

ژئومکانیک مخازن هیدروکربوری

Hydraulic Fracturing in Oil and Gas Reservoirs

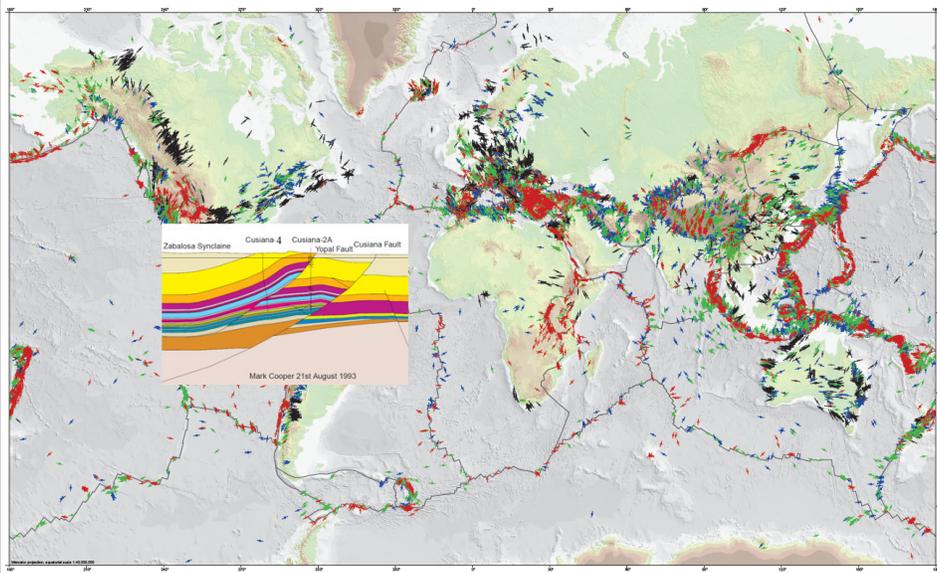
Petroleum Geomechanics

Hasan Ghasemzadeh

<https://wp.kntu.ac.ir/ghasemzadeh/>

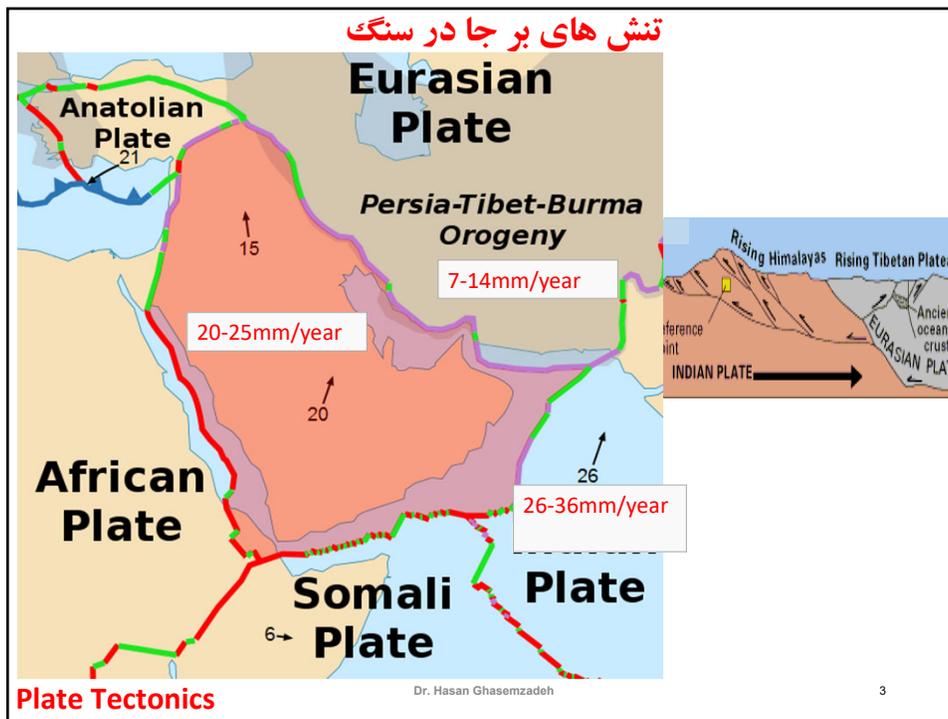
Faulting & Stress Regimes

تنش های بر جا در سنگ



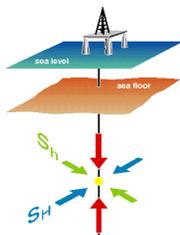
Heidbach, Oliver; Rajabi, Mojtaba; Reiter, Karsten; Ziegler, Moritz (2016): World Stress Map 2016. GFZ Data Services.
<http://doi.org/10.5880/WSM.2016.002>

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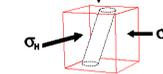
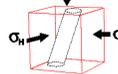
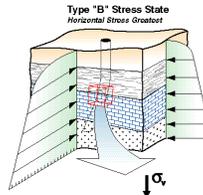
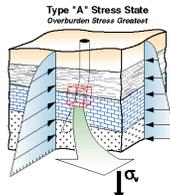


In situ Geological Stresses

- Normal Assumption – Vertical and Horizontal stress orientations

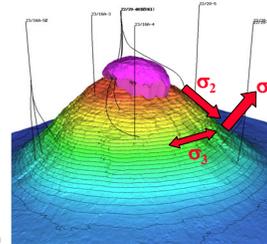
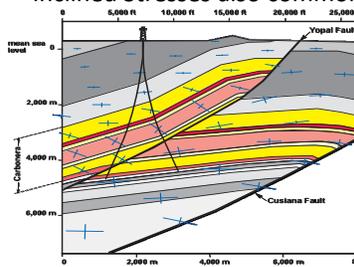


From, S. Bell



From, Mclean et al. 1990

- Inclined Stresses also common, but largely ignored in many analyses



adeh

5

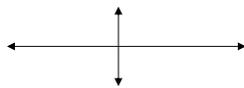
تنش های بر جا در سنگ

اهمیت تعیین تنش در سنگ

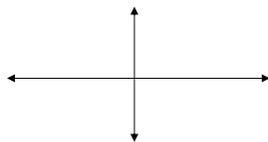
مهندسی معدن، عمران و نفت
ژئو فیزیک و زمین شناسی

تنظیم تنشهای اطراف بازوهای زیرزمینی نظیرتونلها،
معدن، محورهای عبور آب، شفت ها وحفره های زیرزمینی

تنش های در جا در محیط معمولاً ناشی از بارهای ثقلی و بارهای
سازه های فوقانی و کرنش های ایجاد شده توسط فعالیت های
تکتونیکی پوسته زمین می باشد



