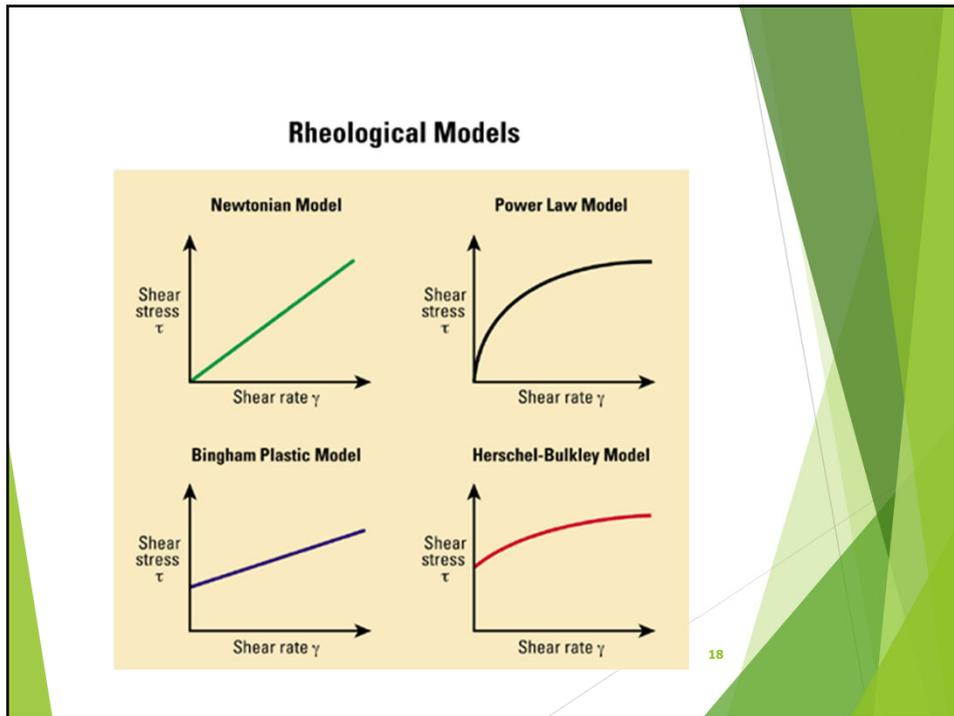
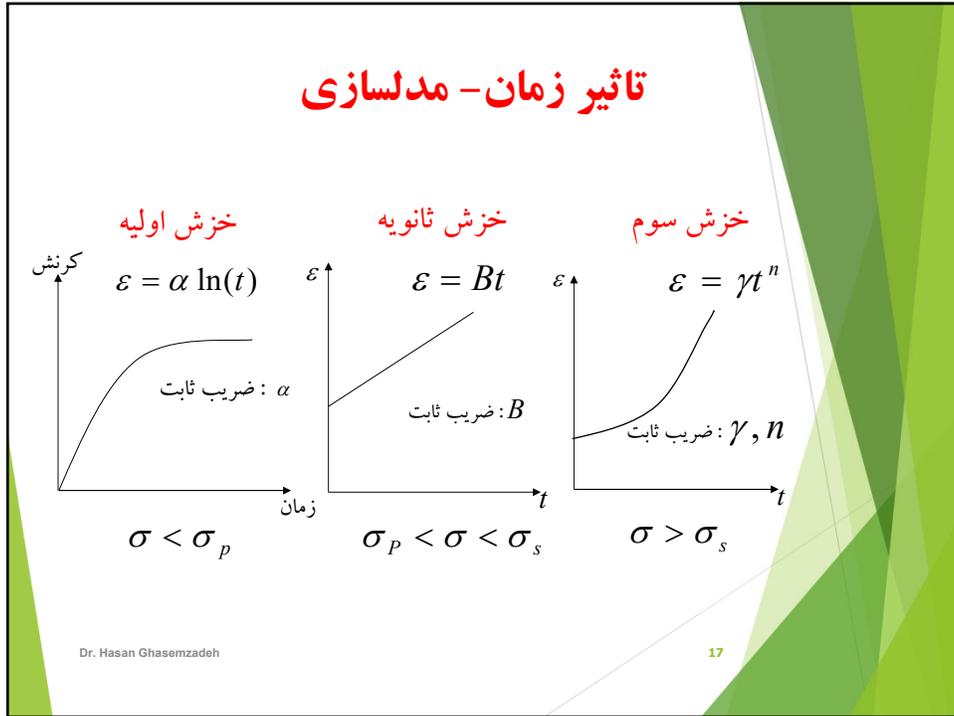
- ۱- طبیعت تنش
  - ۲- میزان تنش و نرخ بارگذاری یا کرنش
  - ۳- فشار جانبی
  - ۴- درجه حرارت
  - ۵- بارگذاری سیکلی
  - ۶- رطوبت و بخار آب
  - ۷- عوامل ساختمانی (بافت سنگ)
- هر چه دانه ها (بافت) سنگ درشت تر باشد خزش کمتر است

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12







### تأثير زمان

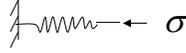
Elastic Hookean substance    <i>Spring</i>	Elastoviscous    <i>Maxwell model</i>	Elastoplastic    
Viscoelastic    <i>Kelvin model</i>	Viscous Newtonian substance    <i>Dashpot</i>	Viscoplastic    
Plastoelastic    	Plastoviscous    	Plastic St. Venant substance    <i>Slider</i>

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### تأثير زمان

توصيف  
كرنش الاستيكيك  
و همزمان

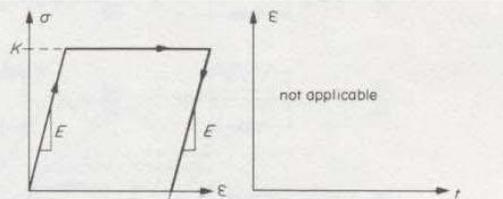
رابطه تنش و کرنش



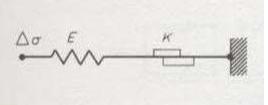
$\sigma = E \epsilon$

رفتار الاستيكيك  
نام مدل رونولوژی  
هوك (Hook)

رفتار الاستوپلاستيكيك



not applicable

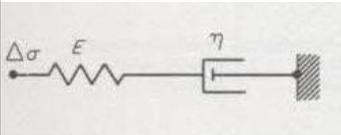


Dr. Hasan Ghasemzadeh 20

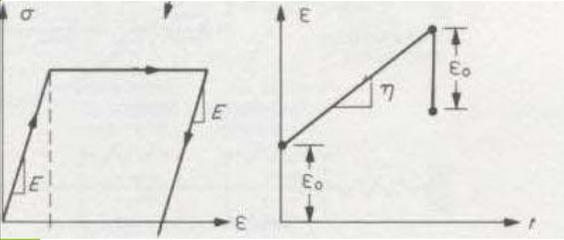
### تأثير زمان

رفتار ویسکوالاستیک

مدل ماکسول میراگر خطی نیوتن  
مناسب برای خزشی ثانویه



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



21

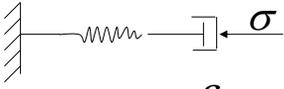
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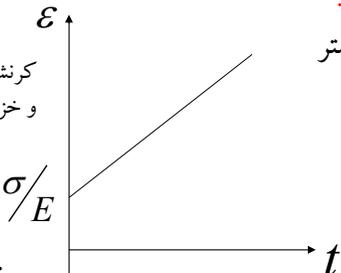
### تأثير زمان

رفتار ویسکوالاستیک

ماکسول با دو پارامتر  
خزشی ثانویه

کرنش کشسان هم زمان  
و خزشی ثانویه





$$\varepsilon_T = \varepsilon_S + \varepsilon_t$$

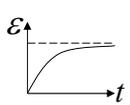
$$\sigma = E\varepsilon_S = \eta \frac{d\varepsilon_t}{dt}$$

$$\varepsilon_T(t) = \frac{\sigma(t)}{E} + \int_0^t \frac{\sigma(\theta) d\theta}{\eta} \quad \sigma_{(t)} = \sigma_o \Rightarrow \varepsilon_T = \frac{\sigma_o}{E} \left(1 + \frac{E}{\eta} t\right)$$

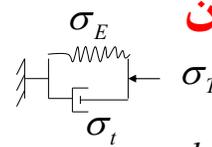
22

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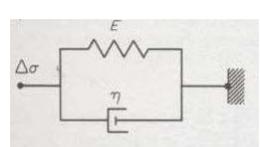
### تأثير زمان

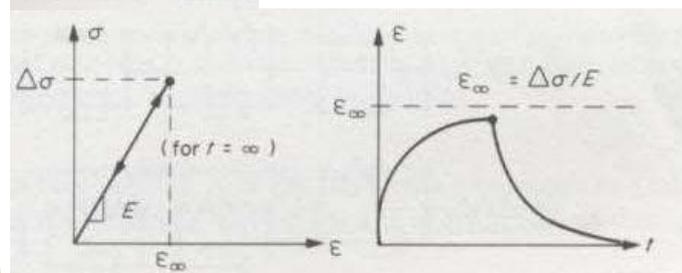


$\sigma_T = \sigma_E + \sigma_t = E\varepsilon + \eta \frac{d\varepsilon}{dt}$



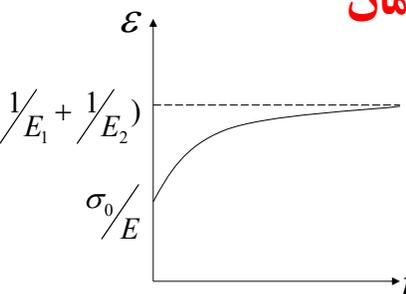
رفتار ویسکوالاستیک  
مدل کلویین  
خزشی مقدماتی



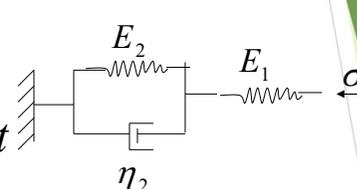


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23

### تأثير زمان



مدل با سه پارامتر



$\varepsilon = \varepsilon_1 + \varepsilon_2$

$\sigma = E_1\varepsilon_1 = E_2\varepsilon_2 + \eta_2 \frac{d\varepsilon_2}{dt}$

$\sigma \left( \frac{E_1 + E_2}{\eta_2} \right) + \frac{d\sigma}{dt} = E_1 \left( \frac{E_2}{\eta_2} \varepsilon + \frac{d\varepsilon}{dt} \right)$

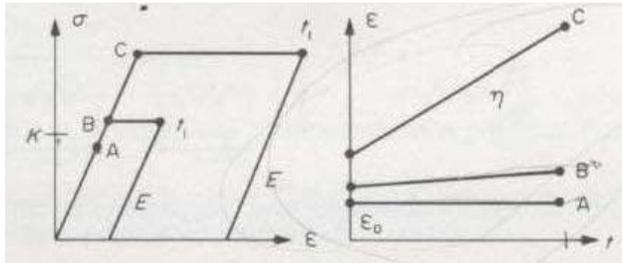
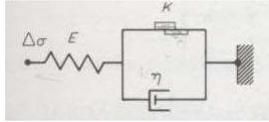
زمان خزش  $\tau_2 = \frac{\eta_2}{E_2}$

$\sigma(t) = \sigma_0 = cte \Rightarrow \varepsilon(t) = \sigma_0 \left( \frac{1}{E_1} + \frac{1}{E_2} (1 - e^{-t/\tau_2}) \right)$

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24

## تأثير زمان

رفتار الاستو ویسکو پلاستیک

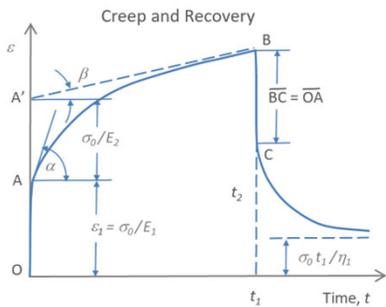
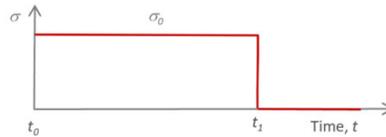
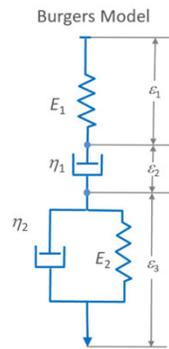


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25

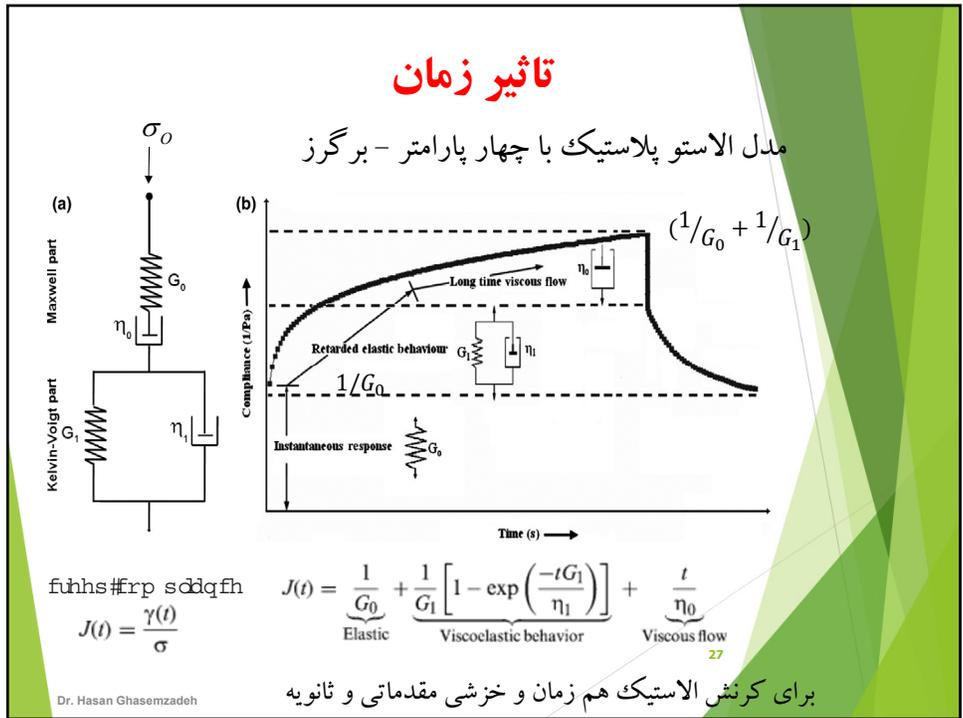
## تأثير زمان

مدل ویسکوالاستیک با چهار پارامتر - برگرز



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برای کرنش الاستیک هم زمان و خزشی مقدماتی و ثانویه



### Fractional Models:

With Fractional element (soft element or Abel pot or springpot) complex viscoelastic behaviors can be simulated with fewer elements.

