Introduction to Geomechanics and Wellbore Stability

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Need of geomechanical model

- Exploration
  - Prediction of pore pressure
  - Hydrocarbon column height and fault seal potential
- Development
  - Optimize wellbore stability
    - Determination of well trajectories
    - Casing set points
    - Mud weights
    - Permeability anisotropy in fracture reservoirs
- Production
  - Selection of optimal completion methods
  - Prediction of changes in reservoir performance during depletion and assessment of techniques, such as repeated hydraulic fracturing, to optimize total recovery
- During EOR phases of reservoir development by optimizing processes such as water flooding and steam injection

Geomechanics Applications

- Formation Evaluation
  - Velocity log interpretation
  - Well testing interpretation
  - P/Z interpretation
  - Porosity / Reserve Correction
  - 4D Seismic
- Drilling
  - Well Trajectory and Location
  - Wellbore stability
  - Lost circulation
- Completion / Production
  - Permeability Loss /gain
  - Solids production / Fines plugging
  - Whole reservoir failure
  - Casing integrity
  - Hydraulic fracturing
  - Fault activation & seal breakthrough
- Reservoir Engineering
  - Compaction drive
  - Water flood & sweep efficiency
  - Thermal induced failure
  - Premature breakthrough
  - Thermal enhanced recovery
- Environment / Safety
  - Compaction / subsidence
  - Induced seismicity
  - Waste disposal

Objectives

- Understand pore pressure and stress models prior to drilling and use results of drilling to calibrate model
    - Awareness of how to use data from drilling geomechanics for structural interpretation
    - Awareness of how to use structural data to inform well planning and operations geology
    - Understand impact of stress on drilling direction
    - Define mechanical stratigraphy and impact on drilling and stresses
- Learn to interpret wellbore stability and identify wellbore instability
- Understand and minimize risks in drilling through faults

Geomechanics in Drilling Design

- Reduce drilling cost and duration
- Predict well bore instability prior to drilling and reduce or eliminate stuck pipe, formation collapse, formation fracture, lost circulation etc
- Predict Wellbore trajectory for complication free drilling
- Establish the mud weight boundaries for safe and stable drilling