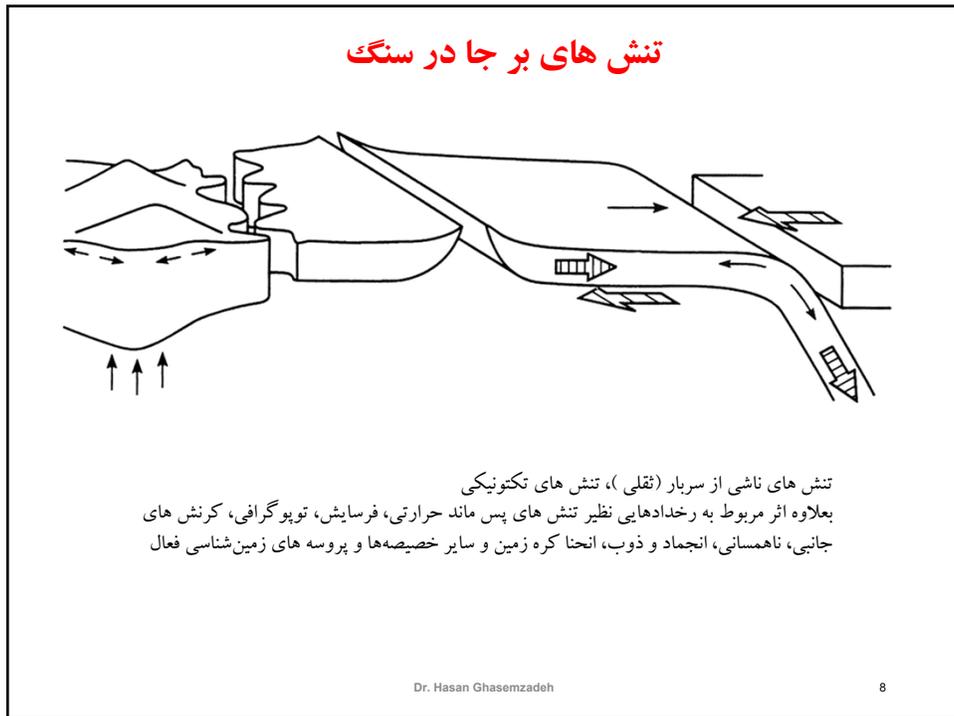
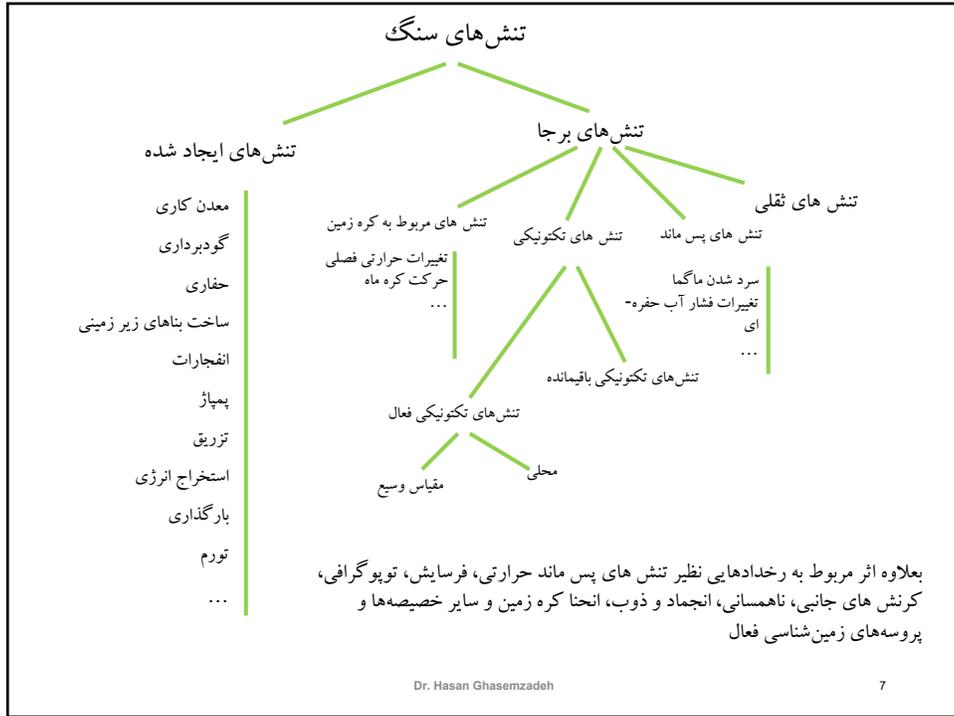
تنش نزدیک سطح



تنش در عمق معمولاً هیدرواستاتیک
در نظر گرفته می شود

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6



تنش های بر جا در سنگ

Normal Faults and Fractures

Extension: "pull-apart"

$\sigma_v = \sigma_1, \sigma_{HMAX} = \sigma_2, \sigma_{hmin} = \sigma_3$

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تنش های بر جا در سنگ

Reverse Faults and Fractures

$\sigma_v = \sigma_3, \sigma_{HMAX} = \sigma_1, \sigma_{hmin} = \sigma_2$

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تنش های بر جا در سنگ

Strike-Slip Faults & Fractures

$\sigma_v = \sigma_2, \sigma_{HMAX} = \sigma_1, \sigma_{hmin} = \sigma_3$

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تنش های بر جا در سنگ

$K_a < K < K_p$

کولمب $K_p = \tan^2(45 + \phi/2) + q_u/\gamma \cdot 1/z$
 $K_a = \cot^2(45 + \phi/2) - [(q_u/\gamma) \cot^2(45 + \phi/2)] \cdot 1/z$

$K = K_a$ در گسل عادي

$K = K_p$ و در گسل معكوس

هوك و براون

$0.3 + \frac{100}{Z} < \bar{K} < 0.5 + \frac{150}{Z}$

\bar{K} : ضريب فشار جانبی متوسط بدست آمده از آزمایشات صحرايي

Z : عمق

تنش های ناشی از سازه های فوقانی مطابق با منحنی هایی که در مکانیک خاک دیده اید قابل محاسبه است
 البته باید دقت نمود که در اکثر این منحنی ها فرض بر هموزن و الاستیک و همسانگرد بودن سنگ است

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تنش های بر جا در سنگ

تنش های ناشی از فعالیت های تکتونیکی

این تنش ها معمولا "بموازات پوسته زمین و افقی در نظر گرفته می شود. با فرض وجود تنش های تکتونیکی در راستای آزمون α در یک محیط الاستیک همگن و همسانگرد داریم

$\sigma_x = T_h$	تنش های تکتونیکی در راستای آزمون α
$\sigma_y = KT_h \approx \nu T_h$	تنش افقی عمود بر راستای آزمون α
$\sigma_z = \psi T_h \approx 0$	آزادی حرکت در جهت قائم

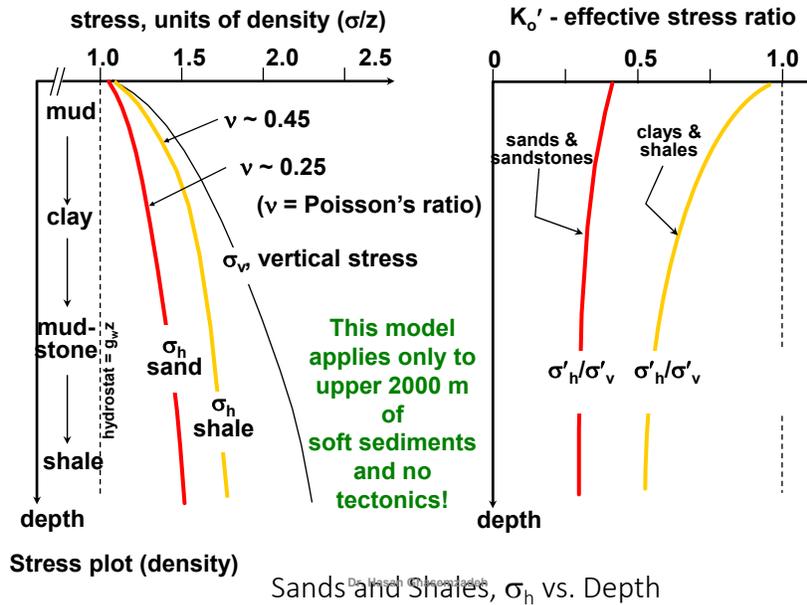
$$K = 0.25 + 7E_b(0.001 + 1/z)$$

E_b (GPa) مدول تغییر شکل پذیری

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13

تنش های بر جا در سنگ



14

تنش های بر جا در سنگ

- If there has been no tectonic activity, σ_h is less than σ_v
- In sands, the ratio K'_o (defined as the ratio of horizontal to vertical stress, σ'_h/σ'_v), can be as low as 0.3, usually 0.4 – 0.6
- Shales have a low angle of friction, usually K'_o is 0.6 – 0.8, even as high as 0.95 in muds

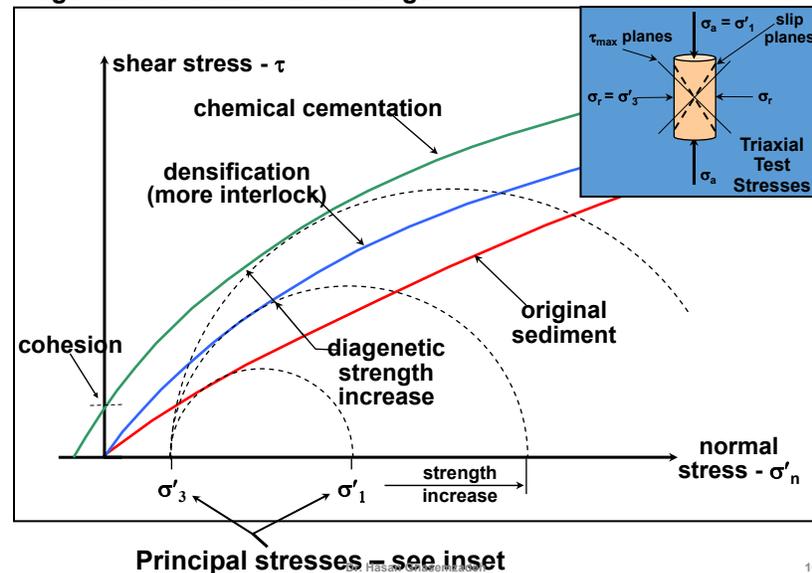
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15