The constitutive equation of springpot:  $\sigma(t) = \eta D^\alpha \varepsilon(t)$

$$D^\alpha f(t) = \frac{1}{\Gamma(1-\alpha)} \int_0^t \frac{f'(\tau)}{(t-\tau)^\alpha} d\tau$$

Creep model of springpot in constant stress  $\varepsilon(t) = \frac{\sigma_0}{\eta} \frac{t^\alpha}{\Gamma(1+\alpha)}$

Creep model of springpot in constant strain  $\sigma(t) = \eta \varepsilon_0 \frac{t^{-\alpha}}{\Gamma(1-\alpha)}$

#### 4.3.1 The Gamma Function

The Gamma function was apparently first defined by the Swiss mathematician Euler. In terms of real variable  $x$ , it took a product form

$$\Gamma(x) = \frac{1}{x} \prod_{n=1}^{\infty} \frac{(1 + \frac{1}{n})^x}{(1 + \frac{1}{n})} \quad (4.13)$$

The notation Gamma function was first used by Legendre in 1814. From the infinite product, the usual integral form can be derived

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt, \quad x > 0 \quad (4.14)$$

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$x$	$\Gamma(x)$
1.00	1.00000
1.01	0.99433
1.05	0.97350
1.10	0.95135
1.15	0.93304
1.20	0.91817
1.30	0.89747
1.40	0.88726
1.50	0.88623
1.60	0.89352
1.70	0.90864
1.80	0.93138
1.90	0.96177
2.00	1.00000

It is clear that all negative integers eventually contain  $\Gamma(0)$ , since

$$\Gamma(n-1) = \Gamma(n)/(n-1) = \Gamma(n+1)/[n(n-1)], \text{ and so on} \quad (4.19)$$

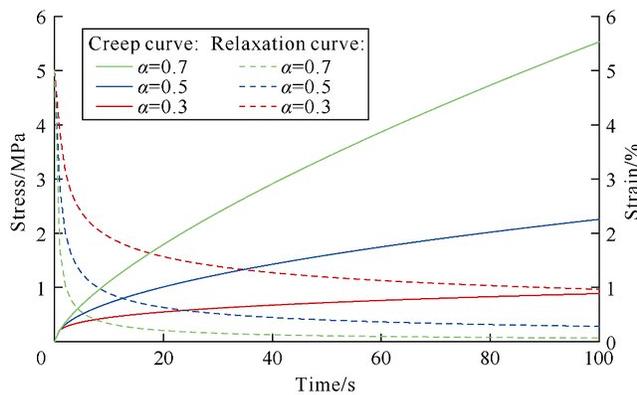
hence,  $\Gamma(n)$  is always infinite for negative integers.

Occasionally, the range of integration in Eq. 4.14 is not infinite, and this defines the *incomplete Gamma function*

$$\Gamma(x, \tau) = \int_0^{\tau} t^{x-1} e^{-t} dt, \quad x > 0, \tau > 0 \quad (4.20)$$

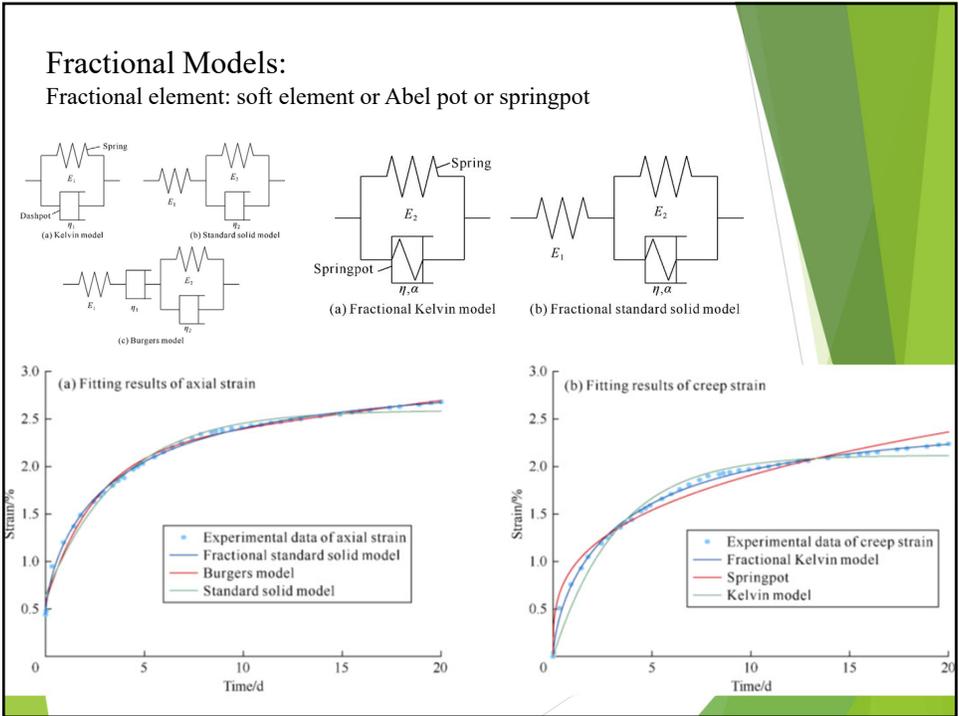
### Fractional Models:

Fractional element: soft element or Abel pot or springpot



Creep and relaxation curves of springpot at different fractional orders. The initial stress is 1 MPa, the initial strain is 1 and the fractional consistency coefficient is 5 MPa·s.

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## تنش اطراف چاه

### The "simplest" borehole stress analysis model

#### Hollow cylinder model

(Usually,  $b \gg a$ )

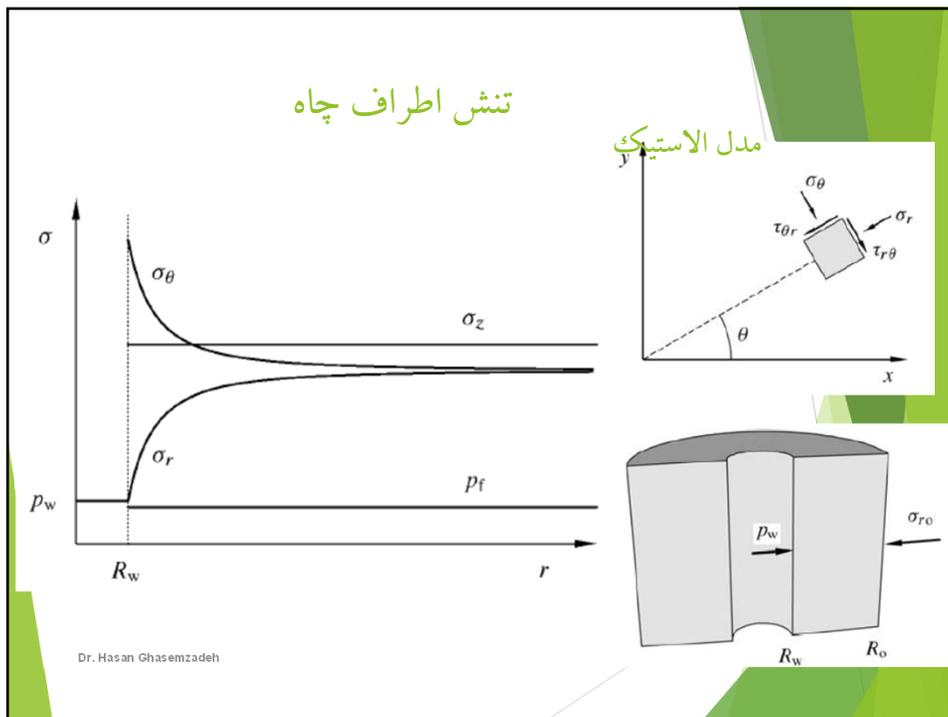
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#### Elastic stress solution (Lamé)

$$\sigma_{\theta} = \frac{b^2(r^2 + a^2)}{r^2(b^2 - a^2)} p_b - \frac{a^2(r^2 + b^2)}{r^2(b^2 - a^2)} p_a$$

$$\sigma_r = \frac{b^2(r^2 - a^2)}{r^2(b^2 - a^2)} p_b - \frac{a^2(r^2 - b^2)}{r^2(b^2 - a^2)} p_a$$

(Another equation is used to calculate radial displacements)



### تنش اطراف چاه

مدل الاستیک

$$\sigma_r = \frac{R^2}{r^2} p + \frac{\sigma_{xx} + \sigma_{yy}}{2} \left(1 - \frac{R^2}{r^2}\right) + \frac{\sigma_{xx} - \sigma_{yy}}{2} \left(1 + \frac{3R^4}{r^4} - \frac{4R^2}{r^2}\right) \cos 2\theta +$$

$$\sigma_{yy} \left(1 + \frac{3R^4}{r^4} - \frac{4R^2}{r^2}\right) \sin 2\theta + \delta \left[ \frac{\beta(1-2\nu)}{2(1-\nu)} \left(1 - \frac{R^2}{r^2}\right) - \phi \right] (p - p_t)$$

$$\sigma_\theta = -\frac{R^2}{r^2} p + \frac{\sigma_{xx} + \sigma_{yy}}{2} \left(1 + \frac{R^2}{r^2}\right) - \frac{\sigma_{xx} - \sigma_{yy}}{2} \left(1 + \frac{3R^4}{r^4}\right) \cos 2\theta -$$

$$\sigma_{yy} \left(1 + \frac{3R^4}{r^4}\right) \sin 2\theta + \delta \left[ \frac{\beta(1-2\nu)}{2(1-\nu)} \left(1 + \frac{R^2}{r^2}\right) - \phi \right] (p - p_t)$$

$$\sigma_z = \sigma_z - 2\nu(\sigma_{xx} - \sigma_{yy}) \frac{R^2}{r^2} \cos 2\theta - 4\nu \sigma_{xy} \frac{R^2}{r^2} \sin 2\theta +$$

$$\delta \left[ \frac{\beta(1-2\nu)}{1-\nu} - \phi \right] (p - p_t)$$

$$\sigma_{r\theta} = \sigma_{xy} \left(1 - \frac{3R^4}{r^4} + \frac{2R^2}{r^2}\right) \cos 2\theta - \frac{\sigma_{xx} - \sigma_{yy}}{2} \left(1 - \frac{3R^4}{r^4} + \frac{2R^2}{r^2}\right) \sin 2\theta$$

34

CHEN Mian, JIN Yan, ZHANG Guangqing.  
Petroleum engineering rock mechanics. Beijing: Science Press, 2008

### جابجایی اطراف چاه

$$u_r = -p \frac{1+\nu}{E} \frac{R^2}{r} + \frac{\sigma_{xx} + \sigma_{yy}}{2E} (1+\nu) \frac{R^2}{r} +$$

$$\frac{\sigma_{xx} - \sigma_{yy}}{2E} \left[ -(1+\nu) \frac{R^4}{r^3} + (1-\nu^2) \frac{4R^4}{r} \right] \cos 2\theta +$$

$$\frac{1+\nu}{E} \sigma_{xy} \sin 2\theta \left[ -\frac{R^4}{r^3} + (1-\nu) \frac{4R^2}{r} \right] +$$

$$\frac{\delta}{E} (p - p_t) \left[ \frac{\beta(1-2\nu)}{2(1-\nu)} (1+\nu) \frac{R^2}{r} \right]$$

جابجایی الاستیک

Young's modulus can be replaced by the creep compliance of fractional standard solid model

$$u_r = -\frac{A}{E_2} \left\{ (1+\nu) \frac{R^2}{r} - \delta \left[ \frac{\beta(1-2\nu)}{2(1-\nu)} (1+\nu) \frac{R^2}{r} \right] \right\} +$$

$$\left\{ \frac{\sigma_{xx} + \sigma_{yy}}{2E_2} (1+\nu) \frac{R^2}{r} + \frac{\sigma_{xx} - \sigma_{yy}}{2E_2} \cos 2\theta \left[ -(1+\nu) \frac{R^4}{r^3} + (1-\nu^2) \frac{4R^4}{r} \right] + \right.$$

$$\left. \frac{1+\nu}{E_2} \sigma_{xy} \sin 2\theta \left[ -\frac{R^4}{r^3} + (1-\nu) \frac{4R^2}{r} \right] - \delta \frac{p_t}{E_2} \left[ \frac{\beta(1-2\nu)}{2(1-\nu)} (1+\nu) \frac{R^2}{r} \right] \right\} \times$$

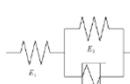
$$\left[ 1 - E_{\sigma,1} \left( -\frac{t^\alpha}{\tau_2} \right) \right] H(t)$$

جابجایی ویسکوز  
اضافه می شود

$$\frac{1}{\hat{E}} = \frac{1}{E_1} + \frac{1}{E_2} \frac{1}{1 + \tau_2 s^\alpha}$$

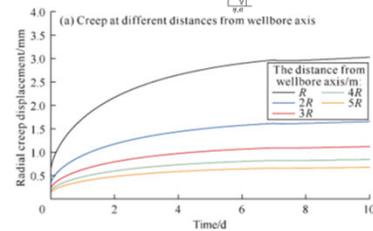
35

### جابجایی اطراف چاه نفت

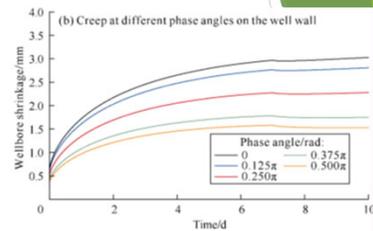


مدل ویسکوالاستیک جامد استاندارد فرکشنال

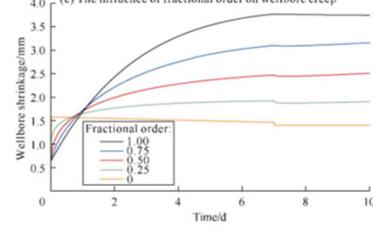
(a) Creep at different distances from wellbore axis



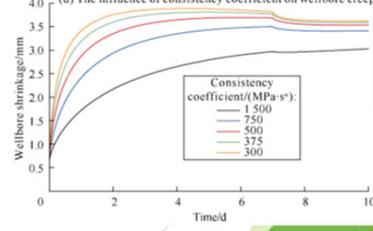
(b) Creep at different phase angles on the well wall