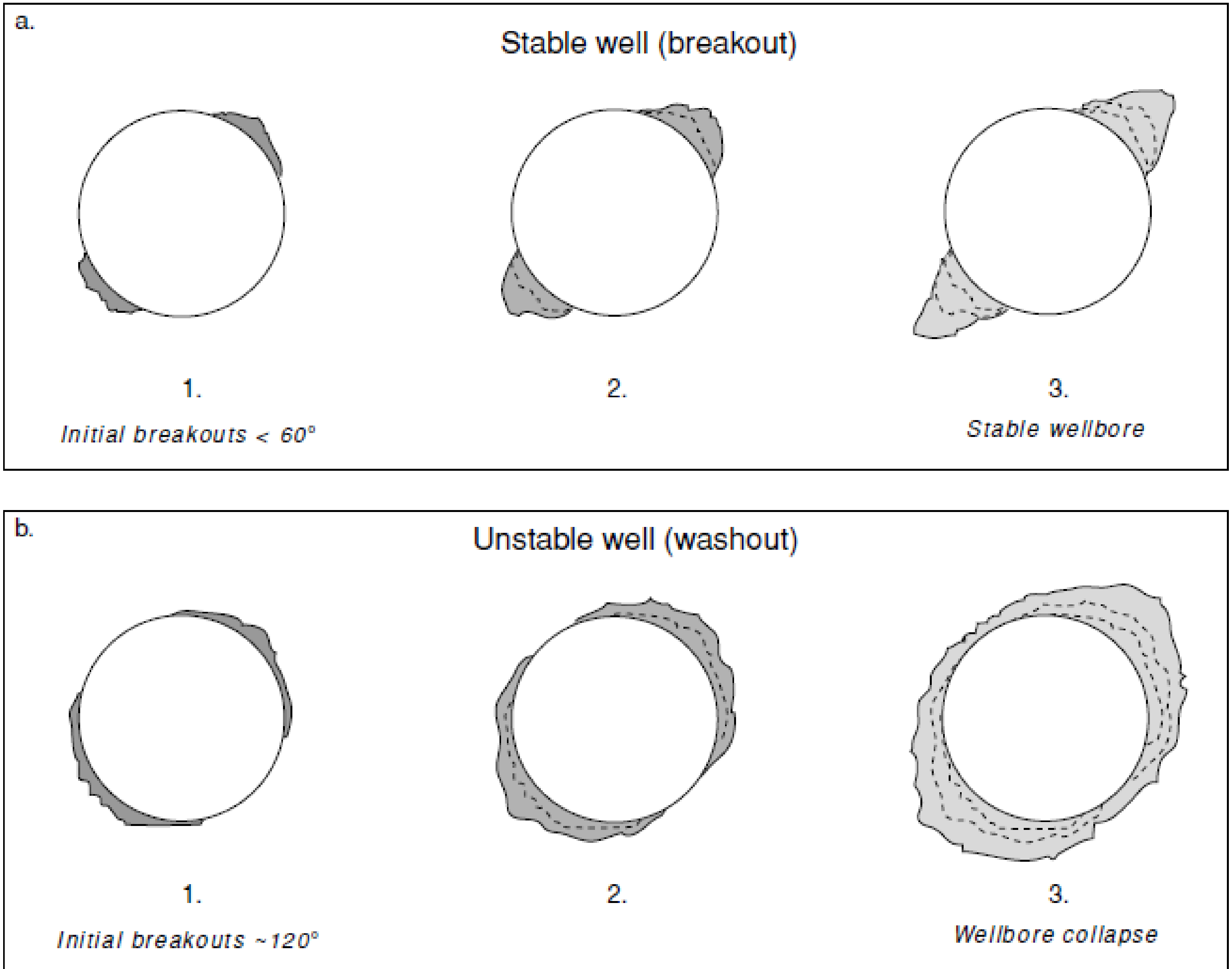
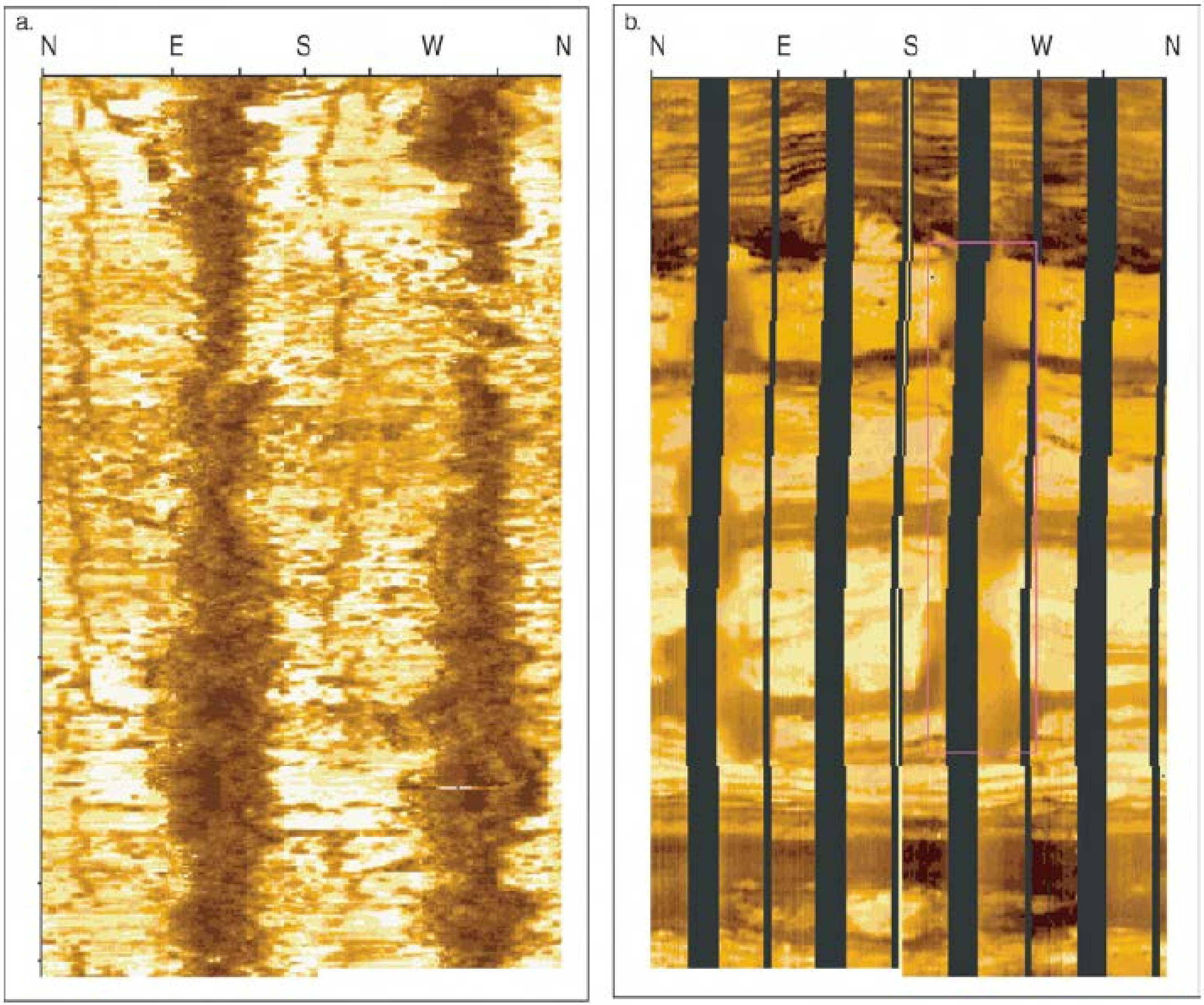
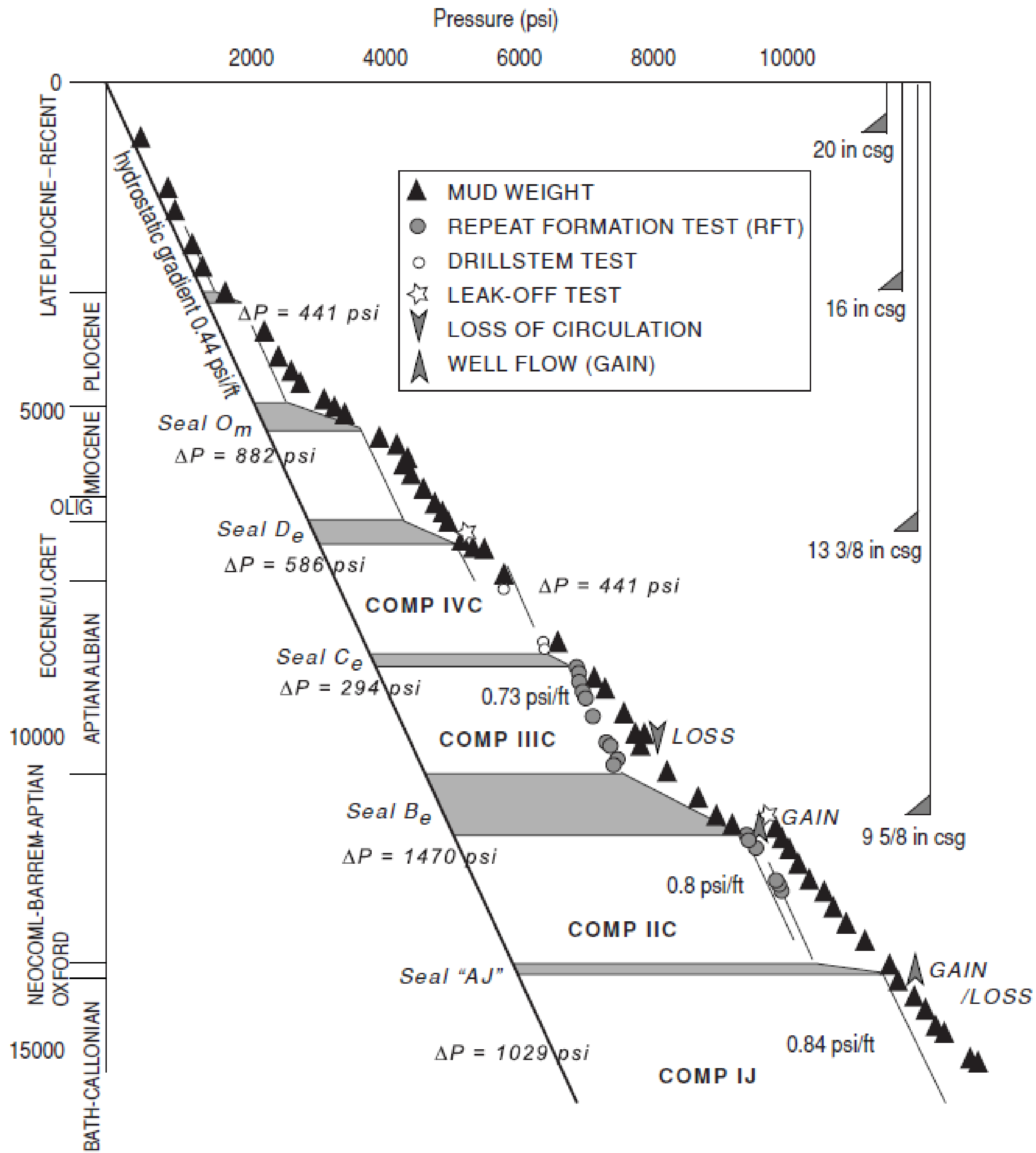