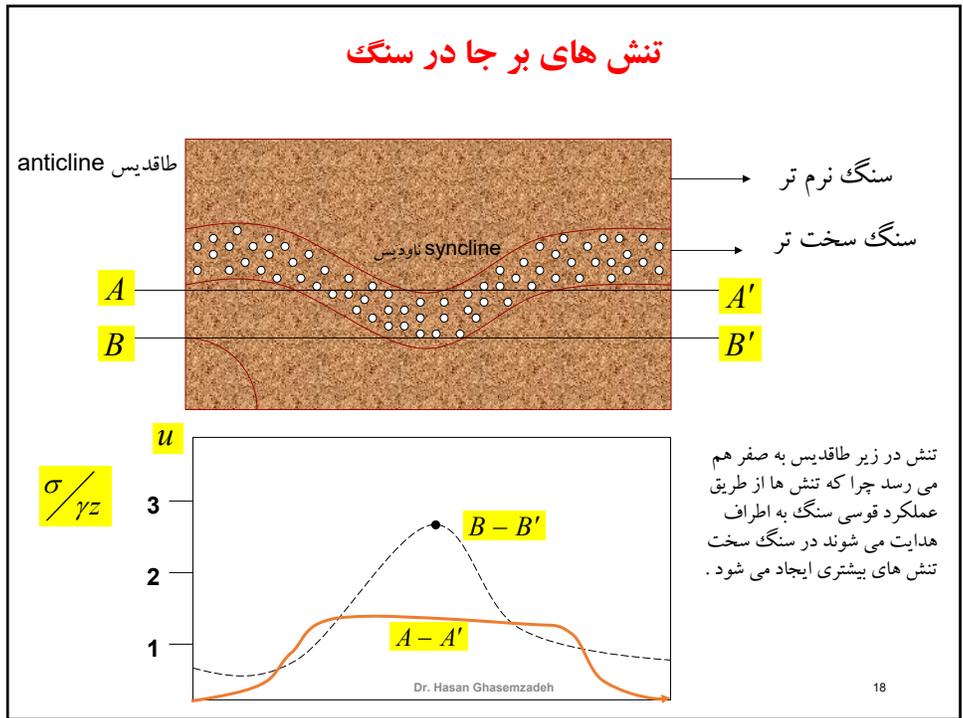
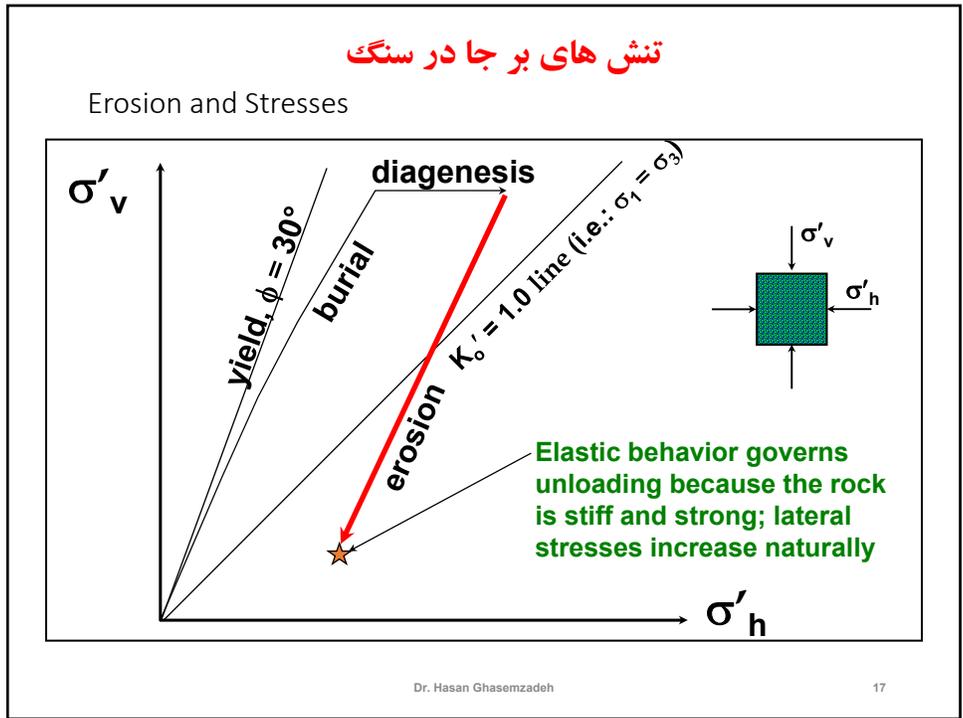
تنش های بر جا در سنگ

Diagenesis effects on the strength

تأثیرات سنگ زایی بر مقاومت



16



تنش های بر جا در سنگ

قانون : (Heim Rule)

بر طبق این قانون در اعماق زیاد تنش های مختلف با یکدیگر مساوی هستند زیرا ماده سنگ نمی تواند در مقابل اختلاف تنش های بزرگ ایستادگی نموده و از راه تسلیم و یا تغییر شکل سعی به کاهش اختلاف تنش های موثر می نماید. این وضعیت در اثر تنش های آنی و دگر شکلی های وابسته به زمان حاصل می شود. بدین ترتیب به مرور زمان در عمق زیاد تمام تنش ها مساوی می گردند . وضعیت تنش حاصل را هیدرواستاتیک و یا (litho static) می نامند.

• قانون هیم در مورد سنگهای تقریباً ضعیف مثل کربناتها ، زغال ها و اوپوریت ها نتیجه خوبی داده است .

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19

تنش های بر جا در سنگ

تخمین های تئوری تنش های بر جا دقت خوبی ندارد زیرا عواملی نظیر لایه بندی، درز و ترک ها ، گسل ها ، چین خوردگی ها و ناهمگنی های میکروسکوپی و عوامل مختلف موثر بر تنش برجا، مقادیر تنش واقعی برجا را متفاوت از مقادیر تنش تئوری می سازد.



20

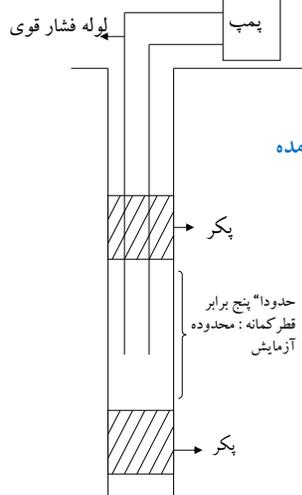
تنش های بر جا - شکست هیدرولیکی



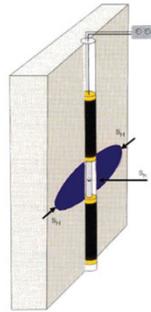
اعمال و افزایش فشار در مقطعی از یک گمانه

تا ایجاد ترک های جدید (HF) Hydraulic Fractures Test

یا بازشدن ترک های موجود (HTPF) Hydraulic Test On Pre-existing Fractures



اندازه گیری فشار سیال لازم در یک عمق مشخص برای بازشدن، ایجاد، گسترش، دوباره باز کردن ترک ها در سنگ ارتباط دادن به تنش های برجای موجود در منطقه مشاهده و محاسبه ی راستای درزه باز شده یا ترک های بوجود آمده



در گمانه های قائم با عمق زیاد و بسیار زیاد (بین ۶ تا ۹ کیلومتر)

فرضیات:

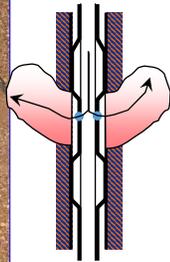
- تنشهای افقی و قائم، تنشهای اصلی
- تنش قائم = وزن سربار سنگ
- تغییرات تنشها با عمق خطی است

Hydraulic Fracturing Test (HF)



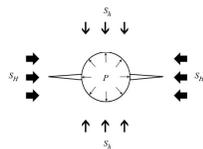
جستجوی مقاطع بکر و بدون ترک شکستن سنگ توسط پمپاژ آب یا گل حفاری در مقطعی از گمانه تعیین راستای ترک حاصل با استفاده از