(c) The influence of fractional order on wellbore creep



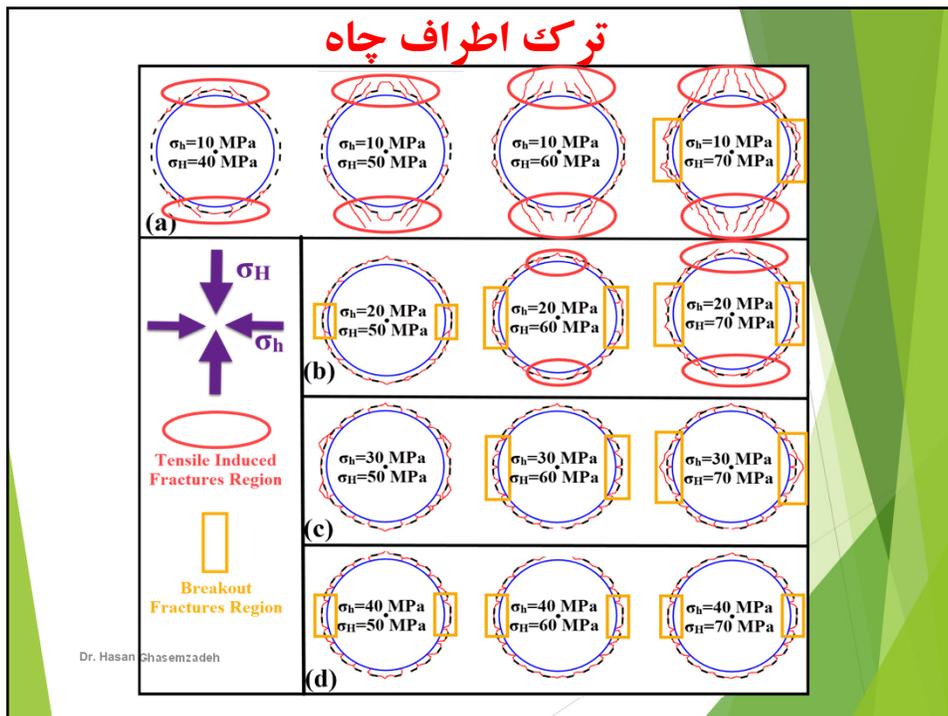
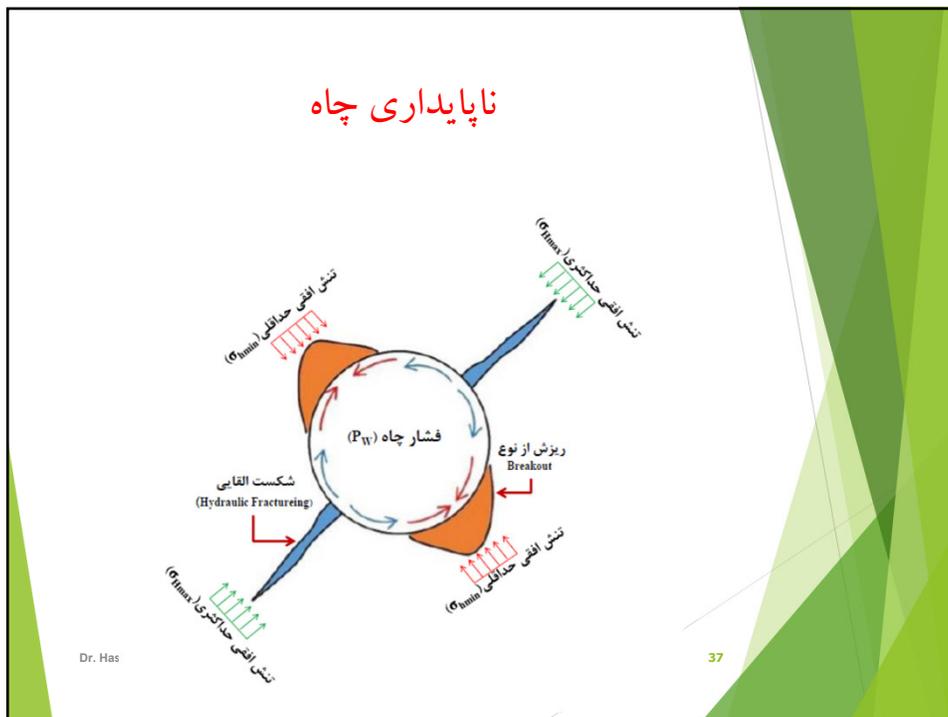
(d) The influence of consistency coefficient on wellbore creep



اصطلاحاً به چاهی کشته شده یا مرده می گویند که فشار سرچاه برابر با فشار اتمسفر باشد. برای کشتن چاه گل حفاری را با سیال با وزن مخصوص بیشتر جایگزین می کنند در شکل بالا روز هفتم چاه کشته شده است

36

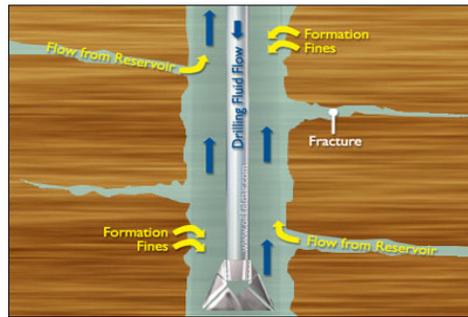
Dr. Hasan Ghasemzadeh



## Blowout Conditions

شرایط فوران

- ▶ When mud pressure is no longer enough to balance a high-pressure fluid (oil, gas, water) that flows at a high rate...  $p_o > p_w$
- ▶ However, we now use underbalanced drilling where  $p_o > p_w$  all the time! But...
  - ▶ Only if there is no large amount of oil or gas in a high permeability zone
  - ▶ Only if the shale is strong enough to stand without wall support
  - ▶ Generally limited to relatively shallow drilling

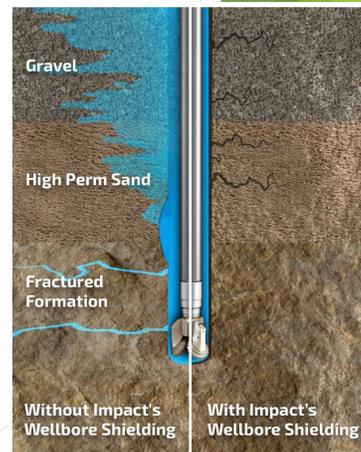


## LC - Lost Circulation

هرزروی گل حفاری

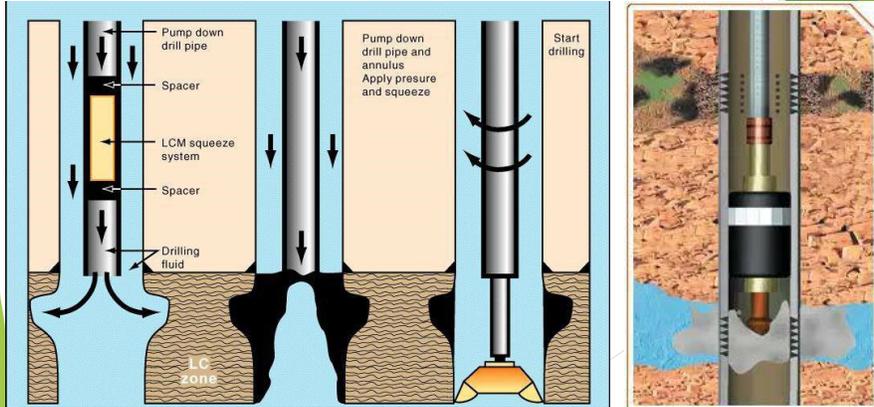
- ▶ Occurs in two ways:
  - ▶ In zones with large diameter pores or channels (vuggy carbonates, rubble zones, fractured zones, fault zones...)
  - ▶ In conditions where  $p_w > \sigma_{hmin}$  and a hydraulic fracture propagates beyond the borehole region
- ▶ Pressure controlled drilling helps avoid LC/BO
- ▶ “Strengthening” the borehole wall...
  - ▶ Increasing the stress around the borehole wall
  - ▶ Plugging initiating fractures with solids...

روش های اصلی معمول برای کنترل و از بین رفتن هرزروی  
 (۱) استفاده از LCM Pill  
 (۲) استفاده از مگنست پلاگ  
 (۳) سیمانکاری منطقه هرزروی



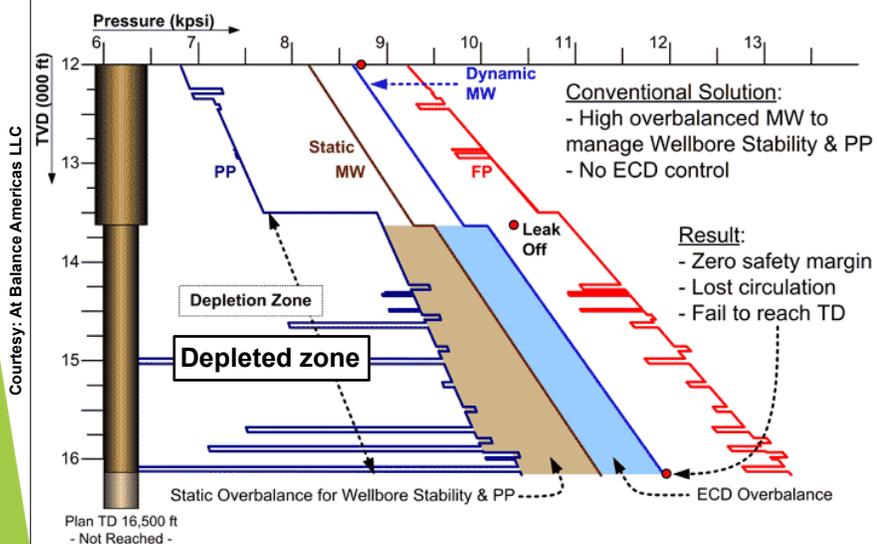
### روش های اصلی معمول برای کنترل هرزروی

- ✓ مواد ( LCM ( Lost Circulation Materials ) موادی همچون Mica، Shell Fish و سایر مواد ورقه ای و فیبری است که شکاف ها، گسل ها و فضای متخلخل سازند را پر کرده و از هرزروی گل جلوگیری می کنند.
- ✓ مگنست یک سیمان زودگیر است که در اسید کاملاً حل می شود و برای جلوگیری از هرزروی های مخزن مناسب است
- ✓ برای مقابله با هرزروی گل به غیر از مخزن می توان از پمپاژ سیمان به داخل قسمت هرزروی Lost Zone استفاده نمود



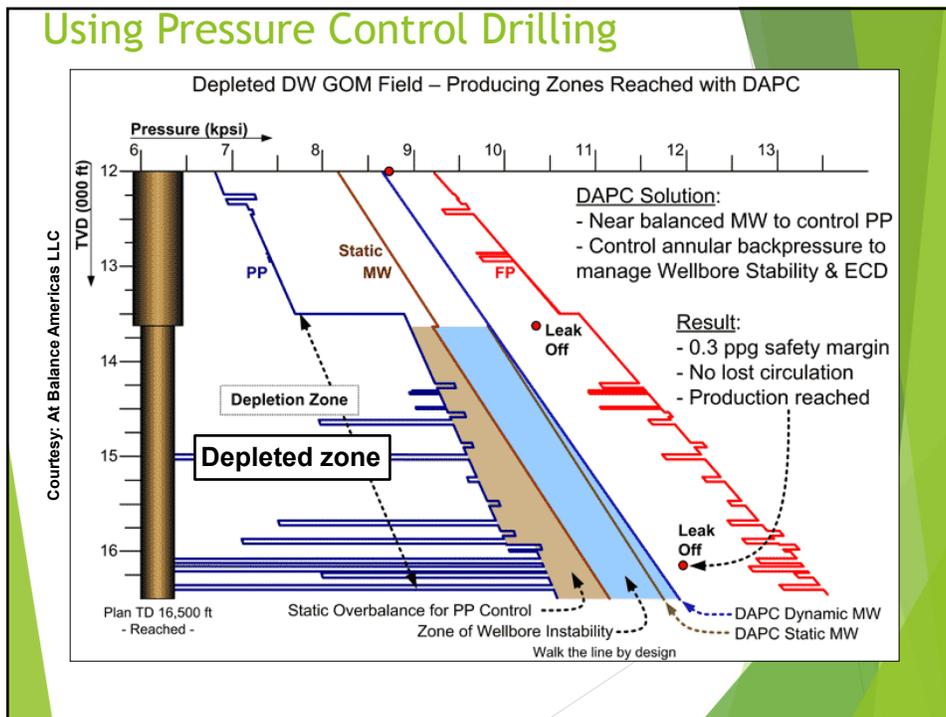
### LC in Depleted Zones

Depleted DW GOM Field - Producing Zones Unreachable by Overbalance Drilling



ECD: Equivalent Circulating Density : The sum of pressure exerted by hydrostatic head of fluid, drilled solids, and friction pressure losses in the annulus divided by depth of interest

## Using Pressure Control Drilling



## Chemical Shale Instability

- ▶ Chemically sensitive ductile shales...
  - ▶ Smectite-rich clays that swell (chemistry)
  - ▶ Younger and shallower shales (<5000 m depth)
  - ▶ Higher  $\phi$  (lower density) shales, ductile, few natural fractures
- ▶ Chemical compatibility with drilling mud is difficult to achieve over a long open hole
- ▶ Heating at the upper casing shoe leads to stress increase and sloughing of shale
- ▶ Oil-base muds very effective in ductile shale

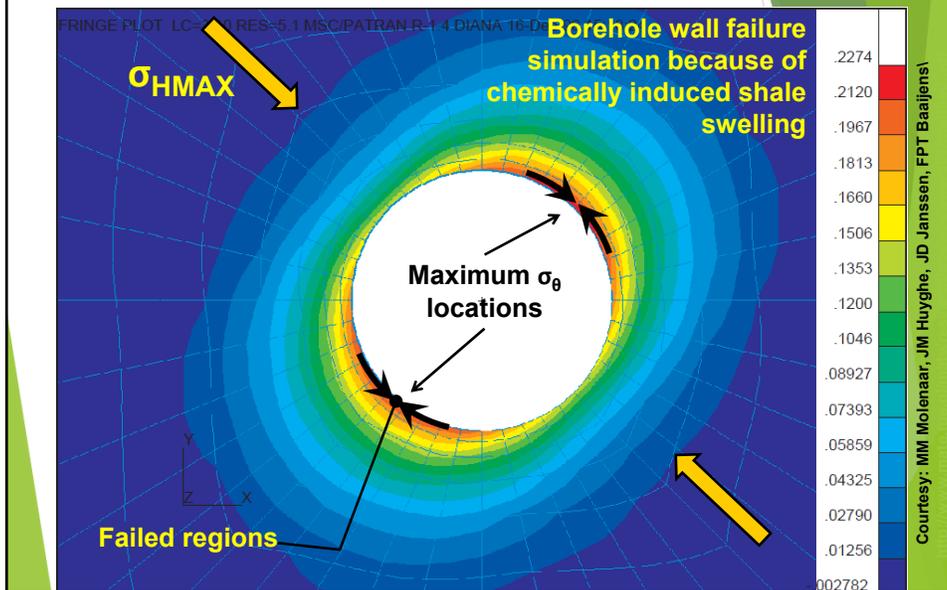
## Signs of Geochemical Instability

- ▶ Usually only with WBM(Water-Based Muds)
- ▶ Increase in cavings volume
- ▶ Cuttings are mushy and rounded
- ▶ Bit balling, BHA balling, increased ECD
- ▶ Gradual continued increase in torque
- ▶ Overpull off slips during trips
- ▶ Pump pressure gradually increasing
- ▶ Gradual changes in mud system properties, rheology, solids content and type...