a.
Stable well (breakout)
1.
Initial breakouts < 60°
2.
3.
Stable wellbore
b.
Unstable well (washout)
1.
Initial breakouts ~120°
2.
3.
Wellbore collapse

Image Logs





Pressure (psi)
2000
4000
6000
8000
10000
0
5000
10000
15000
LATE PLIOCENE–RECENT
PLIOCENE
MIOCENE
OLIG
EOCENE/U.CRET
APTIAN ALBIAN
NEOCOML-BARREM-APTIAN
OXFORD
BATH-CALLONIAN
hydrostatic gradient 0.44 psi/ft
MUD WEIGHT
REPEAT FORMATION TEST (RFT)
DRILLSTEM TEST
LEAK-OFF TEST
LOSS OF CIRCULATION
WELL FLOW (GAIN)
20 in csg
16 in csg
13 3/8 in csg
9 5/8 in csg
ΔP = 441 psi
Seal O_m
ΔP = 882 psi
Seal D_e
ΔP = 586 psi
ΔP = 441 psi
COMP IVC
Seal C_e
ΔP = 294 psi
0.73 psi/ft
LOSS
COMP IIIC
Seal B_e
ΔP = 1470 psi
GAIN
0.8 psi/ft
COMP IIC
Seal "AJ"
GAIN
/LOSS
ΔP = 1029 psi
0.84 psi/ft
COMP IJ

Some Relevant Questions

- Why do we see wellbore failures?
- When will a fault slip?
- What will depletion do to the reservoir?