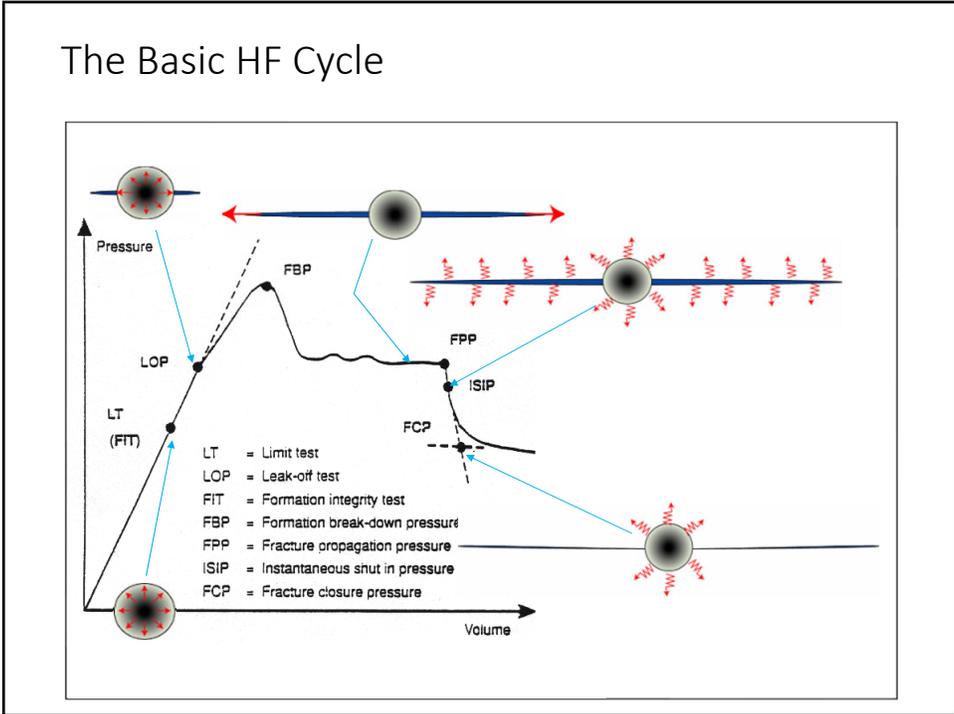
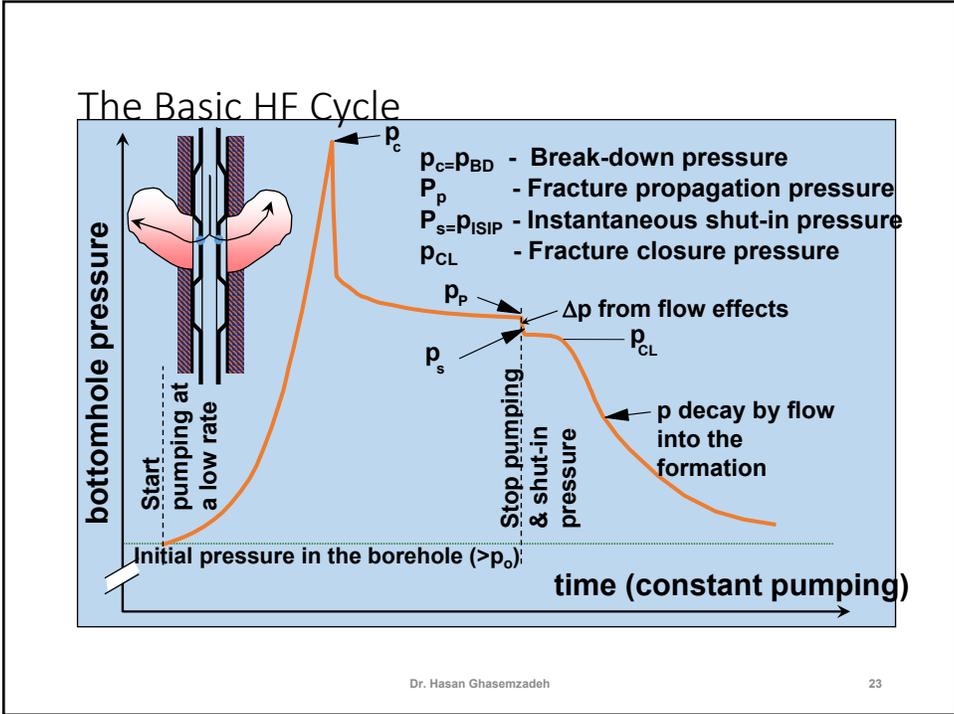
Impression Packers پکر های شکل پذیر
Borehole Televiwer دوربین های درون گمانه ای



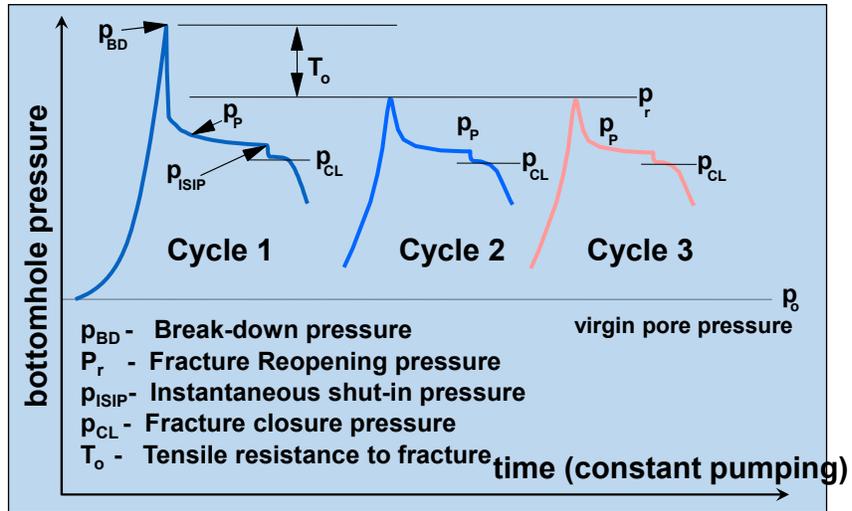
محدودیت ها:

- تنشهای بسیار زیاد
- درجه حرارت های فوق العاده زیاد (بالای ۲۰۰ درجه)
- رفتار غیر خطی و شکل پذیر
- رفتار شکننده و ترد توأم با تخریب دیواره گمانه





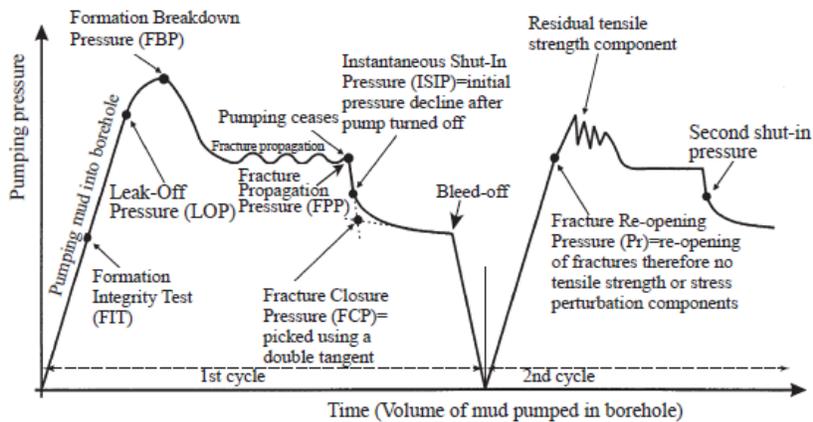
Hydraulic Fracture Cycles



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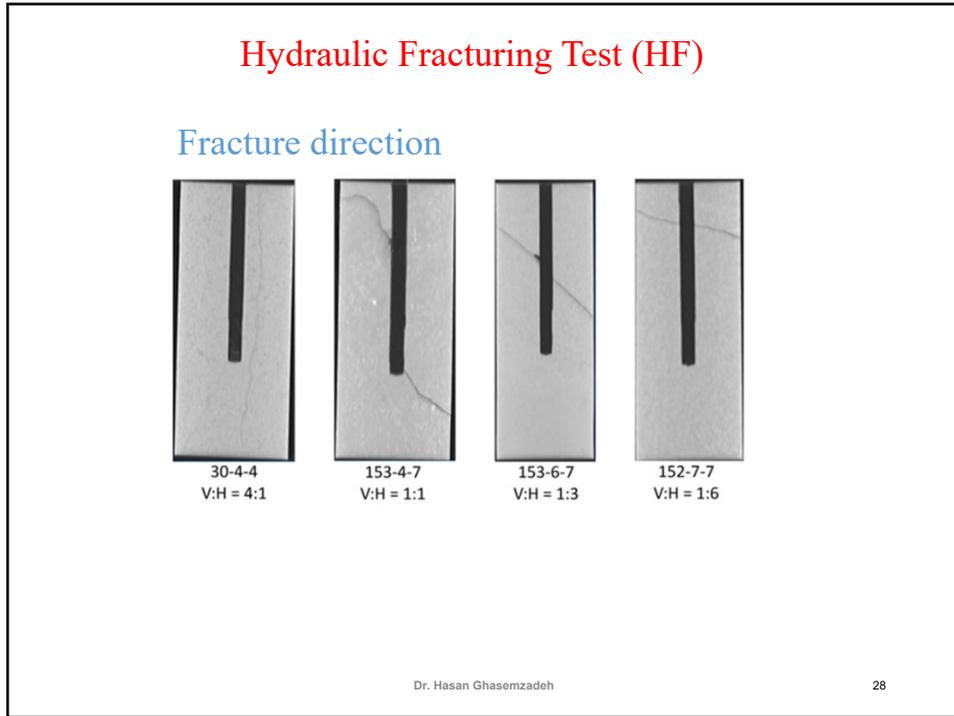
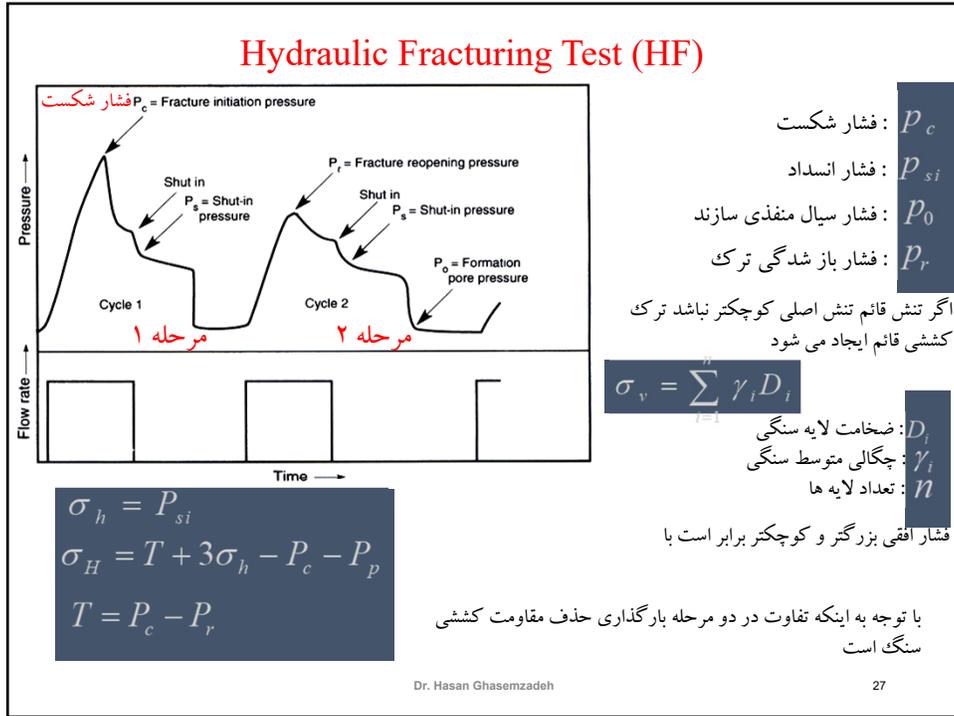
25