BHA : Bottom Hole Assembly

## Failed Zone from Shale



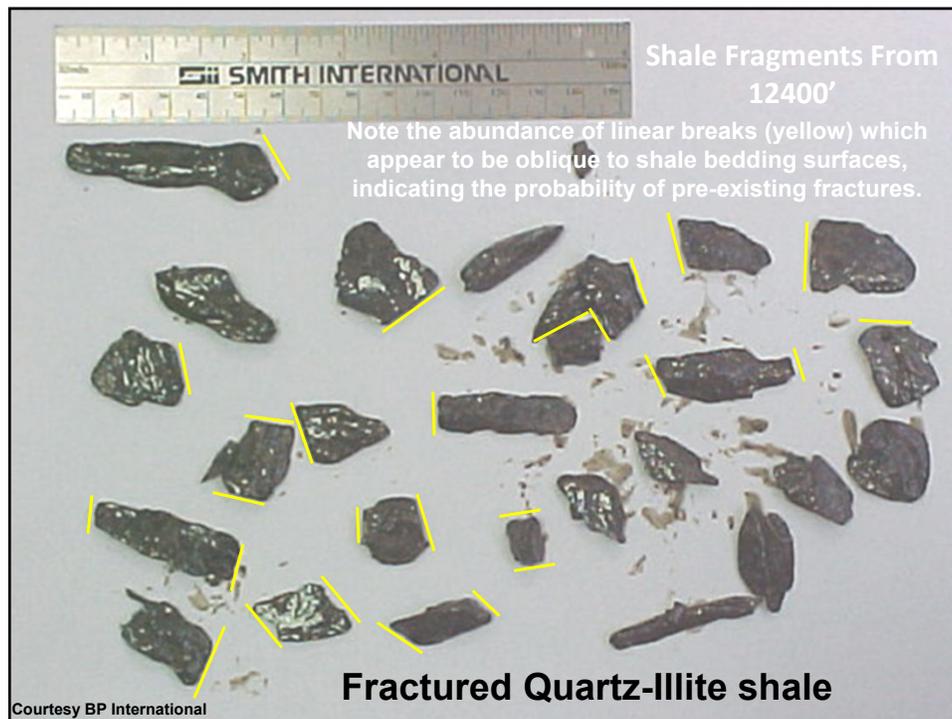
## Chemical Instability

- ▶ Dispersion and softening of the swelling shale leads to hole instability, mud rings, bit balling, etc.
- ▶ Some examples



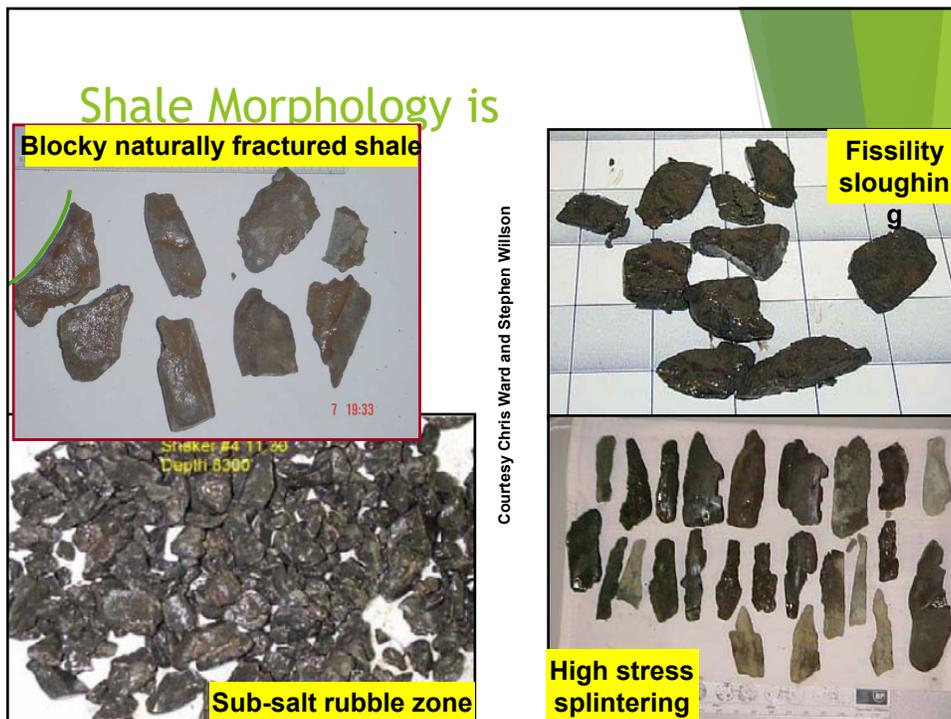
## Mechanical Shale Instability

- ▶ Stiff fractured Quartz-Illite shales
  - ▶ Natural fractures reduce the effects of pressure support of the borehole by mud cake
  - ▶ Oil-based muds are not effective
- ▶ Fissile shales in long-reach horizontal wells
  - ▶ Large-scale sloughing and washouts because the fissile shale on the top of the hole sloughs
- ▶ Carbonaceous shales (thin coal partings)
  - ▶ Fluids penetrate easily along partings, especially oil-based muds



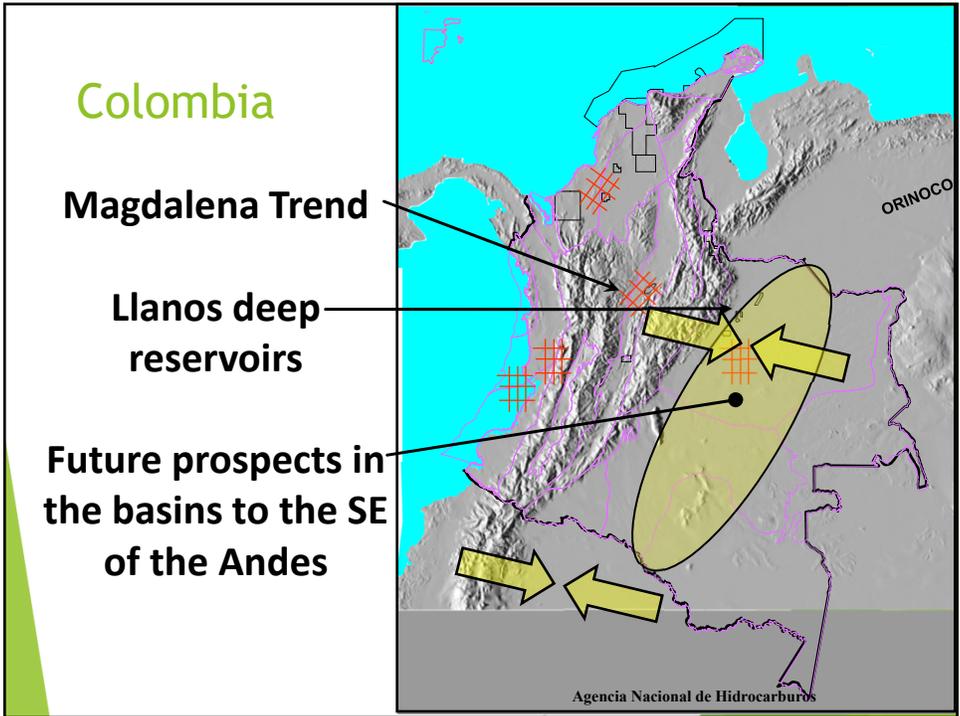
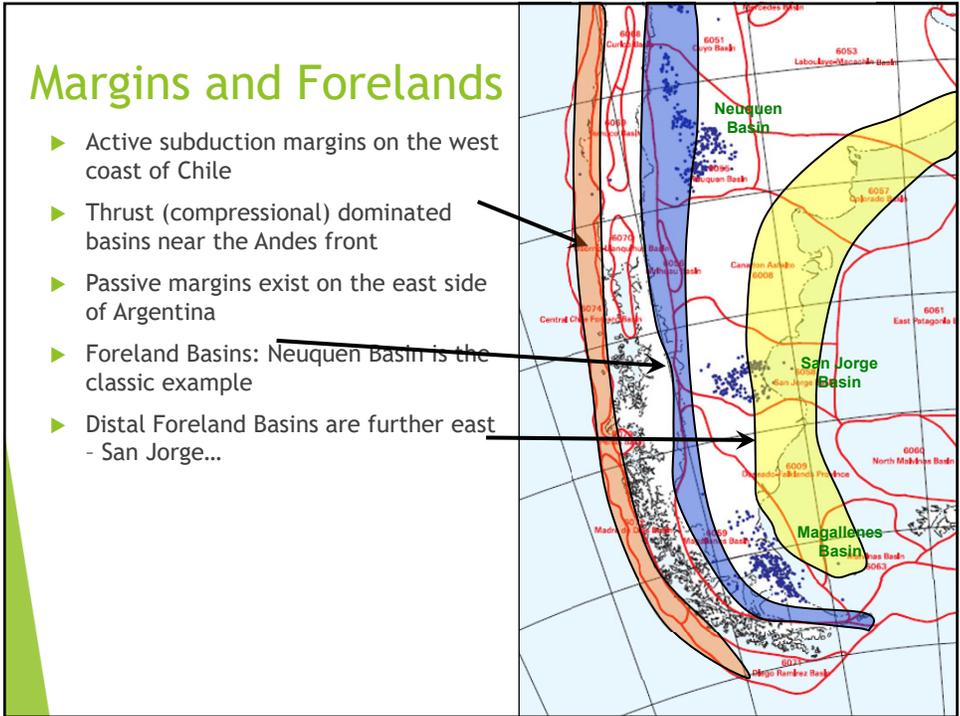
## Signs of Mechanical Instability

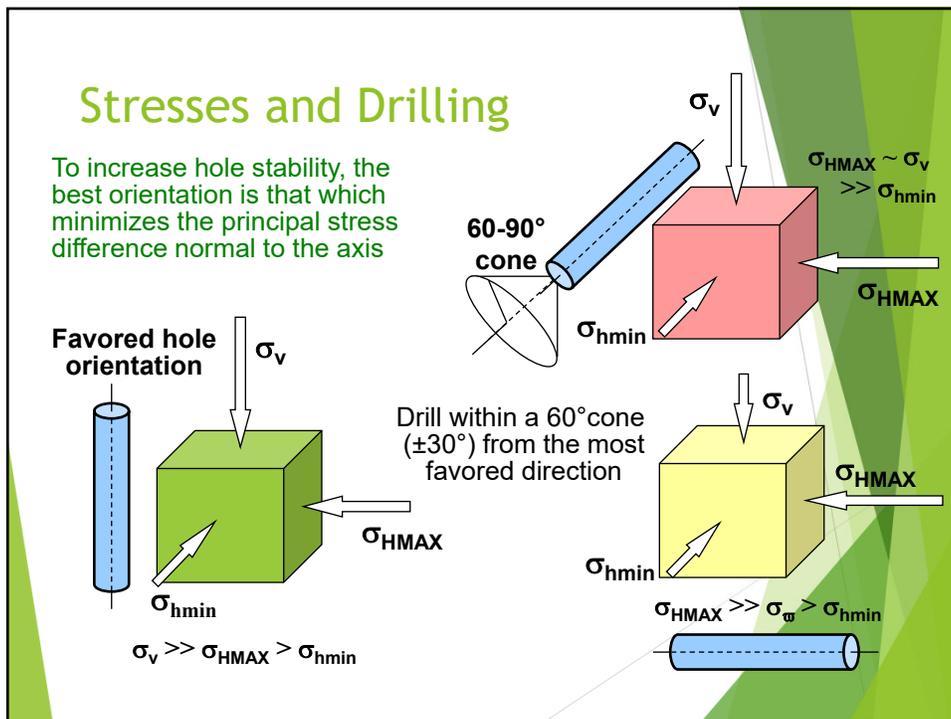
- ▶ All types of mud
- ▶ Large cuttings and cavings, odd shapes, increases of shale on shaker (in surges?),
  - ▶ Splintery cavings, blocky chunks of shale...
- ▶ Hole fill on connections and trips
- ▶ Stuck pipe because of bridging, pack-offs
- ▶ Lost circulation in shale zones (MW too high), including ballooning effects
- ▶ Changes in the pump pressure, often surges
- ▶ Sudden erratic changes in torque



## High Differential Stress Instability

- ▶ Usually found in compressive stress regimes near mountains
  - ▶ The difference  $\sigma_1 - \sigma_3$  is very large, so...
  - ▶ The shear stresses in the borehole wall are large
  - ▶ And the shale fractures, shears, develops microcracks, and wall support is lost
- ▶ Characterized by very large borehole breakouts, continued shale sloughing
  - ▶ Often, raising MW has limited effects

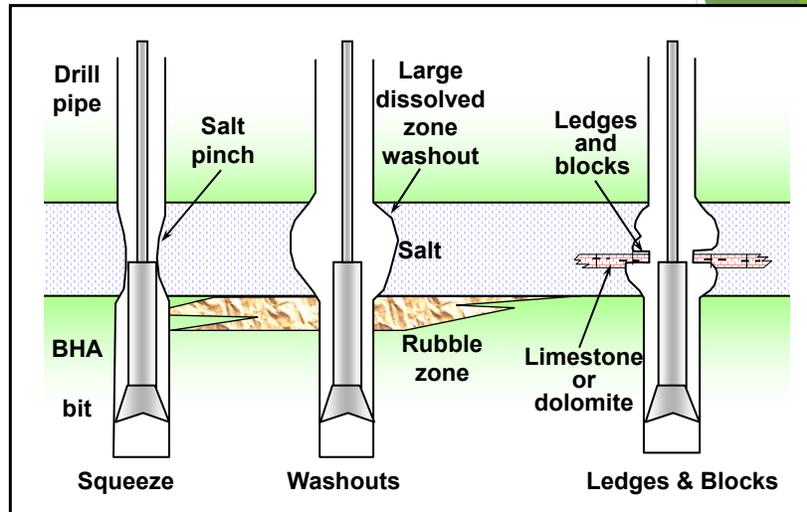




## Salt Squeeze

- ▶ Salt is a viscoplastic material
  - ▶ It flows (creeps) under differential stress
  - ▶ The higher the stress, the faster the creep
  - ▶ The higher the temperature, the faster the creep
- ▶ Also, there are other issues...
  - ▶ It is highly soluble (washouts possible)
  - ▶ Low density means different stress gradients
  - ▶ The presence of dolomite or limestone beds can impact drilling
  - ▶ Rubble zones under thick salt bodies (GoM)

## Drilling Problems in Salt Rock

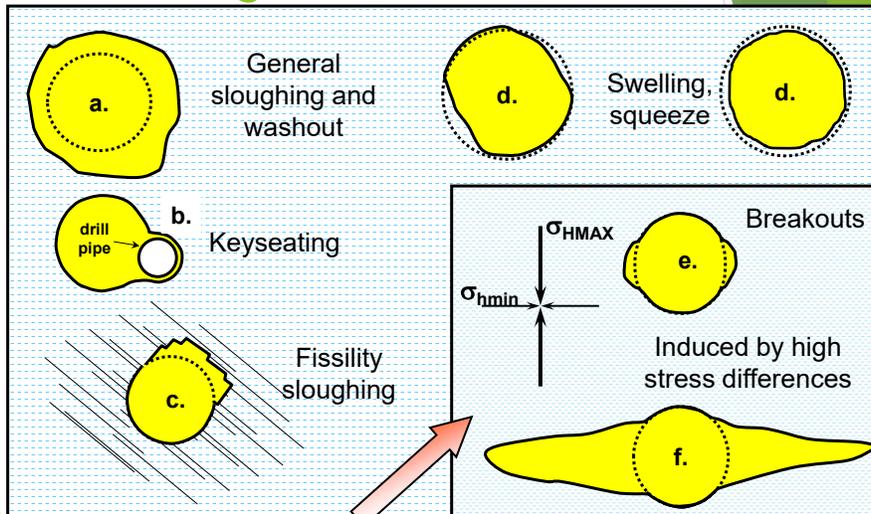


## Slip of High-Angle Joints

- ▶ High angle joints can slip and decrease the borehole diameter, giving trip problems
  - ▶ High mud weight high in an open-hole section
  - ▶ Pore pressure permeates into the joint
  - ▶ Slip happens, pinching the hole diameter
- ▶ Raising MW makes it worse
- ▶ Blocking flow into the joint helps prevent it
- ▶ Back reaming with a top-drive system makes it possible to drill out of the hole