Fundamental Concepts

- Stress
- Pore pressure
- Rock strength

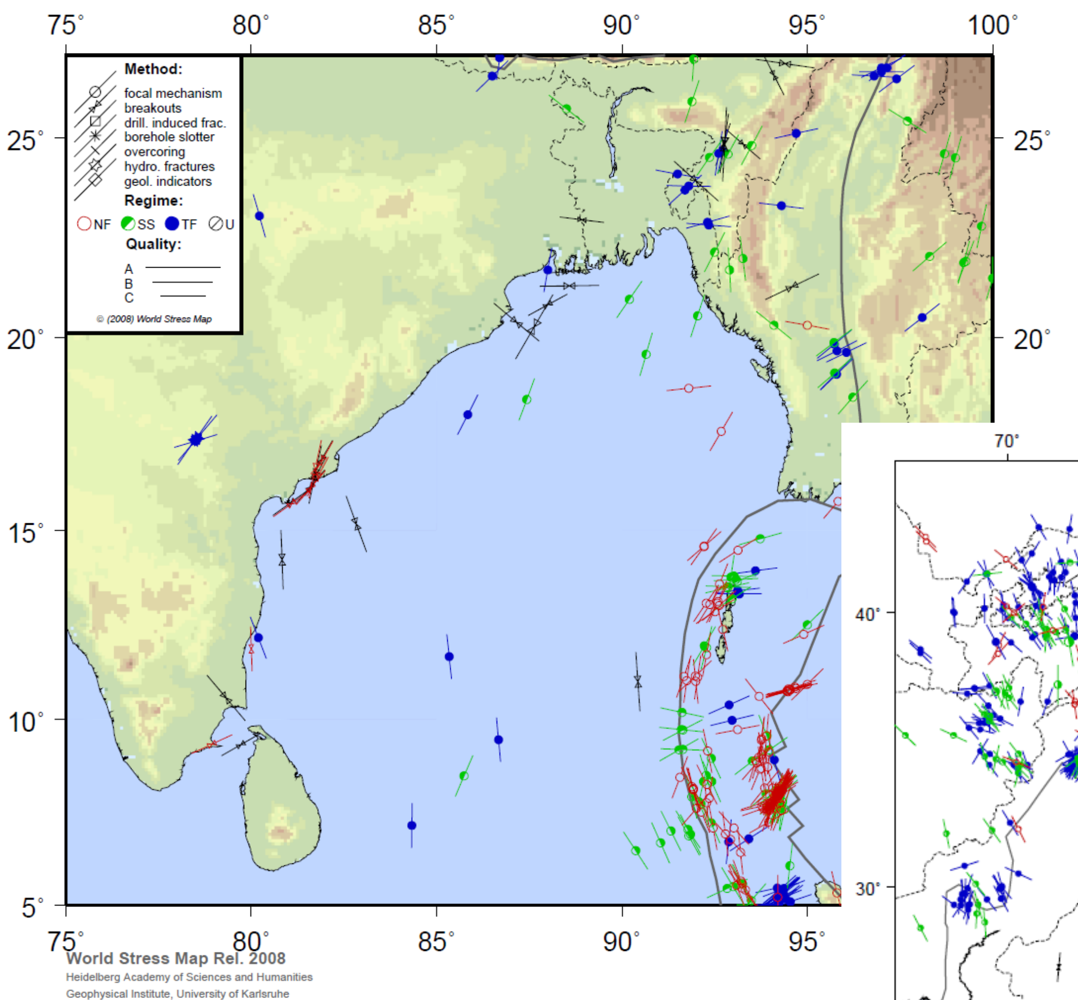
Stress – Very Important Point

- The key component of a comprehensive geomechanical model is
  - Current state of STRESS
- Compressive stress exists everywhere at depth in the earth.
- Stress magnitude depends on
  - Depth
  - Pore pressure
  - Active geological processes

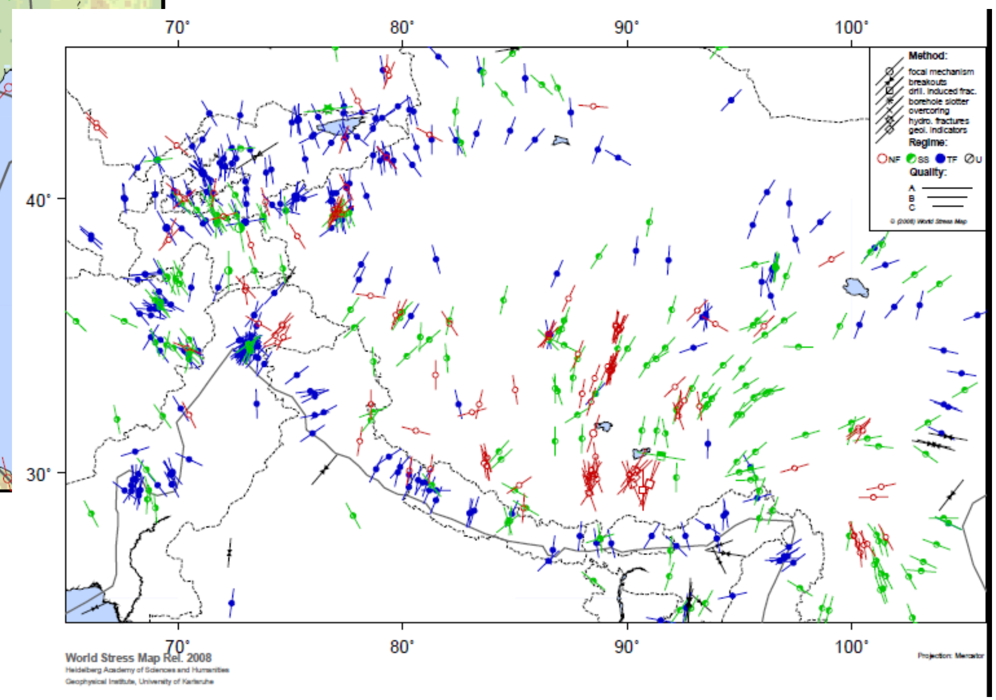
Horizontal principal stress measurement methods

- **Stress orientation**
  - Stress-induced wellbore breakouts
  - Stress-induced tensile wall fractures
  - Hydraulic fracture orientations
  - Earthquake focal plane mechanisms
  - Shear velocity anisotropy
- **Relative stress magnitude**
  - Earthquake focal plane mechanisms
- **Absolute stress magnitude**
  - Hydraulic fracturing/leak-off tests
  - Modeling stress-induced wellbore breakouts
  - Modeling stress-induced tensile wall fractures
  - Modeling breakout rotations due to slip on faults