The Basic HF Cycle



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26



Hydraulic Test On Pre-existing Fractures (HTPF)

بازکردن مجدد یک ترک موجود با راستای معلوم
قبل از اعمال نیرو، مجزا کردن ترک، توسط دو پکر از سایر بخشها

گمانه ی حفر شده الزاماً قائم نبوده

عدم فرض عمود بودن راستای محور گمانه بر مؤلفه تنش برجا

تنها روش تعیین تنش برجا در اعماق زیاد

Cornet(1986)

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29

Hydraulic Fracturing (HF)

- 1) Enhanced oil / gas recovery technique
- 2) In situ recovery of valuable mineral
- 3) Preconditioning and Blasting in hard rock mining
- 4) Geothermal energy
- 5) Adjust ground stress

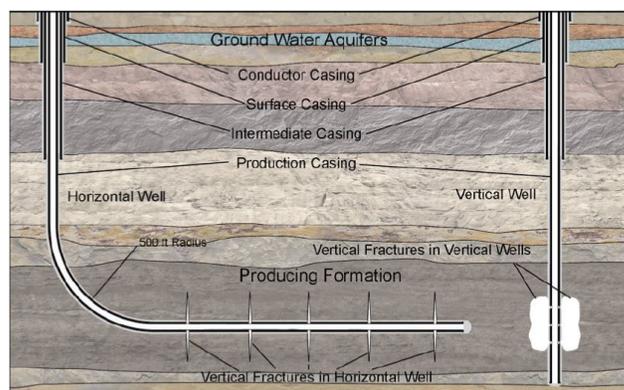
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30

Hydraulic Fracturing (HF) Enhanced oil / gas recovery technique

- 1) Fluid flow inside the fracture
- 2) Mechanical deformation of the surrounding rock
- 3) Exchange of fluid between the fracture and porous medium (infiltration or leak-off)
- 4) Propagation of fracture (HF is a moving boundary problem)



31

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31

Hydraulic Fracturing (HF) Enhanced oil / gas recovery technique

HF proved to be successful in stimulating hydrocarbon reservoirs.

Currently used for all types of reservoirs from unconventional (very low permeability) oil-shale or gas-shale to high permeability sandstones.

- **60%** of the newly drilled wells are hydraulically fractured.

- environmental effects such as:
 - contamination of underground fresh-water reservoirs
 - increasing the level of regional seismicity.

32

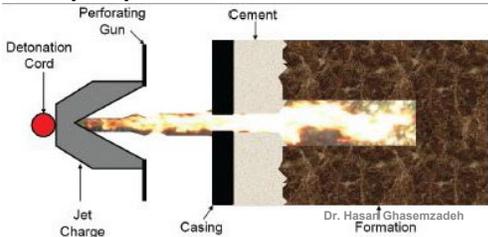
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32

Hydraulic Fracturing (HF) Enhanced oil / gas recovery technique

Typical HF operations at the field require:

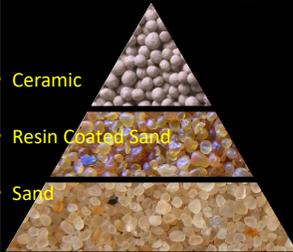
- Perforating Gun (detonation)
- Injecting Fluid
- Proppants (sand)
- Other fluid additives (gelling agents, breakers)
- Injection pumps