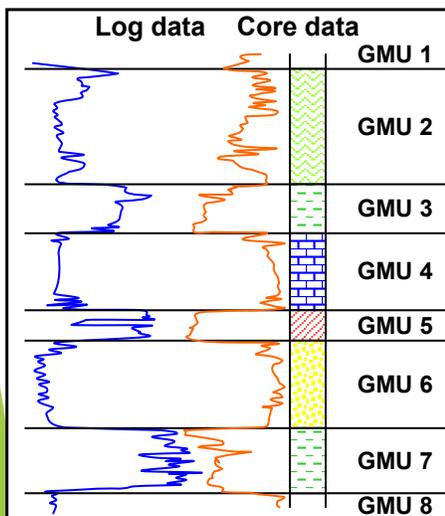


### Some Diagnostic Hole



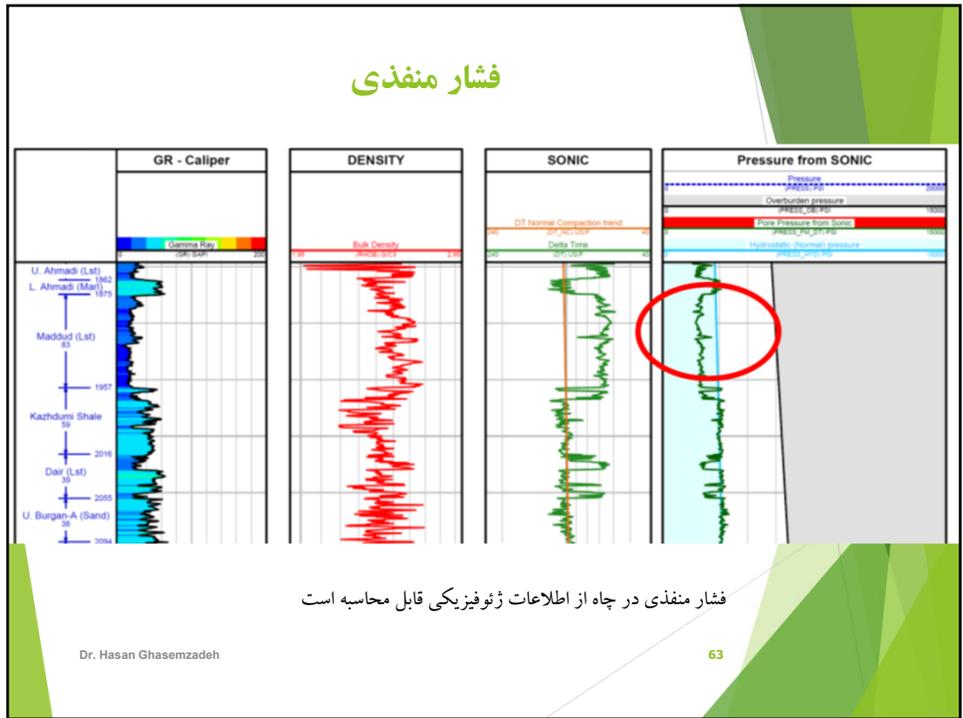
Only breakouts are symmetric in one direction with an enlarged major axis

### واحد ژئومکانیکی (GMU) Geo-Mechanics Unit



- ▶ Nature is too complex to “fully” model
- ▶ Simplification needed
- ▶ A GMU is a “single unit” for design and modelling purposes
- ▶ 1 GMU = 1 set of mechanical properties
- ▶ GMU selected from logs, cores, judgment

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### فشار منفذی

رابطه فشار منفذی ایتون

Velocity-base:  $P_p = P_{ov} - (P_{ov} - P_H) \left( \frac{V_n}{V_i \text{ or } V_{Log}} \right)^k$ , sandstone  $k=3$

Eaton, 1972

Resistivity-base:  $P_p = P_{ov} - (P_{ov} - P_H) \left( \frac{R_{Log}}{R_n} \right)^k$ , sandstone  $k=1.2$

$P_H$  فشار هیدرواستاتیک در عمق موردنظر  
 $P_p$  فشار منفذی برآورد شده  
 $P_{ov}$  فشار روباره  
 $V_n$  سرعت عمودی برای افق شیلی با روند تراکم نرمال  
 $k$  ثابت ایتون  
 $V_{int}$  سرعت بازه ای که از داده های لرزه ای بدست می آید

معایب این روش  
 مدنظر قرار دادن لایه های شیلی متراکم نشده، به عنوان تنها فاکتور برآورد فشار غیرعادی  
 نیاز به پروفیل عمودی شیل متراکم در صورتی که در بیشتر موارد قابل دسترس نیست.

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## فشار منفذی

$$V = V_0 + A \left( \frac{P_{ef}}{P_{ef}^{1-u}} \right)^B,$$

رابطه فشار منفذی باورز

$$P_{ef-max} = \left( \frac{V_{max} - V_0}{A} \right)^{\frac{1}{B}}.$$

Bowers, 1994

فرآیند باربرداری در این روش در نظر گرفته می شود

$V_0$  میزان سرعت در رسوبات نامتراکم و اشباع از سیال

$A$  و  $B$  ضرایب کنترل کننده تغییرات سرعت در نتیجه افزایش فشار مؤثر

$P_{ef}$  فشار مؤثر

$P_{ef-max}$  فشار مؤثر ماکزیمم برای شروع باربرداری

$u$  ثابت باربرداری

$V_{max}$  حداکثر سرعت مشاهده شده

این روش برای سنگهای کربناته مناسب است و تا عمق سه هزار متری نتایج مشابه با روش ایتون دارد

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65

## گرادیان شکست

$$FG = CSR \times (\sigma_v - \alpha P_p) + \alpha P_p$$

$FG$  گرادیان شکست

$\alpha$  ضریب بیو

$P_p$  فشار منفذی

$\sigma_v$  تنش عمودی

$CSR$  نسبت تنش - تنش مؤثر افقی بر تنش مؤثر عمودی - با فرض الاستیک بودن رفتار سنگ بر حسب ضریب پواسون قابل محاسبه است

$$CSR = \nu / (1 - \nu)$$

بدلیل تغییر شکلهای پلاستیک هنگام رسوب و فشرده شدن سنگ ها ضریب پواسون اصلاح شده در رابطه فوق بکار می رود تا گرادیان شکست بهتر تخمین زده شود. دینز ۱۹۸۲ یک پارامتر اصلاحی به این رابطه افزود.

$$CSR = l + \nu / (1 - \nu)$$

متیوس کلی ۱۹۶۷ رابطه  $CSR$  را تابعی از تنش مؤثر عمودی ارایه کرد

$$CSR = [(-3 \times 10^{-9}) \times (TVD_M)^2] + [(8 \times 10^{-5}) (TVD_M)] + [0.2347]$$

$TVD_M$  عمق واقعی عمودی تصحیح شده چاه

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66

## ضریب پواسون اصلاح شده

### Eaton - Gulf Coast

(Above 4999.9 ft)

$$v = [(-7.5 \times 10^{-9}) \times (TVD_M)^2] + [(8.0214286 \times 10^{-5}) \times (TVD_M)] + [(0.2007142857)]$$

(Below 5000 ft)

$$v = [(1.77258 \times 10^{-10}) \times (TVD_M)^2] - [(9.4748424 \times 10^{-6}) \times (TVD_M)] + [(0.3724340861)]$$

### Eaton - Deep Water Mexico Golf

(Above 4999.9 ft)

$$v = [(-6.089286 \times 10^{-9}) \times (TVD_M)^2] + [(5.7875 \times 10^{-5}) \times (TVD_M)] + [(0.3124642857)]$$

(Below 5000 ft)

$$v = [(-1.882 \times 10^{-10}) \times (TVD_M)^2] + [(7.2947129 \times 10^{-6}) \times (TVD_M)] + [(0.4260341387)]$$

$$TVD_M = TVD - D_{Airgap} - D_{Waterdepth} \quad \text{عمق واقعی عمودی تصحیح شده چاه}$$

$TVD$  عمق واقعی عمودی چاه

$D_{Airgap}$  عمق آب

$D_{Waterdepth}$  ارتفاع هوا - ارتفاع هوای موجود از سکوی حفاری تا سطح حفاری

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67

## گرادیان شکست

ضریب پواسون با استفاده از داده های لرزه ای

$$v = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

بعضاً سرعت موج برشی را درجه نداریم :

### John Castagna mud rock line linearized equation

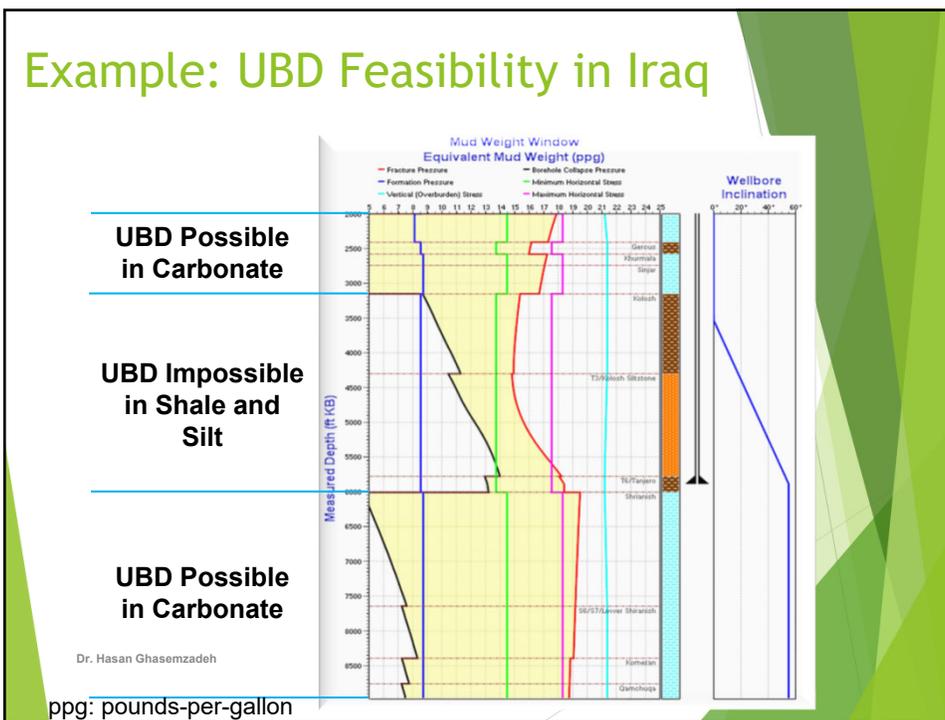
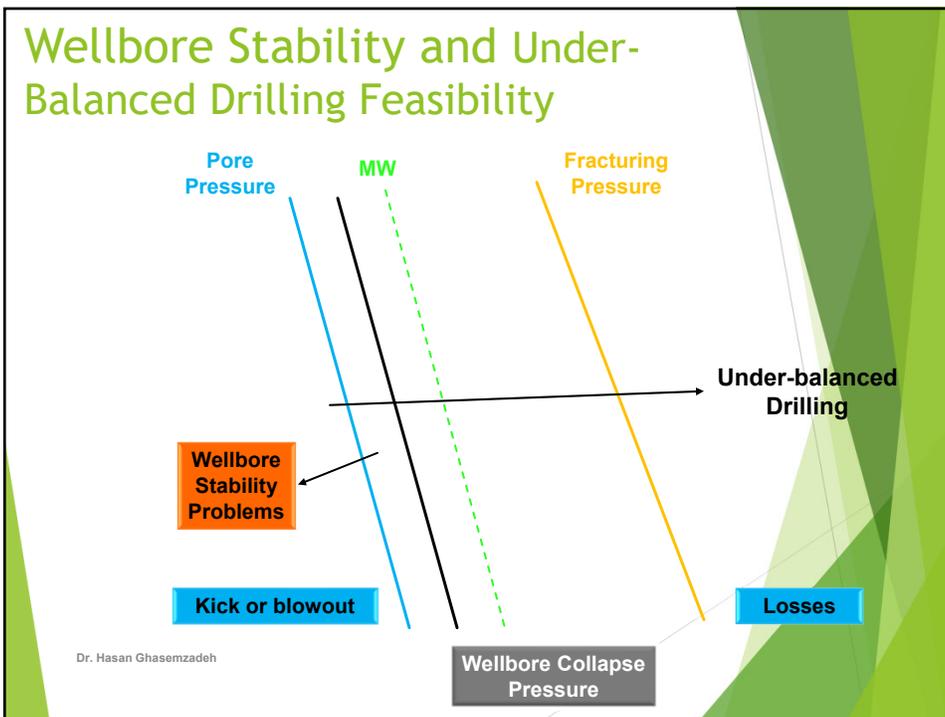
$$V_p = 1.16V_s + 1360 \text{ (m/s)} \quad \text{Or} \quad V_s = (V_p - 1360) / 1.16 \text{ m/s}$$

$$v = \frac{V_p^2 - 2 \left( \frac{V_p - 1360}{1.16} \right)^2}{2V_p^2 - 2 \left( \frac{V_p - 1360}{1.16} \right)^2}$$

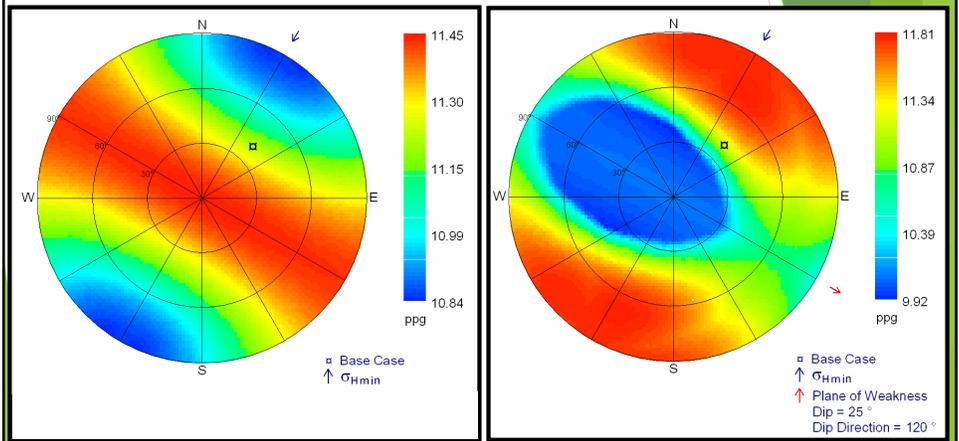
ضریب پواسون با استفاده از سرعت موج فشای برای گلسنگ