Stress Maps

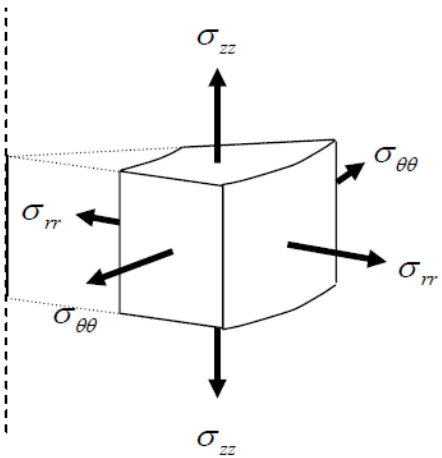


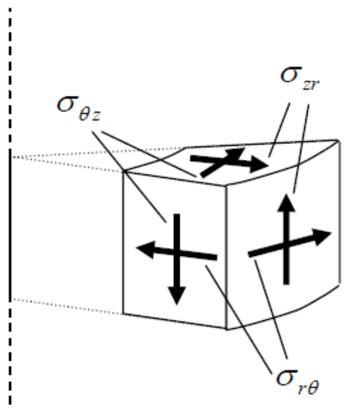
75° 80° 85° 90° 95° 100°
25° 20° 15° 10° 5°
Method:
focal mechanism
breakouts
drill. induced frac.
borehole slotter
overcoring
hydro. fractures
geol. indicators
Regime:
NF SS TF U
Quality:
A
B
C
© (2008) World Stress Map
World Stress Map Rel. 2008
Heidelberg Academy of Sciences and Humanities
Geophysical Institute, University of Karlsruhe

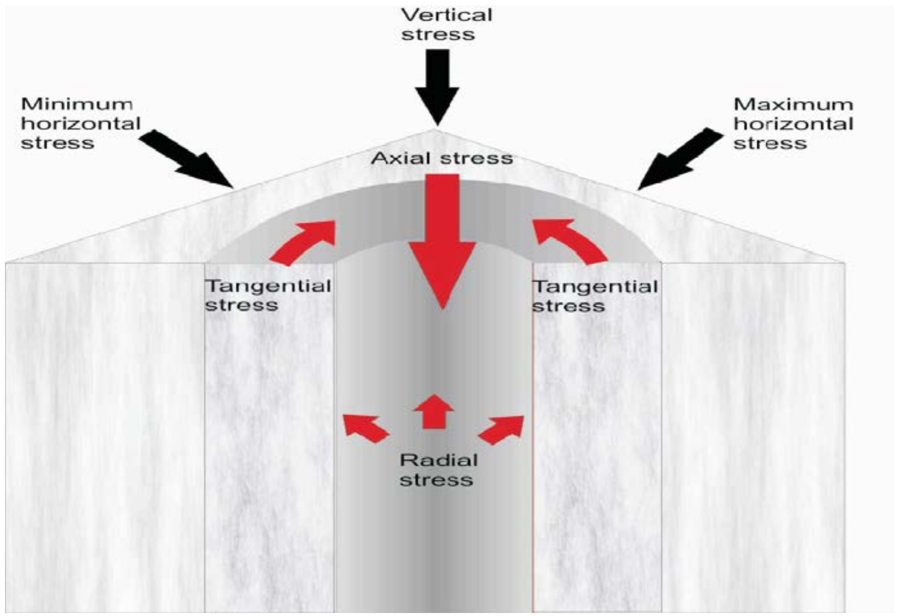


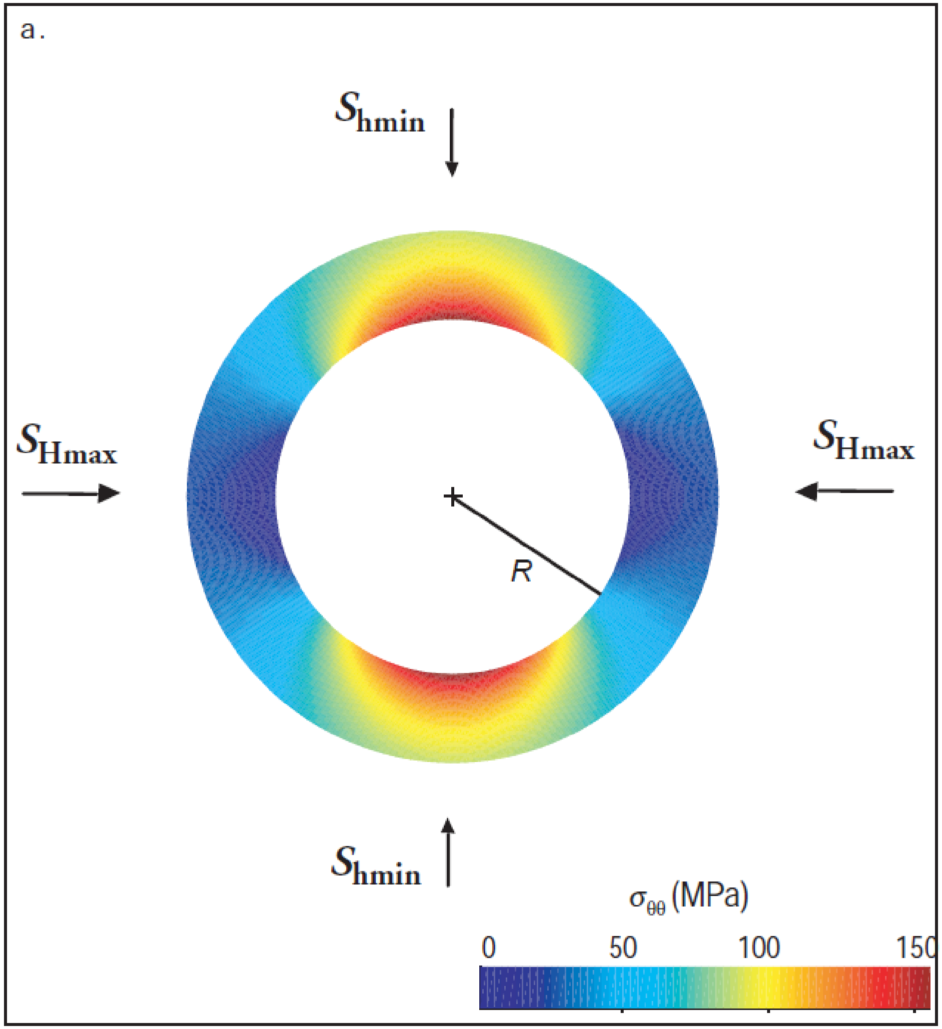
70° 80° 90° 100°
40° 30°
Method:
focal mechanism
breakouts
drill. induced frac.
borehole slotter
overcoring
hydro. fractures
geol. indicators
Regime:
NF SS TF U
Quality:
A
B
C
World Stress Map Rel. 2008
Heidelberg Academy of Sciences and Humanities
Geophysical Institute, University of Karlsruhe
Projection: Mercator