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Formation



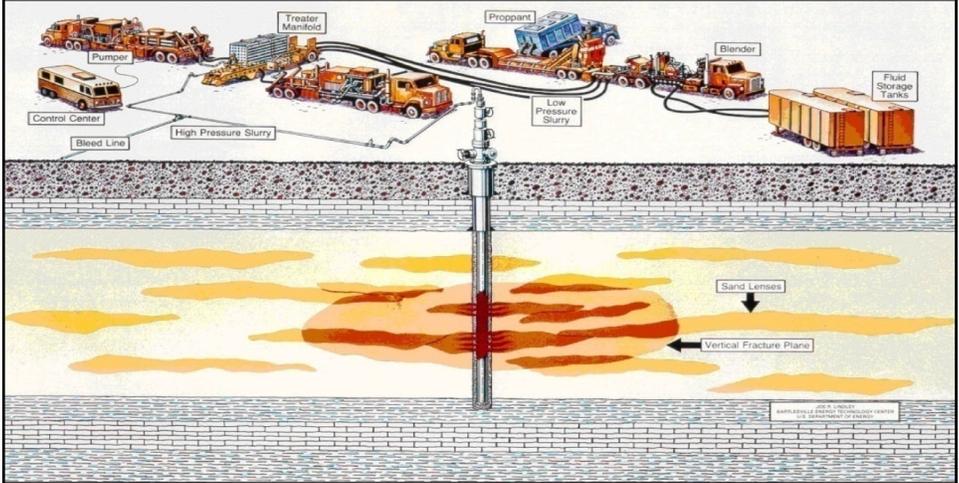
Gelling Agents

- Ceramic
- Resin Coated Sand
- Sand

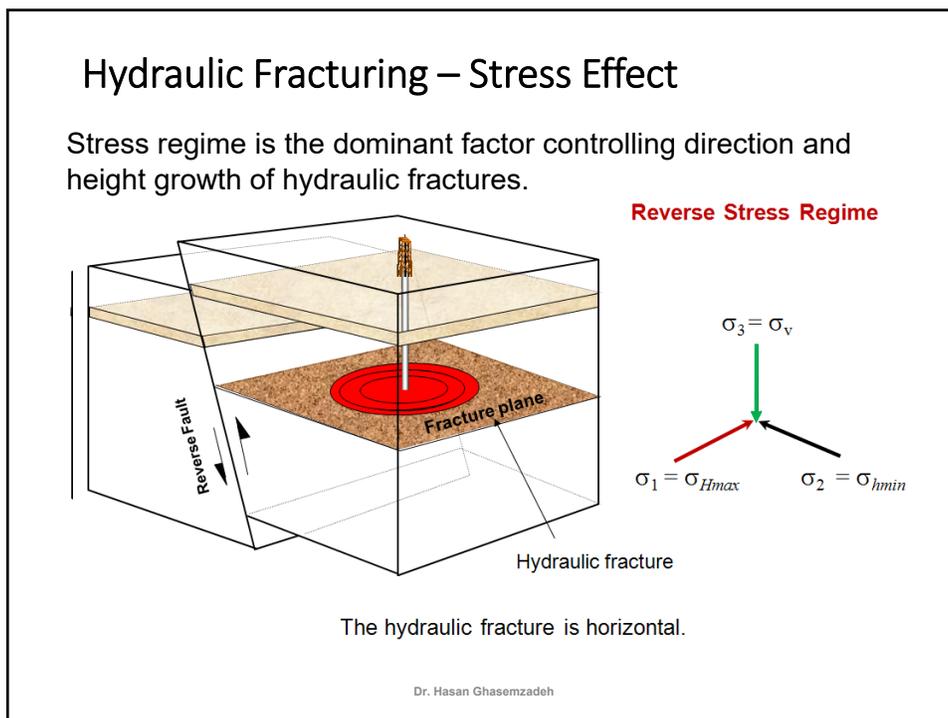
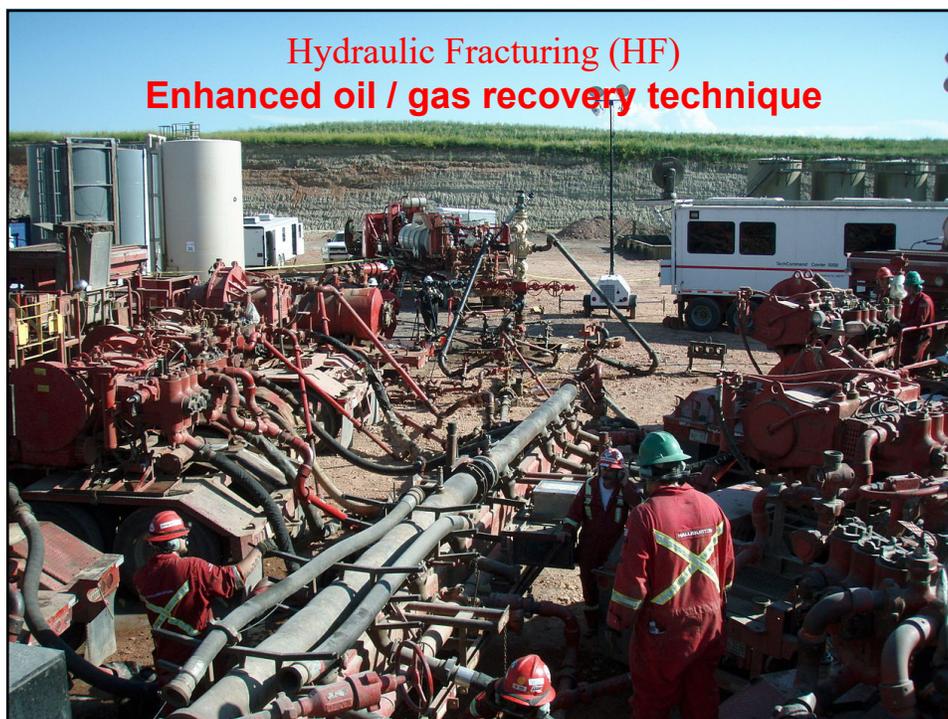
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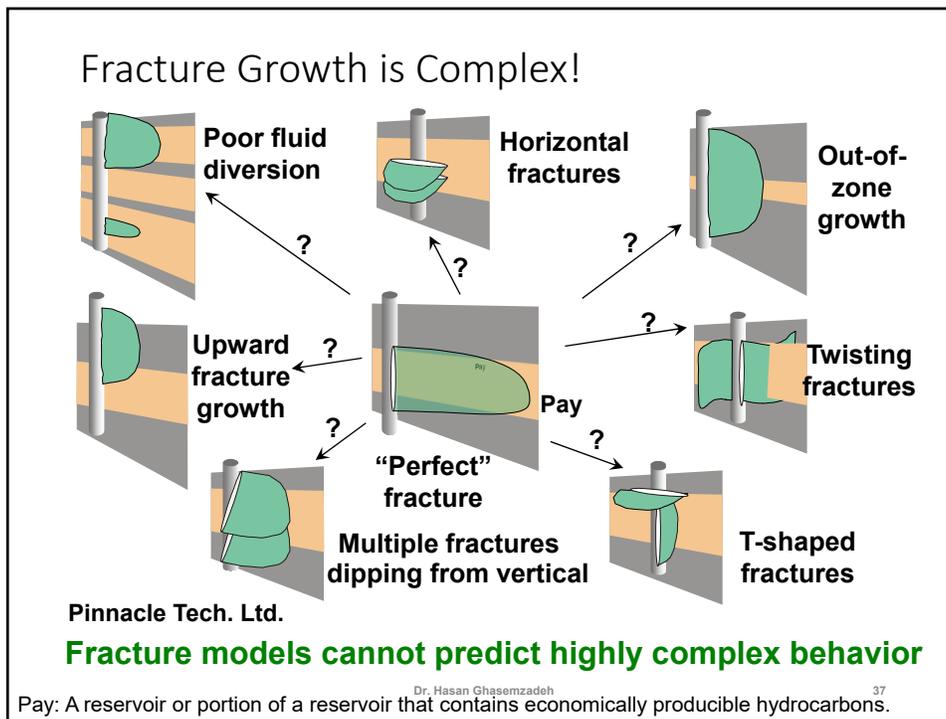
Hydraulic Fracturing (HF) Enhanced oil / gas recovery technique



34

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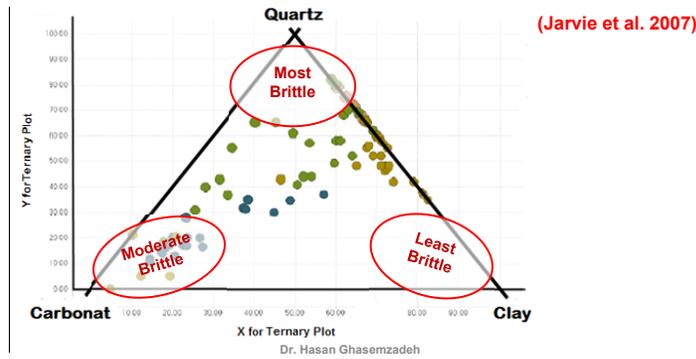
Where to Frac?

- In brittle rocks hydrofracture is more likely to be long enough to connect the highest amount of rock volume to the parent wellbore.
- Thus, it is very important to find intervals that are brittle, in order to maximize hydraulic stimulation.

Brittleness determining Mineralogy Approach

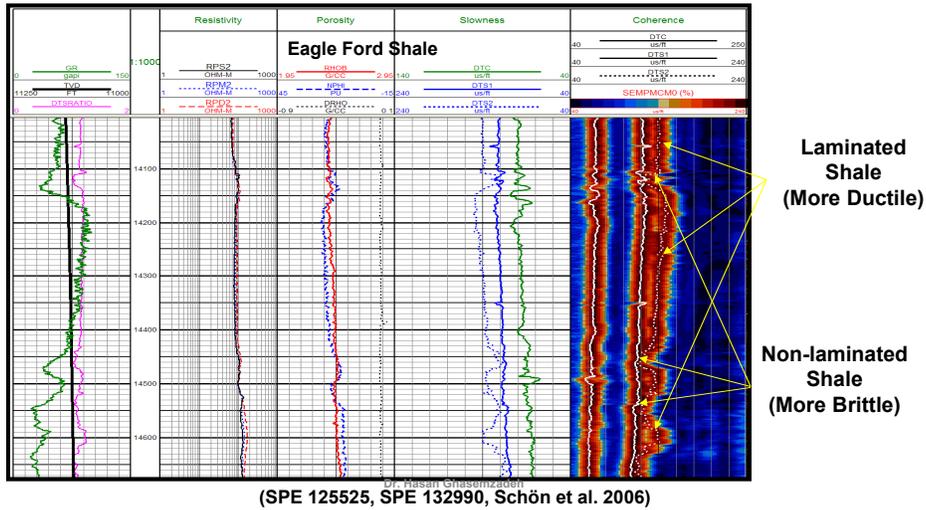
- Q-C-C (Quartz-Clay-Carbonate)

$$BRITTLNESS \% = \frac{Quartz}{Quartz + Carbonates + Clays}$$



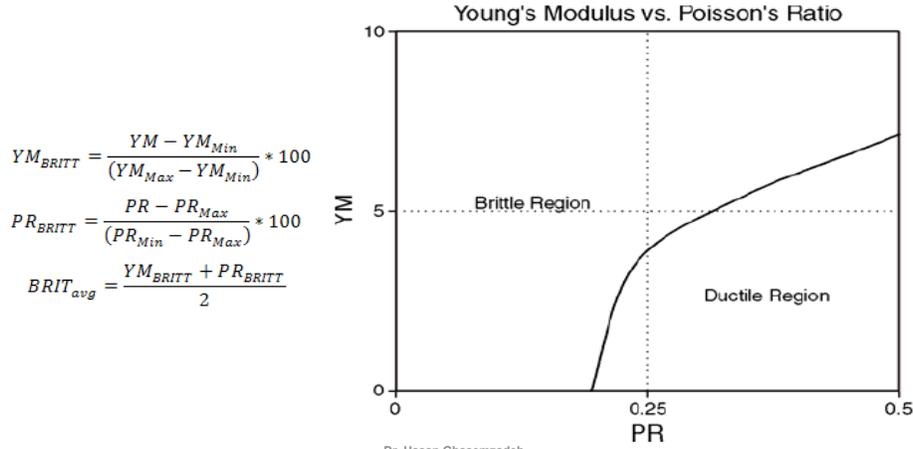
Brittleness determining Anisotropy Method