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68



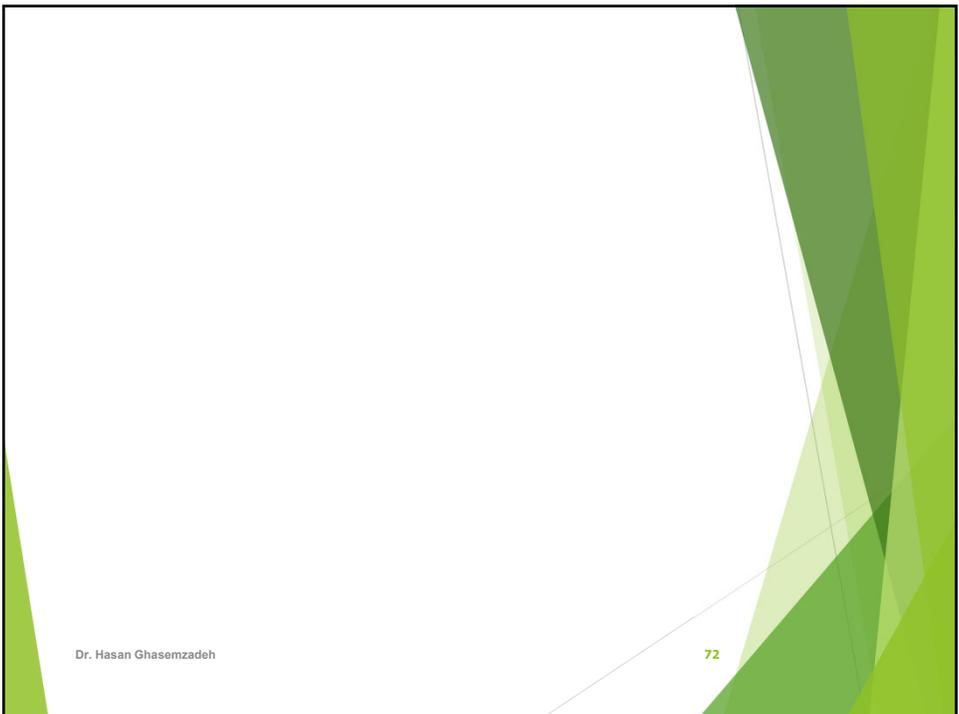
### Effect of Anisotropy on Wellbore Stability



**Collapse gradient for isotropic formation**

**Collapse gradient for anisotropic formation**

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72

# Solutions to Borehole Instability Problems

## What is Your Problem?

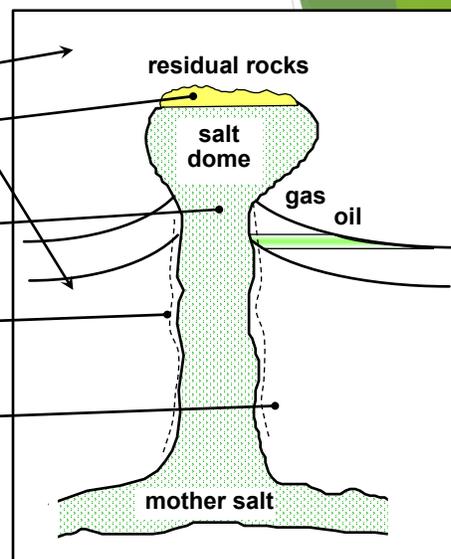
- ▶ Correct identification of the problem is essential to find a good cure...
  - ▶ High differential stresses?
  - ▶ Swelling shale? Chemically sensitive.
  - ▶ Fractured shale?
  - ▶ Slip of joints, or fracture planes?
  - ▶ Squeeze of salt?
  - ▶ Fissile or carbonaceous shale sloughing?
  - ▶ Heating of the borehole causing sloughing?
- ▶ You must establish the reason first...

## What Keeps a Borehole Stable?

- ▶ Favorable natural conditions
  - ▶ Strong rock (carbonates, anhydrite...)
  - ▶ Low stresses and small stress differences
- ▶ Good mud properties
  - ▶ Good support of the wall (good filter cake)
  - ▶ Proper hole cleaning, viscosity, gel strength
  - ▶ Proper MW programs, lower T, other effects
- ▶ Good drilling practices and trajectory
  - ▶ Tripping and connections practices
  - ▶ Early identification of trouble (cavings volumes...)
  - ▶ Proper choice of well trajectory

## Example: Drilling near Salt

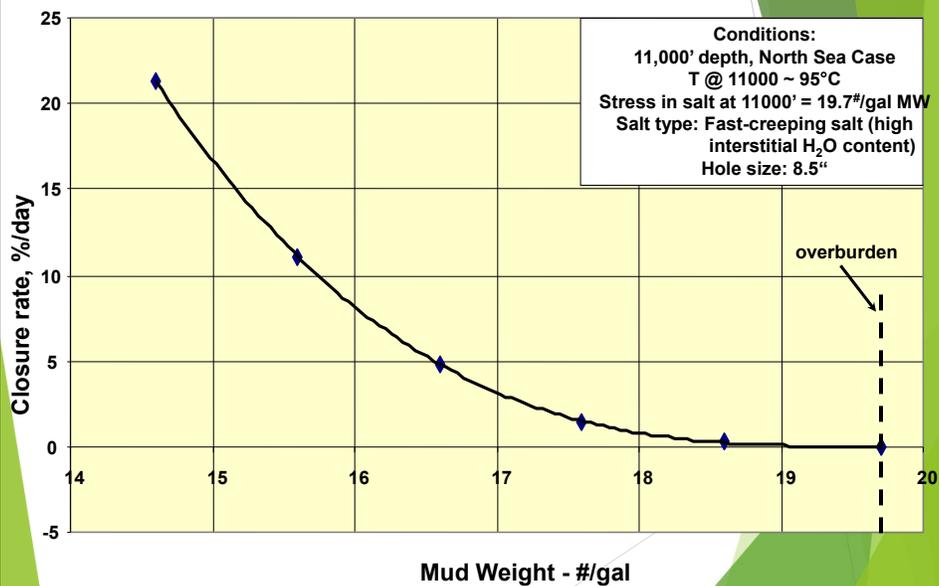
- ▶ Instability of surrounding shales
- ▶ Lost circulation in residual rocks
- ▶ Squeeze in salt
- ▶ Sheared zone on the flanks of the dome
- ▶ Low  $\sigma_{hmin}$  near flanks of salt dome
- ▶ What is the most important problem?

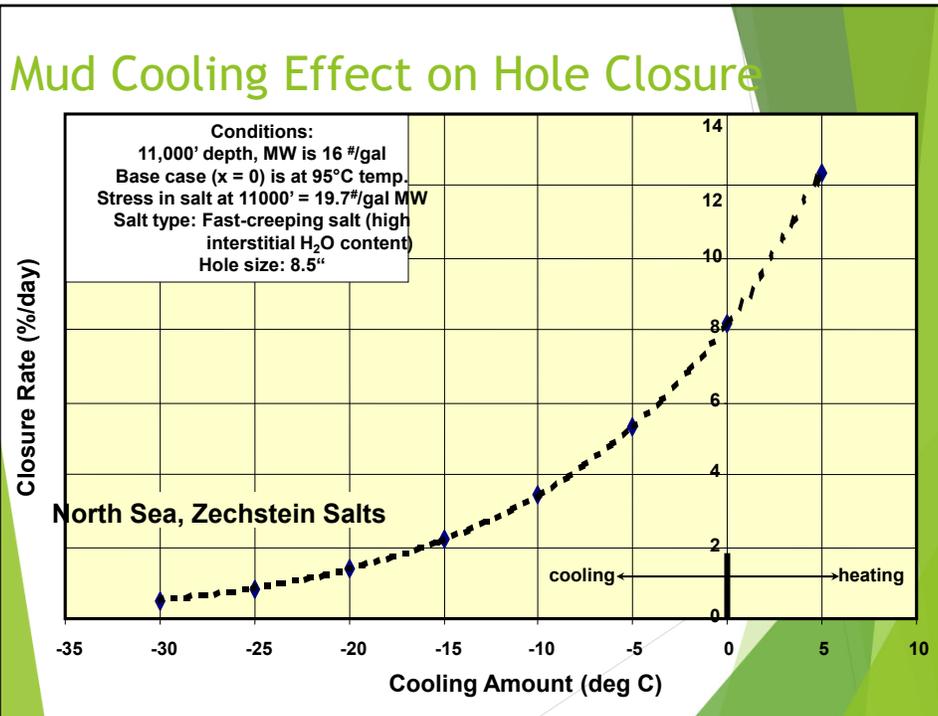


## Solutions to Salt Drilling Problems

- ▶ Maintain a salt-saturated drilling mud with a small amount of free salt in the fluid
- ▶ To slow down squeeze of boreholes in salt, there are only two possibilities:
  - ▶ Reduce the temperature to reduce the salt creep rate around the borehole
  - ▶ Increase MW so that there is less differential stress: that is - minimize  $(\sigma - p_w)$
- ▶ Increase your drilling rate! This means that salt has less time to squeeze

## Mud Weight vs. Hole Closure Rate

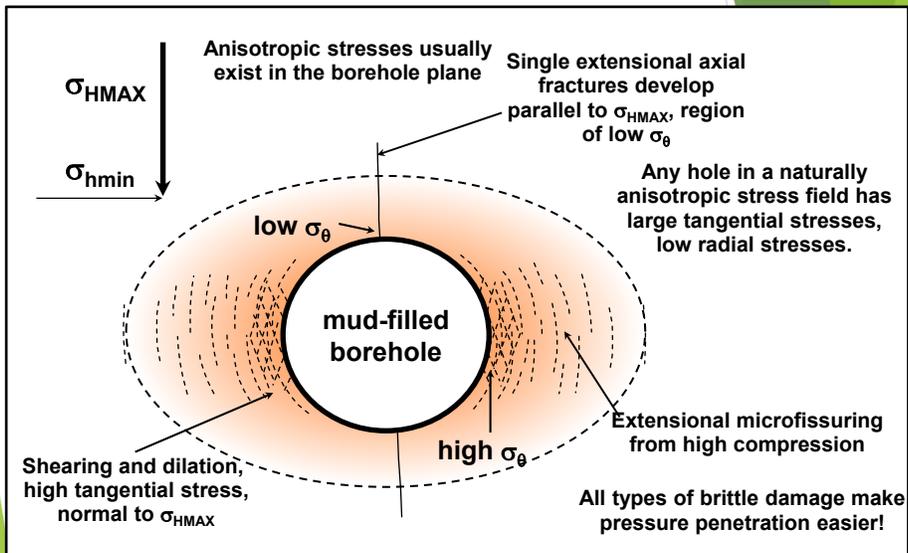




## Shale Problems in Drilling

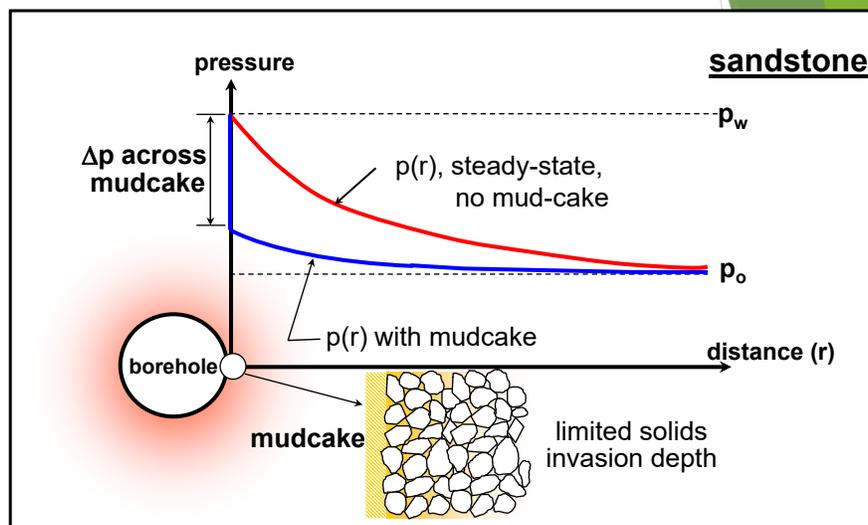
- ▶ Continued sloughing and hole enlargement
  - ▶ Hole cleaning difficulties, hole fill on trips
  - ▶ Mud rings and blockages
  - ▶ Swabbing pressures on trips to change the bit
  - ▶ Difficulty in controlling drilling mud properties
- ▶ Sudden collapse (usually when  $p_o > p_{mud}$ )
- ▶ Instability in shale also increases the risk of blowouts and lost circulation
- ▶ Increased torque, overpull on trips...

## Circumferential Fissuring in Shale



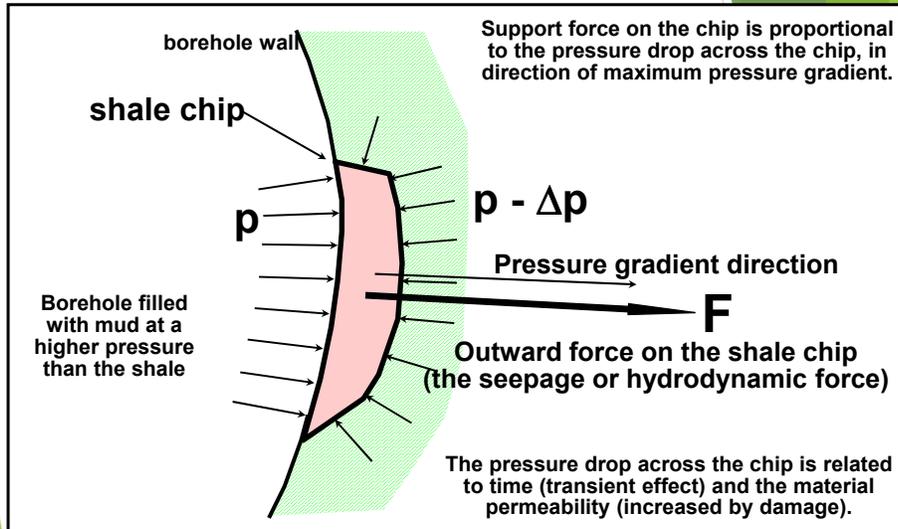
Understanding stresses and shale damage is vital!

## Mudcake and $\Delta p$ Support



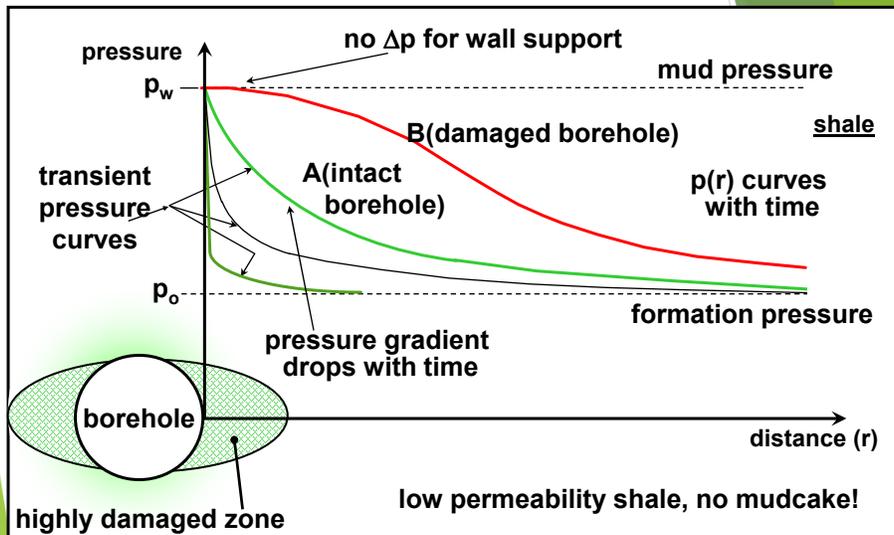
Understanding the pressure support effect is vital!