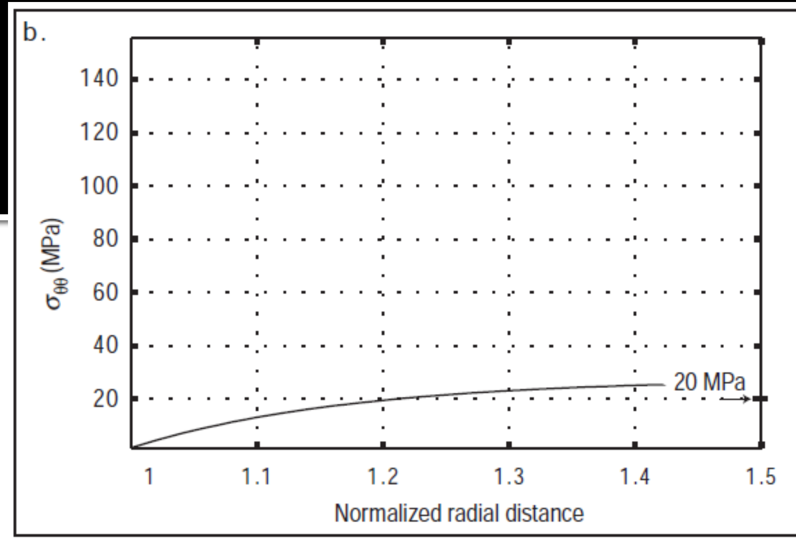
Stress orientation around wellbore

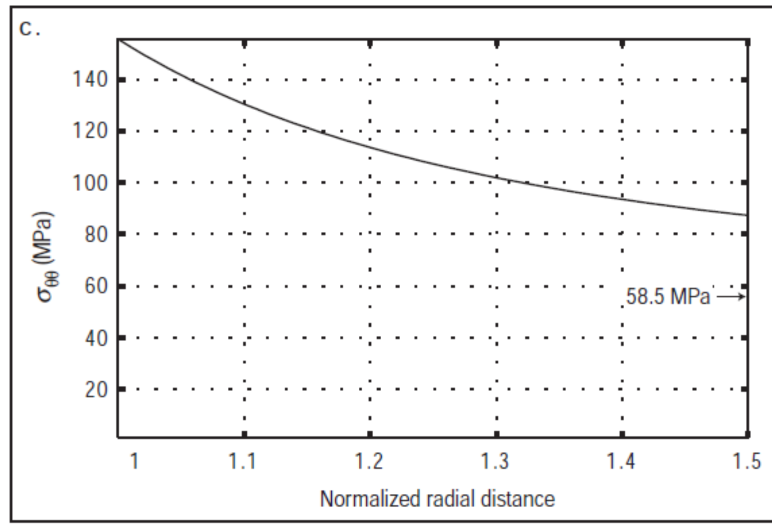












S_{Hmax} = 90 Mpa

S_{Hmax} orientation is N90E (East West)

S_V = 88.2 Mpa (depth 3213 m)