Laminated Shale is More Ductile and Non-laminated Shale is More Brittle



Brittleness determining Dynamic Elastic Constants Method

Brittle rocks have higher Young's Modulus (YM) and lower Poisson's Ratio (PR)



$$YM_{BRITT} = \frac{YM - YM_{Min}}{(YM_{Max} - YM_{Min})} * 100$$

$$PR_{BRITT} = \frac{PR - PR_{Max}}{(PR_{Min} - PR_{Max})} * 100$$

$$BRIT_{avg} = \frac{YM_{BRITT} + PR_{BRITT}}{2}$$

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Brittleness determining Laboratory Methods

- Punch penetration test (Saffet, 2009)
- Compressive and tensile strengths measurement:
 - $BI = (\sigma_c - \sigma_t) / (\sigma_c + \sigma_t)$ (Hunca & Das, 1974)
 - $BI = (\sigma_c \times \sigma_t) / 2$ (Altindag, 2002)

Rock brittleness classes (Goktan & Yilmaz, 2005)

Class	BI	Description
1	>25	Very brittle
2	15 < BI < 25	Brittle
3	10 < BI < 15	Moderately brittle
4	BI < 10	Low brittleness

Best rock to frac

Hydraulic Fracturing (HF) Enhanced oil / gas recovery technique Fundamental Complexities of HF:

- In its simplest form,
- HF is a coupled **Hydro Mechanical (HM)** problem
equations of "equilibrium" and "mass conservation of fluid" .
- Thermal treatments: **Thermo-Hydro-Mechanical (THM)** problem
with equations of "energy"
- Chemical treatments: **Chemical-Hydro-Mechanical (CHM)** problem
with equations of "chemical reactions"
- Thermal and Chemical treatments: **Thermo-Hydro-Mechanical & Chemical- (THMC)**
- Usually more than one P.D.E's are involved due to different nature of the injecting fluid and the fluids inside the reservoir

43

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43

Other Types of Complexities in HF analysis:

- 1- Fracture propagation criteria:** Stress-based, Strain-based, Energy-based
- 2- Leak-off models:** 1D, 2D, filter cake
- 3-Proppant Movement:** Non-Newtonian (dilatant) Fluid, 2-phase flow (sedimentation), Proppant crushing
- 4- Single versus Multiple induced Fractures in horizontal wells**
or Vertical wells
- 5- Change in the stress field inside the reservoir** due to depletion, existence of natural cracks, non-homogeneities, etc.
- 6- Crack tip issues:** e.g. fluid-lag or invaded zone

44

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44

Design Sequence of HF Operations:

1. Selection of the well and depth of HF operations.
2. Estimating the Volume of the injecting fluid and the sand (proppant), and pump capacity.
3. Design of the fluid and the additives.
4. Simulating the geometry of the hydraulically-induced crack(s) and HF propagation pattern.
5. Estimating the production and productivity index of the well after the HF operations.

Generally no software can handle all the issues mentioned above without different levels of simplifications.

45

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45

Simulation of Hydraulic Fracturing:

Classical closed form models:

In deeply-seated reservoir, because of the normal stress regime $S_v > S_H > S_h$, thus, it is expected that the induced HF is a vertical plane extended at two sides of the well. This simple assumption was the origin of two classical HF simulation models.

The first model was proposed by Khristianovic & Zheltov (1955), which was later amended by Geertsma & deKlerk (1969).

This model is currently called KGD. KGD is a two-dimensional model based on plane strain assumption in which the height of the fracture is known as a priori.

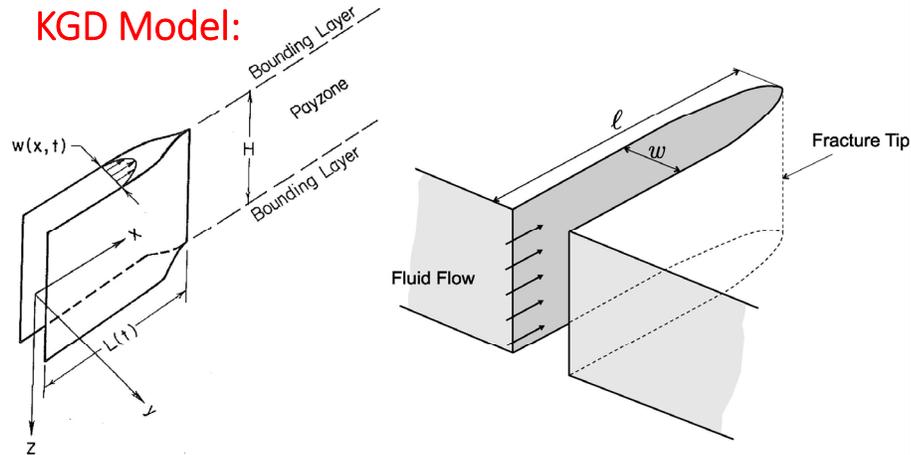
46

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46

Geometry and propagation pattern of the hydraulic fractures

KGD Model:



KGD model provides equations for calculating length of the HF, opening (aperture) of HF, and fluid pressure inside the fracture.

47

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47

Geometry and propagation pattern of the hydraulic fractures

Simulation of Hydraulic Fracturing:

Classical closed form models:

- The second classical model was proposed Perkins and kern (1961) which was later completed by Nordgren (1972) and now is called **PKN model**.
- In **PKN model** the initial height of the crack is known which is assumed that it decreases gradually as the crack propagates. However, the oval shape of the cross section of the crack remains unchanged.

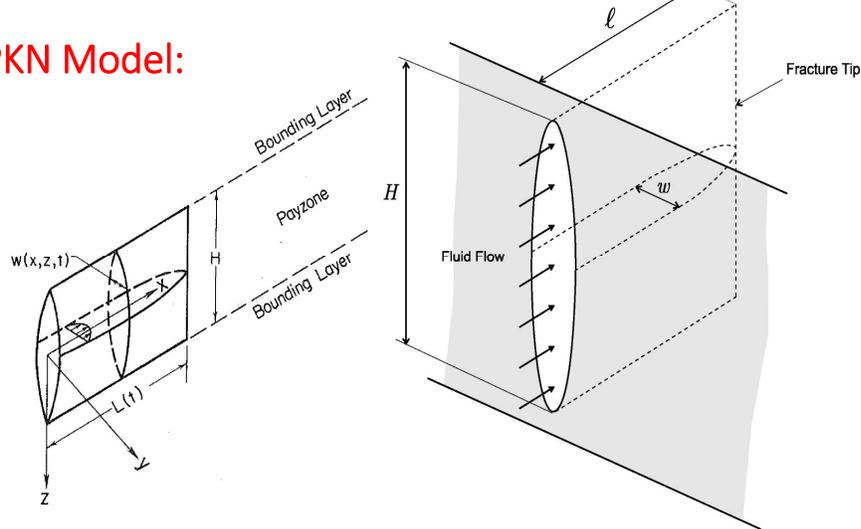
48

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48

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PKN Model:



Length and opening of the HF and fluid pressure inside the crack can be calculated using PKN model equations

49

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49

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Simulation of Hydraulic Fracturing:

Classical closed form models:

If the reservoir is shallow, the assumption of normal stress regime may no longer hold.

For HF in these reservoirs, occurring a **Radial (Penny-shaped) fracture** plane is quite common.

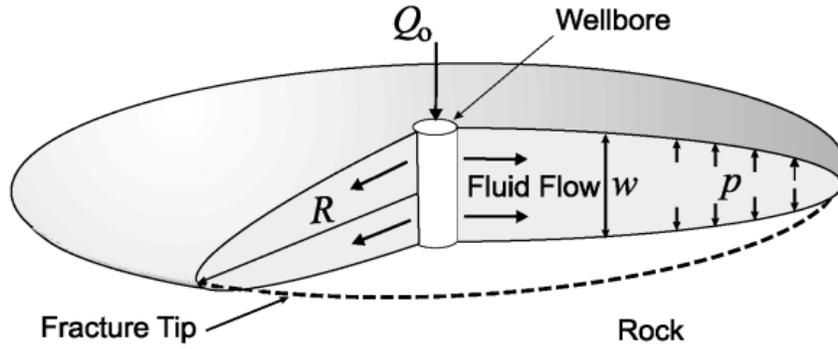
The fracture plane in this model is axially symmetric and the **height of the crack** at the location of the well is considered to be known.