### Chip Support by $\Delta p$ Across Wall



This is why damaged shale can stay in place for some time

### Damage Effect on $\Delta p$ Support

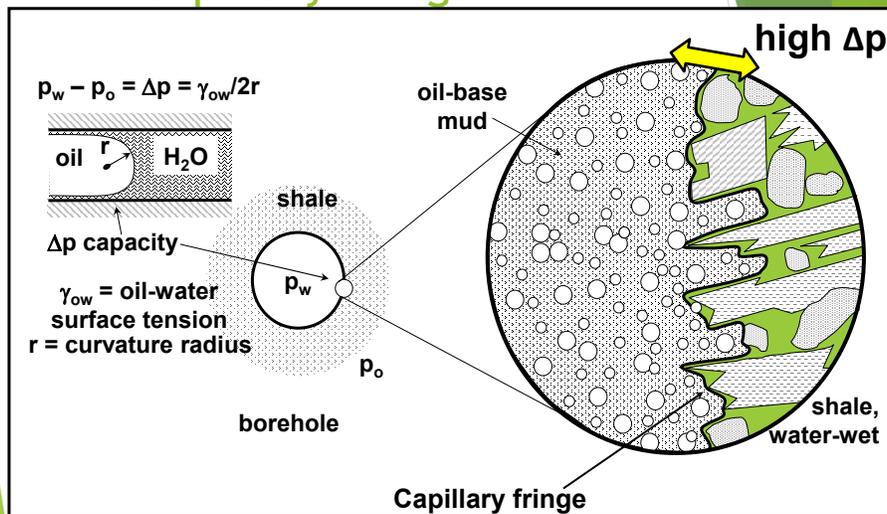


High  $\sigma_0$  leads to rock damage. This permits pressure penetration, loss of radial mud support. It is time-dependent, and reduces stability.

## How Oil Base Muds Work

- ▶ Intact shales have tiny, water-wet pores: a high **capillary entry pressure** exists, therefore the  $p_w - p_o$  acts very efficiently, right on hole wall, giving good support
- ▶ **No filtrate invasion** = little shale deterioration by geochemistry
- ▶ **Shales shrink** ( $-\Delta V$ ) by dewatering because of high salinity of the aqueous phase in OBM
- ▶ **Undrained behavior** ( $-\Delta p$ ) maintained longer because of low  $k$  in shales, little  $H_2O$  transfer
- ▶ All of these are beneficial in general

## The Capillary Fringe



The major OBM effect is the capillary fringe support, which is why they work so well in intact shales

## OBM - However...

- ▶ The capillary effect is lost in fractured shales - poor support, add a plugging agent
- ▶ The salinity effect is irrelevant in non-reactive (Quartz-Illite) shales
- ▶ If fissility planes exist in coaly shales or deep oil shales, OBM often worse than WBM
- ▶ OBM is usually much more expensive
- ▶ It is not the answer to all shale problems
- ▶ When it works (mainly in intact reactive shales), it is absolutely fabulous

## WBM and Shales

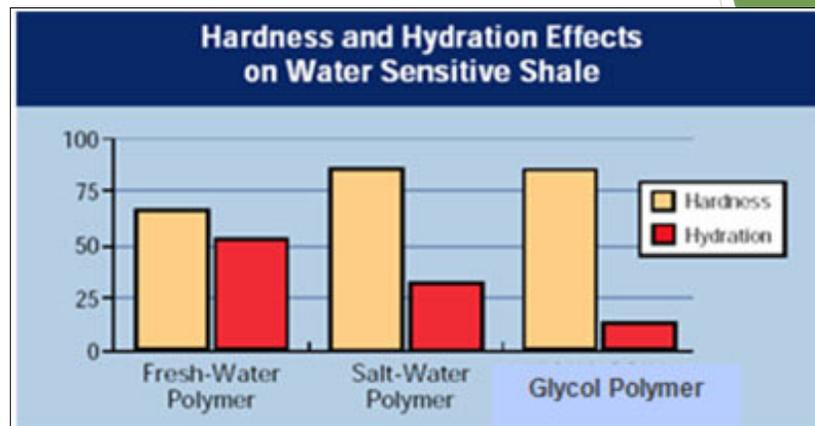
- ▶ We must cope with fractures and fissures
- ▶ We must cope with high wall stresses
- ▶ We must cope with reactive shales
- ▶ Agents to block fissures are useful
  - ▶ Gilsonite, LCM graded mud if large fissures
- ▶ Agents that are chemically beneficial
  - ▶ Reduce clay reactivity
  - ▶ Agents that lead to shrinkage
  - ▶ Agents that reduce permeation and diffusion
- ▶ NaCl-saturated mud is almost always good for reactive ductile shales (but: slow ROP!)

## KCl-Glycol Muds

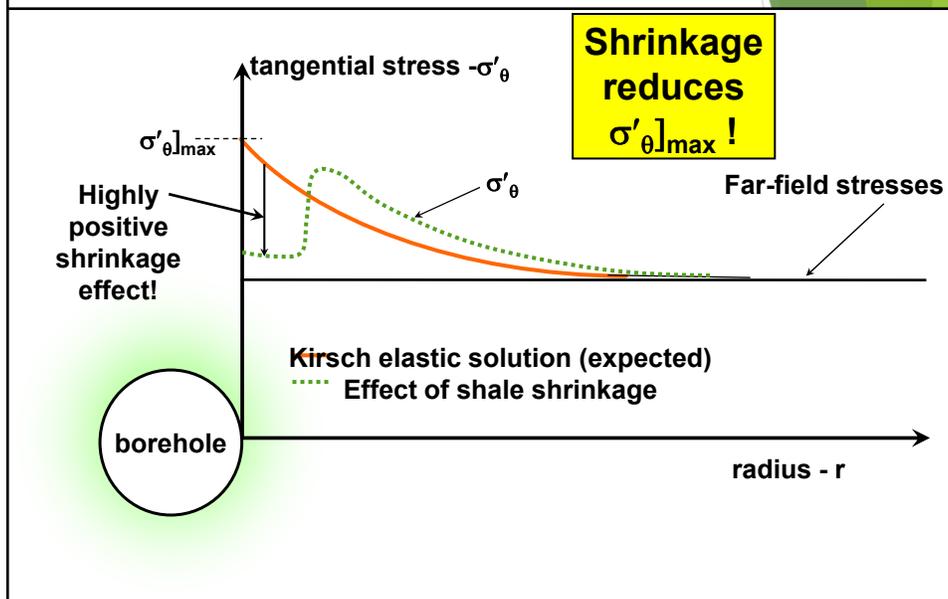
- ▶ Potassium ion displaces  $\text{Na}^+$  in clay minerals
- ▶  $\text{K}^+$  “fits” well into lattice = shale shrinkage
- ▶ Higher concentration of  $\text{K}^+$  = more shrinkage
- ▶ This shrinkage leads to reduced  $\sigma'_0$  near the wall = better stability!
- ▶ Glycol in suspension used. Why?
  - ▶ Glycol particles block microfissures = less flow
  - ▶ This tends to reduce and delay sloughing
  - ▶ Also, glycol tends to adsorb on clay particles
- ▶ All three effects are generally beneficial for borehole stability

## Glycol Effects...

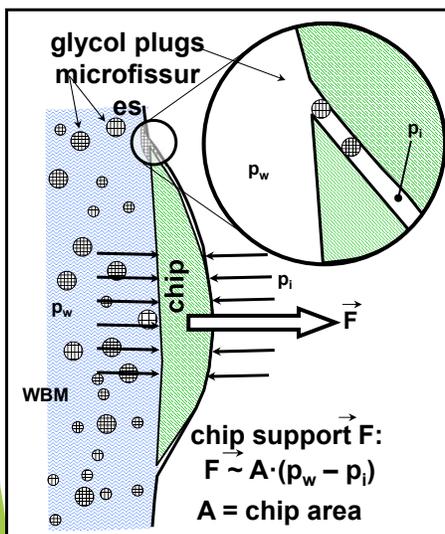
- ▶ Proof of beneficial reduction of hydration



### Effect of K<sup>+</sup>-Induced Shrinkage



### Role of Glycol in K<sup>+</sup>-Glycol Mud

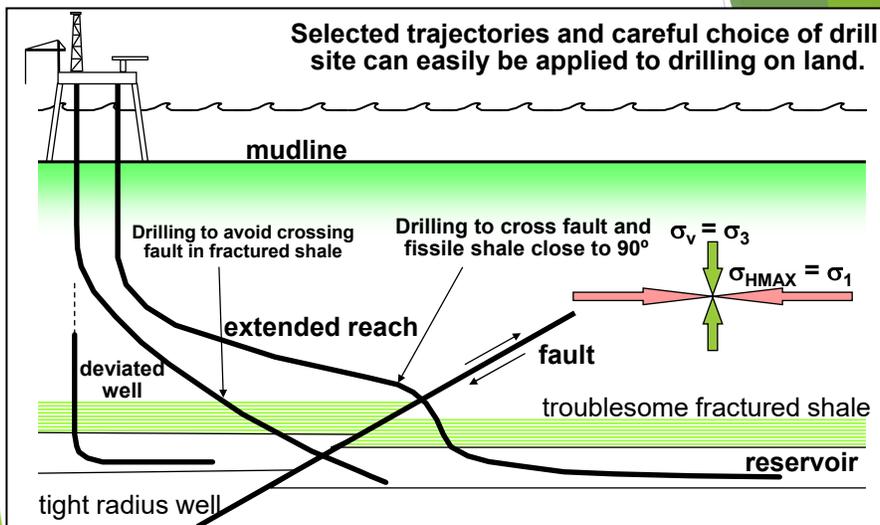


- ▶ It has a chemical effect, reducing swelling...
- ▶ It has a mechanical effect, blocks cracks
- ▶ This helps maintain the support pressure
- ▶ Glycol concentration must be kept above the cloud point (solubility limit) so that free droplets are throughout the mud

## Ca<sup>++</sup>-Based Muds

- ▶ Gyp muds (low pH, CaSO<sub>4</sub>)
- ▶ Lime muds (high pH CaO, Ca(OH)<sub>2</sub>)
- ▶ Lime muds seem particularly effective in controlling geochemically sensitive shales
  - ▶ Cation exchange and shrinkage
  - ▶ Increased interparticle bonding
- ▶ BUT! These high solids muds tend to reduce penetration rate = longer exposure
- ▶ However, they are inexpensive and thus “expendable”, + less environmental impact

## Trajectory Choice (Avoidance?)



Drill through faults and fissile shales at  $90^\circ \pm 25^\circ$

## New Products...

- ▶ Olefin and ester-based drilling fluids
  - ▶ Eliminate swelling of reactive clays
  - ▶ Chips and sloughed shale remain intact
  - ▶ Lowered ECD compared to WBM
- ▶ Clay-free WBM (up to 4100 \$/b!)
  - ▶ Cesium sodium and potassium formates
  - ▶ Extremely inhibitive on shale swelling
  - ▶ Non-corrosive, compared to  $\text{Cl}^-$  brines
  - ▶ Lower torque, ECD, less barite sag
  - ▶ Environmentally more acceptable (no  $\text{Cl}^-$ )
- ▶ Clay-free synthetics (Baroid's Accolade™)

## New Products...

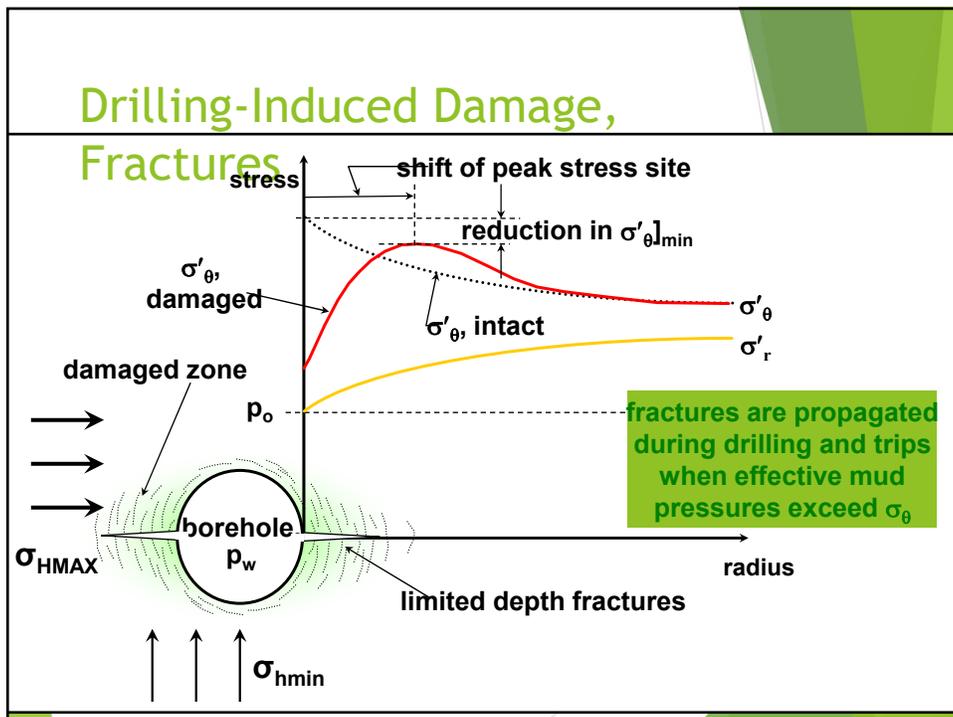
- ▶ Starch/polyglycerol WBM
  - ▶ Polyglycerols reduce swelling (i.e. glycols)
  - ▶ Starch gives viscosity, water-loss control
  - ▶ Environmentally better (cuttings discharge)
  - ▶ Lower ECD than many WBM
  - ▶ Appears good in “ballooning” cases
  - ▶ Should also use graded LCM in these cases
- ▶ Foams
  - ▶ Used in underbalanced drilling ( $MW < p_o$ )
  - ▶ Very high ROP, less exposure time
- ▶ Silicates (blend of Na & K silicates)
  - ▶ Gelation occurs in low pH fmn, sealing pores

## Other Systems...

- ▶ Silicates (blend of Na & K silicates)
  - ▶ Gelation occurs in low pH fmn, sealing pores
  - ▶ pH > -9.5, no precipitation
- ▶ ALPLEX - Aluminum-based ( $\text{Al}(\text{OH})_3$ ) invert emulsion
- ▶ Asphasol
  - ▶ “air-blown” asphalt
  - ▶ Specially treated
  - ▶ Fills fissures, better “cake”, similar to gilsonite
- ▶ And many other polymers, particles, latex, chemicals, inhibitors, etc., etc...

## Strength Reduction in Shales

- ▶ Experiments show that shales almost always weaken when geochemical processes act
  - ▶ changes in concentration
  - ▶ changes in ionic make-up
  - ▶ shrinkage or expansion
- ▶ Micromechanical reasons:
  - ▶ reduced interparticle electrostatic bonding
  - ▶ microstrains deteriorate mineral cementation
  - ▶ concentration changes alter stiffness
- ▶ But, if shale is supported, these effects can be considered secondary



## Coupling of Diffusion Processes

- ▶ Example:  $\Delta T$  affects viscosity, therefore the flow rate into the shale is changed
- ▶ Example:  $C$  affects electrostatic attraction and adsorbed water content can change
- ▶ Example: Adsorbed water content changes affect effective stresses
- ▶ Example: Advective transport in micro-fissures can affect  $T, C \dots$
- ▶ Clearly, a highly complex set of issues!
- ▶ Don't worry about these details too much...