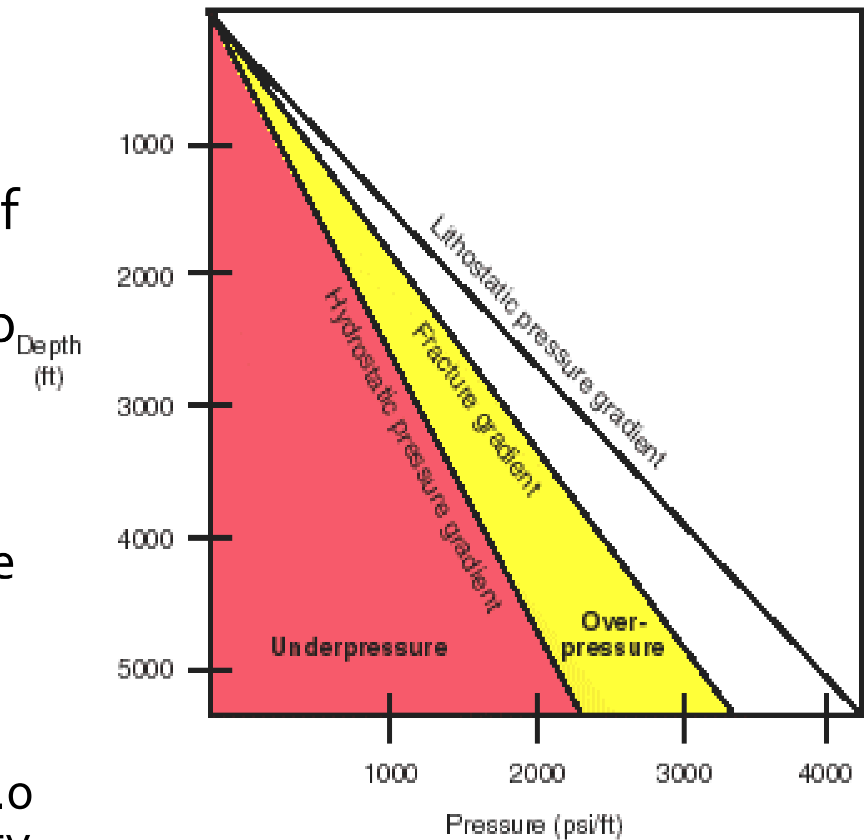
S_{hmin} = 51.5 MPa

$P_p = P_{mud}$ = 31.5 MPa

Understanding Pore Pressure

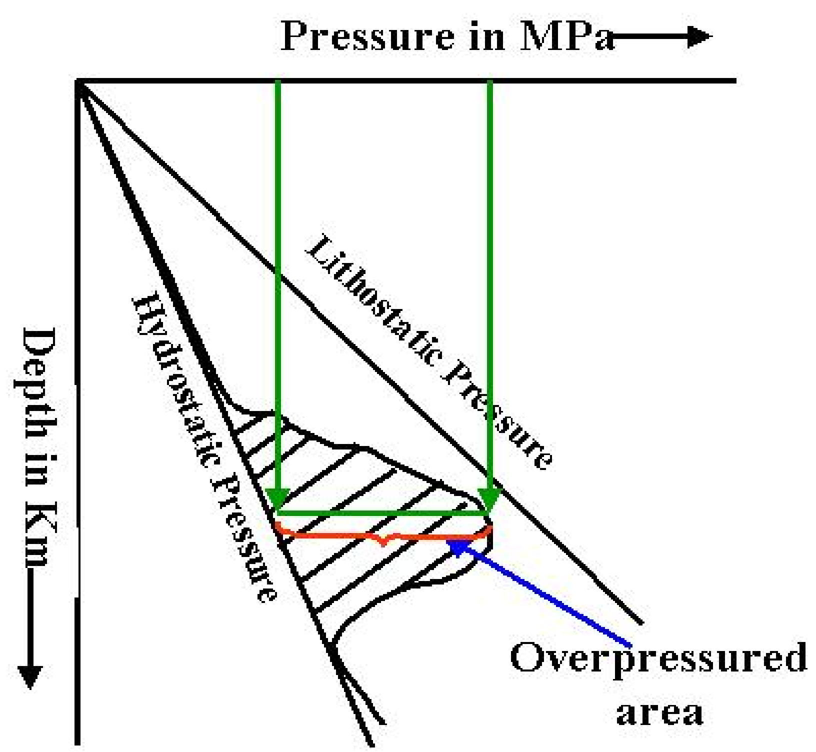
Lithostatic and Hydrostatic Pressure

- **Hydrostatic Pressure:** the amount of pressure exerted by a column of freshwater per unit area, from sea level to a given depth.
- **Lithostatic Pressure**: the amount of pressure exerted by the weight of overlying rocks, on a formation; also called geostatic pressure
  - Weight (summed) of the overlying rock and fluid
  - Calculated from an integration of the density log
  - Estimated from regional trends (or assumed values)
  - In the absence of any log data, use 1.0 to 1.1 psi/ft as the rock weight density