50

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50

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Radial (Penny-shaped) Model:



51

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51

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Classical Models' Closed Form Relations:

Model	Perkins and Kern	Geertsma and deKlerk	Radial
Fracture Extent	$x_f = c_1 t^{1/5}$	$x_f = c_1 t^{2/3}$	$R_f = c_1 t^{4/9}$
	$c_1 = c'_1 \left(\frac{q_i^3 E'}{\mu h_f^3} \right)^{1/5}$	$c_1 = c'_1 \left(\frac{q_i^3 E'}{\mu h_f^3} \right)^{1/6}$	$c_1 = c'_1 \left(\frac{q_i^3 E'}{\mu} \right)^{1/9}$
	$c'_1 = \left(\frac{625}{512 \pi^3} \right)^{1/5} = 0.524$	$c'_1 = \left(\frac{16}{21 \pi^3} \right)^{1/6} = 0.539$	$c'_1 = 0.572$
Width	$w_{w,0} = c_2 t^{1/5}$	$w_w = c_2 t^{1/3}$	$w_{w,0} = c_2 t^{1/9}$
	$c_2 = c'_2 \left(\frac{q_i^2 \mu}{E' h_f} \right)^{1/5}$	$c_2 = c'_2 \left(\frac{q_i^2 \mu}{E' h_f} \right)^{1/6}$	$c_2 = c'_2 \left(\frac{q_i^2 \mu^2}{E'^2} \right)^{1/9}$
	$c'_2 = \left(\frac{2560}{\pi^2} \right)^{1/5} = 3.04$	$c'_2 = \left(\frac{5376}{\pi^3} \right)^{1/6} = 2.36$	$c'_2 = 3.65$
	$\bar{w} = \gamma v_{w,0}$	$\bar{w} = \gamma v_w$	$\bar{w} = \gamma v_{w,0}$
	$\gamma = 0.628$	$\gamma = 0.785$	$\gamma = 0.533$
Net Pressure	$p_{n,w} = c_3 t^{1/5}$	$p_{n,w} = c_3 t^{-1/3}$	$p_{n,w} = c_3 t^{-1/3}$
	$c_3 = c'_3 \left(\frac{E'^4 \mu q_i^2}{h_f^2} \right)^{1/5}$	$c_3 = c'_3 (E'^2 \mu)^{1/3}$	$c_3 = c'_3 (E'^2 \mu)^{1/3}$
	$c'_3 = \left(\frac{80}{\pi^2} \right)^{1/4} = 1.52$	$c'_3 = \left(\frac{21}{16} \right)^{1/3} = 1.09$	$c'_3 = 2.51$

52

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Asymptotic Analytical Approach:

- In recent years, a scaling and asymptotic framework is built to determine the effect of the physical processes involved in HF (Detournay 2004).
- Two competing asymptotic energy dissipation mechanisms are highlighted: Energy dissipated by fracture propagation and Energy dissipated by fluid viscous flow in the fracture.
- Also, two fluid storage processes are considered: fluid leak-off in the porous solid and fluid storage inside the crack

53

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53

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Asymptotic Analytical Approach:

The two sets of *energy dissipation mechanisms* in conjunction with two *fluid storage processes* are associated with the following 4 asymptotic regimes:

- Storage- toughness dominated
- Storage-viscosity dominated
- Leak off-toughness dominated
- Leak off-viscosity dominated

54

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54

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Asymptotic Analytical Approach

• Dimensionless toughness:
$$K = \frac{k'}{(E'^3 \mu' Q_0)^{1/4}} = \frac{4k_{IC} / \sqrt{\pi}}{(3E'^3 \cdot \mu \cdot Q_0)}$$

• Dimensionless viscosity:
$$M = \mu' \frac{E'^3 \cdot Q_0}{K'^4}$$

• Dimensionless Leak-off coefficient:
$$C = 2C_L \left(\frac{E' \cdot t}{(12 \mu Q_0^3)} \right)^{1/6}$$

55

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55

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Asymptotic Analytical Approach

Where:

- K_{IC} : Fracture toughness
- E' : Plane strain plastic modulus
- μ : Fluid viscosity
- Q_0 : injection rate

$$C_L = \frac{K}{\mu} \cdot \frac{\sigma_0}{\sqrt{\pi c}}$$

- κ : intrinsic permeability
- C : diffusion coefficient
- σ : confining stress
- t : time

56

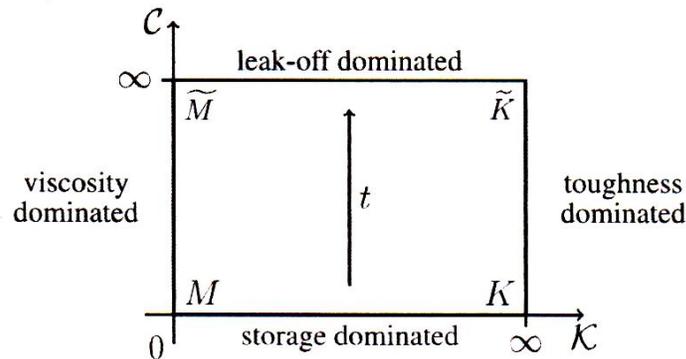
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56

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Asymptotic Analytical Approach:

After Bunger, Detournay, and Garagash (2005)



57

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57

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Asymptotic Analytical Approach:

Governing Equations:

Fluid continuity equation is as follows

$$\frac{\partial \rho \omega}{\partial t} + \frac{\partial W}{\partial S} = 0$$

- ω : local Fracture opening
- ρ : Fluid density
- W : Fluid mass flow rate
- S : longitudinal coordinate (along the fracture length)
- t : time

58

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58

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Asymptotic Analytical Approach:

Governing Equations (1):

Using the cubic law for fracture permeability, one obtains the "lubrication equation".

$$\frac{\partial \rho \omega}{\partial t} + \frac{\partial}{\partial S} \left(\frac{\rho \omega^3}{12\mu} \frac{\partial P_f}{\partial S} \right) = 0$$

- K_f : fluid pressure inside the fracture
- μ : fluid viscosity

59

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59

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Asymptotic Analytical Approach:

Governing Equations (2):

The "elasticity equation" is used to calculate the fracture width due to the net pressure (local fluid pressure minus local confining stress):

$$C.w = K(x, y, t) - p(x, y, t) -$$

The nonlocal Kernel function of C contains all the information about the elastic domain.

$$\sigma_c(x, y)$$

Asymptotic analytical solutions are difficult to construct because of the non-linearity of the equation governing the flow of fluid inside the fracture and the non-local character of the elastic response of the fracture.

60

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60

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Asymptotic Analytical Approach assumptions:

- Fluid lag is Zero (high confining stresses)
- Gravity effect is neglected
- 1D. Leak-off model is valid
- Rock behavior is linear elastic
- Injecting fluid is Newtonian (constant viscosity)
- Reservoir is homogeneous.
- Coupled HM effects are neglected.
- Surrounding rock is impermeable

Although the above assumptions look unrealistic, the asymptotic analytical solutions provide valuable insight into the complicated and interacting phenomena of HF. They are also useful for verification of HF numerical tools.

61

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61

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Are Hydraulic Fractures always planar?

HF may not be planar when the reservoir is:

- nonhomogeneous
- anisotropic
- naturally fractured
- uncemented
- stress field changes in the reservoir
- pay zone is very different from top and bottom layer
- ...

Therefore, we cannot stop at the classical planar fracture models or asymptotic solutions.

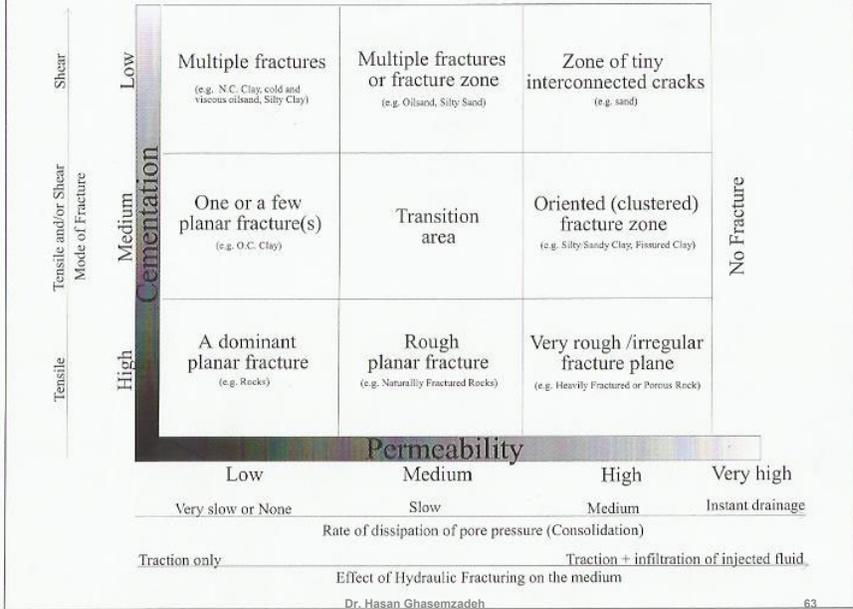
Pak and Chan (2009) has provided a conceptual framework for HF geometry.

62

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62

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63

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63



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64