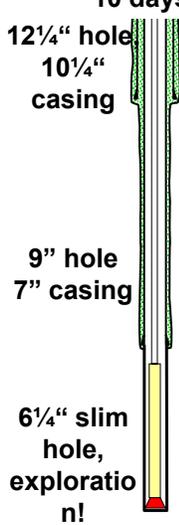
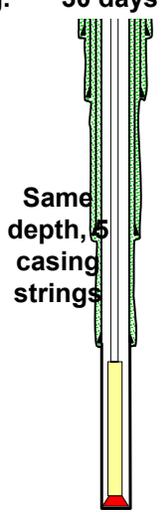
## Permeability Control in Shales

- ▶ Natural  $k$  very low, microfissures increase  $k$  (fractured shales have intrinsic high  $k$ )
- ▶ Two options: reduce microfissure intensity or block the microfissures somehow
- ▶ Reducing microfissure intensity is difficult and causes slower drilling (high MW ...)
- ▶ Blocking microfissures
  - ▶ Starch in NaCl muds
  - ▶ Glycol in KCl-Glycol muds
  - ▶ Gilsonite and other deformable asphalts
  - ▶ Graded LCM for larger fissures

## Is Faster Drilling the Best Cure?

- ▶ Shorter exposure = less  $t$  for diffusion processes to act on the shale, therefore less deterioration develops
- ▶ Approaches to achieve more rapid drilling
  - ▶ Smaller holes (e.g. slim exploration holes)
  - ▶ Reduce or eliminate logging if possible
  - ▶ Longer bit runs = fewer trips
  - ▶ Improved hole hydraulics
  - ▶ Underbalanced or near-balance drilling
- ▶ Small holes also are relatively stronger
- ▶ Expandable liners + bicentre bits...

## Drilling Faster Reduces Problems

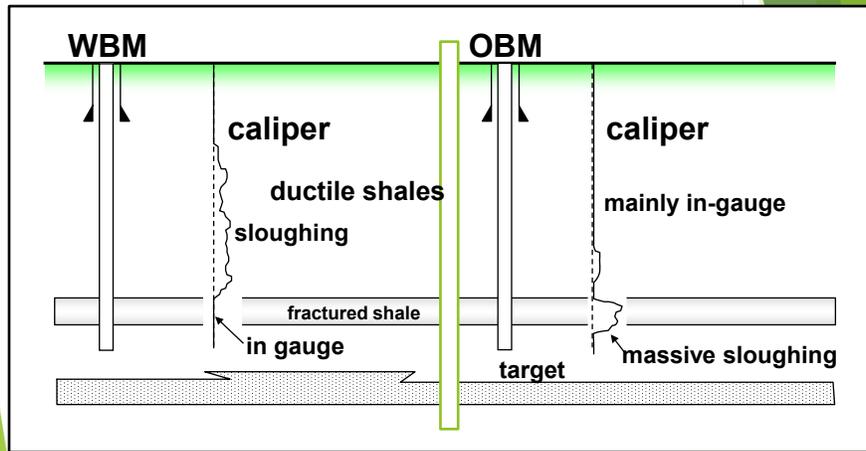
10 days drlg.	30 days drlg.	Drilling exploration or production wells?
<p>12¼" hole 10¼" casing</p> 	<p>Same depth, 5 casing strings</p> 	<ul style="list-style-type: none"> <li>▶ Exploration wells can be slim hole, fast wells</li> <li>▶ Reduced exposure time for troublesome shales</li> <li>▶ Smaller diameter leads to greater stability</li> <li>▶ Lower mud costs, etc.</li> <li>▶ Fewer casing strings!</li> <li>▶ Watch your ECD! <b>Discuss UNOCAL experience in Indonesia</b></li> </ul>

## Pressure Managed Drilling

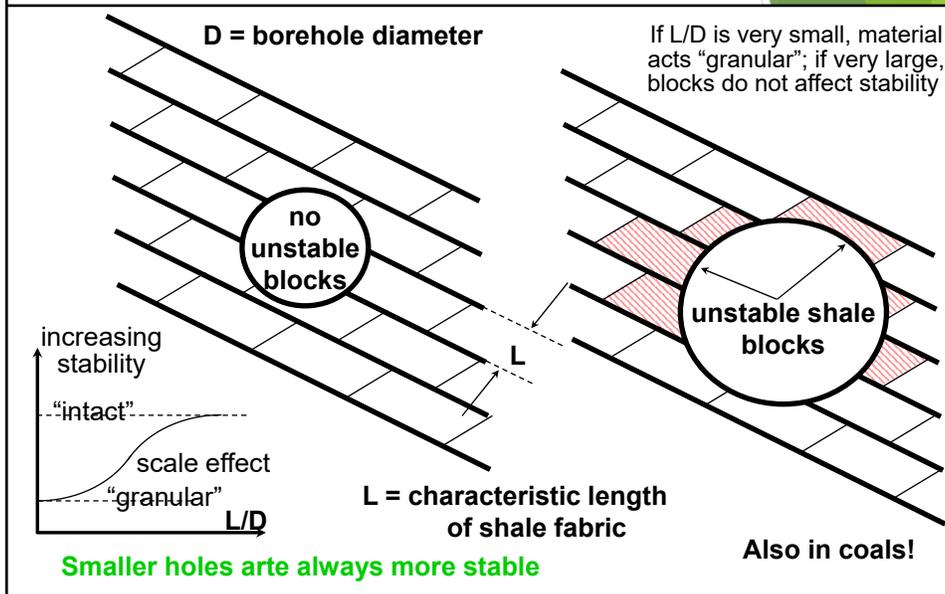
- ▶ A new concept, based on new understanding
- ▶ BHP kept constant using special equipment, ECD is maintained close to zero as possible
- ▶ Eliminate sudden  $\Delta p$  changes...
  - ▶ Cyclic loading of fractured material degrades strength; if it is reduced, shale stays stronger
  - ▶ Reduces filtrate and pressure invasion
  - ▶ Reduces (or eliminates) breathing on connections, reduces uphole ballooning
  - ▶ Allows one to operate closer to  $MW - p_o$  at hole bottom by eliminating ECD, hence faster drlg.
  - ▶ Etc.

## Alberta Example

- ▶ Deep Basin, upper soft, lower fractured
- ▶ OBM best higher up, WBM lower down!



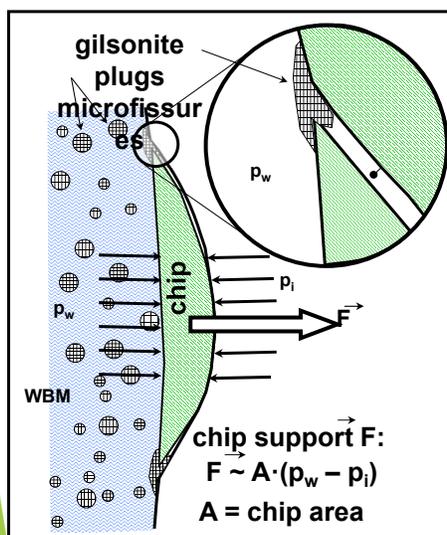
## Scale Effect in Fractured Shales



## Gilsonite, LCM for Fractured Shale

- ▶ Fractured shales slough because of no  $\Delta p$
- ▶ Maintaining some  $\Delta p$  is a major benefit
- ▶ In OBM, solids alone do not seem to bridge
- ▶ In WBM, yes, but gilsonite helps greatly (available for OBM as well)
- ▶ Gilsonite + solids plug the natural fissures, reduce  $k$ , help  $\Delta p$ , improve "cake" efficiency
- ▶ Add designed LCM material to mud to help the fracture plugging
- ▶ Reduce MW rather than increase it
- ▶ Careful trip and connection policy

## Gilsonite Plugs Fissures



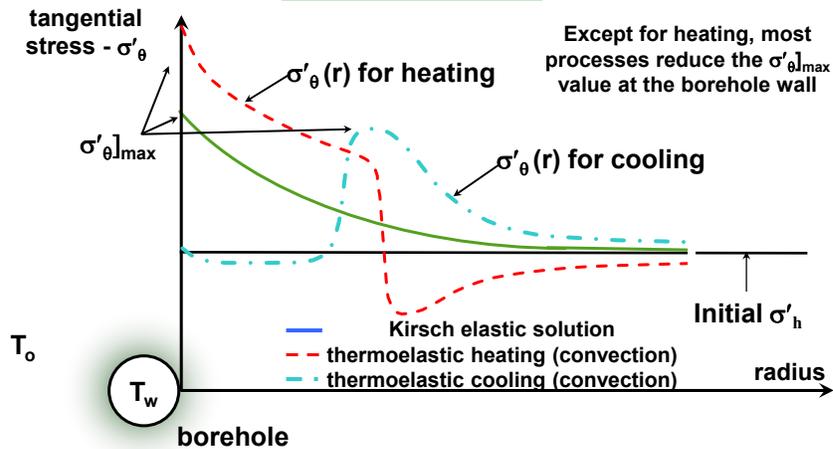
Also available for OBM and synthetic muds

- ▶ Natural asphalt
- ▶ Gilsonite is flexible at the T at depth in holes
- ▶ It can plug induced microfissures
- ▶ It also helps plug in fractured shales
- ▶ This helps sustain support pressure
- ▶ Diffusion of  $p$ ,  $C$  into shale is retarded
- ▶ Shales stay intact longer



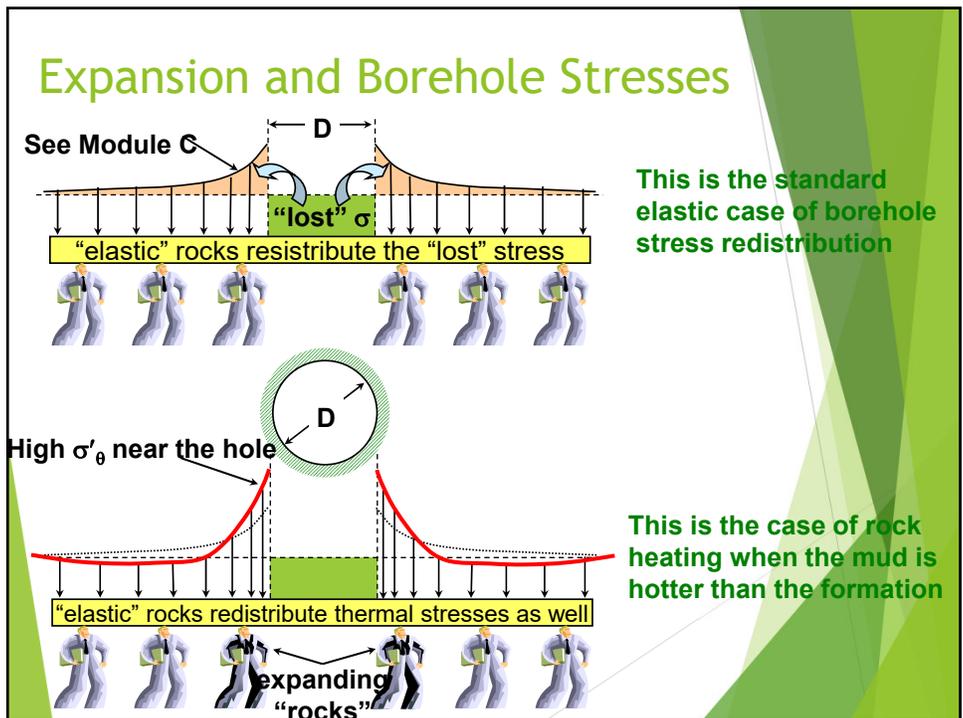
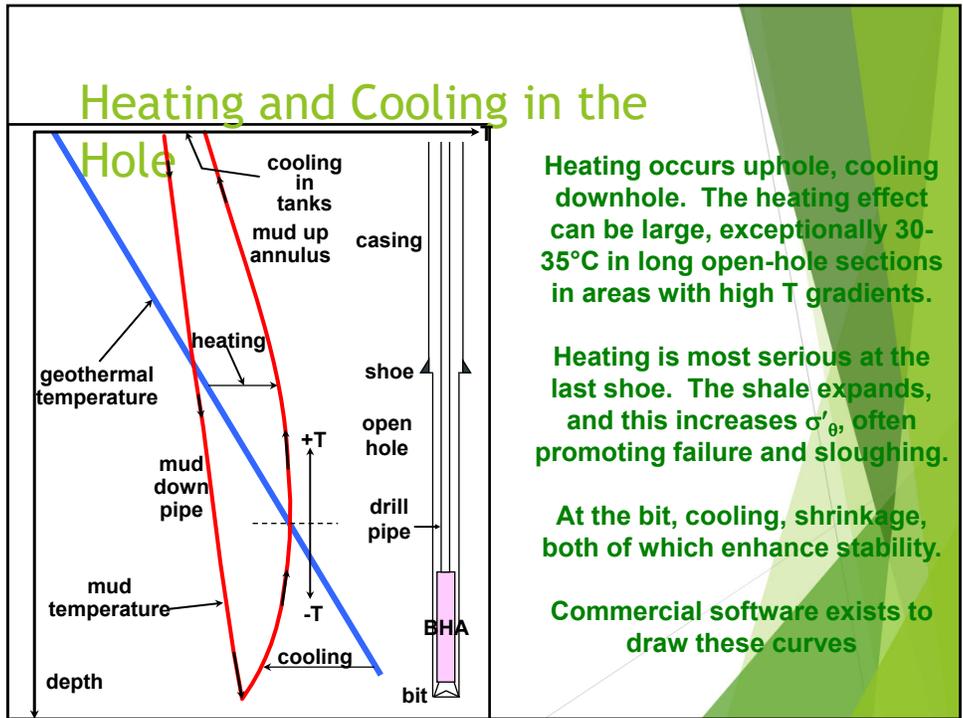
## Thermal Alterations of $\sigma'_\theta$

These curves show hoop stress calculated using an assumption of heating and an assumption of cooling. Heating a borehole increases  $\sigma'_\theta$ , and leads to hole problems. Cooling the borehole is always beneficial to stability.



## What Happens with Hot Mud?

- ▶ The rock in the borehole wall is heated
- ▶ Thermal expansion takes place
- ▶ This “attracts” stress to the expanding zone around the well
- ▶ The peak stress rises right at the borehole wall, and yield and sloughing is likely
- ▶ For cooling, the rock shrinks; this allows the stress concentration to be displaced away from the borehole, helping stability
- ▶ Cooling occurs at and above the bit
- ▶ Heating occurs farther uphole



## Cooling the Drilling Fluid

- ▶ Reduces the stresses on the borehole wall
- ▶ Improves the stability of the mud system
- ▶ Improves safety on the rig, especially offshore in hot drilling areas
- ▶ Reduces the rate of diffusion of chemicals into the shale, slowing down deterioration
- ▶ Helps protect the drill bit and the bottom-hole assembly
- ▶ Should be more widely used

## Summary

- ▶ There are many reasons for borehole instability
- ▶ You must assess the reason for instability
- ▶ Then, solutions will be possible
- ▶ Mud weight and hydraulics control
- ▶ Oil based mud for ductile shale is very good
- ▶ Chemical solutions help as well
- ▶ Plugging the wall for fractured shale
- ▶ Cooling the mud
- ▶ And so on