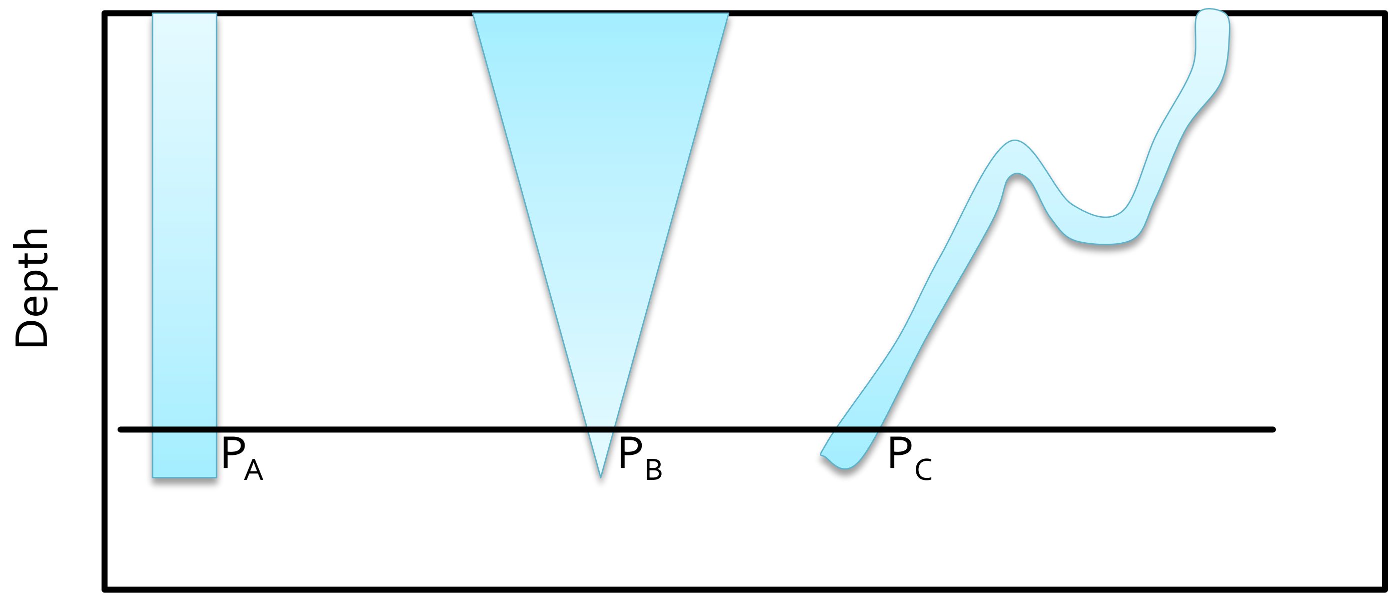
Pore Pressure

- Classification
  - Normal - salt water gradient from surface (Hydrostatic)
  - Abnormal - trapped during deposition (overpressure)
  - Subnormal - mountains, depleted reservoir (underpressure)
- Measured in permeable formations by RFT (Repeat Formation Tester)
- Estimated in shales
  - from logs e.g. sonic, resistivity
  - from seismic velocities
  - from basin modeling



Conceptual model showing relationship between hydrostatic, lithostatic, and overpressure

Fluid in communication



Pore pressure is dependent only on TVD depth

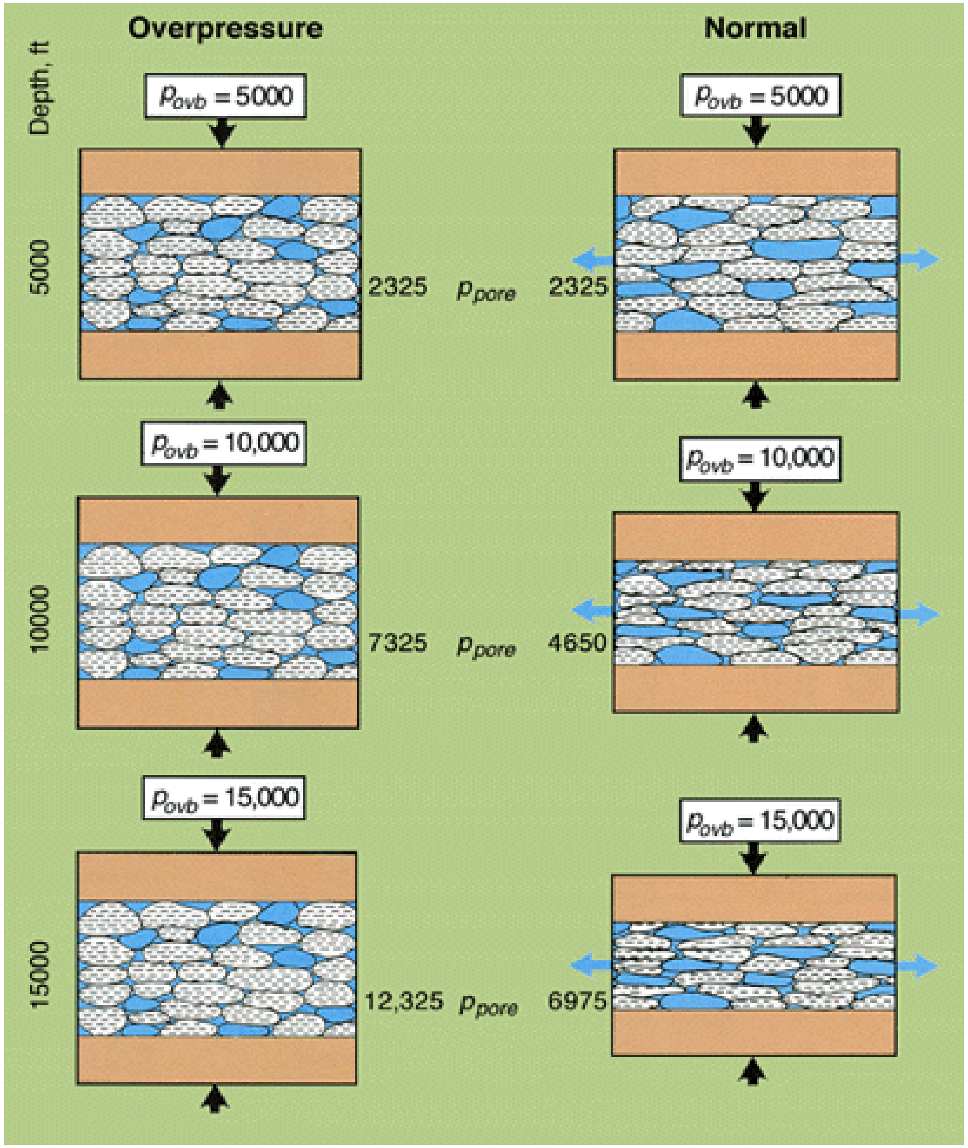
Seal

- Hydrocarbon seal
  - Any lithology that leaks hydrocarbon at a rate slower than the rate of influx of hydrocarbons into a trap
- Pressure seal
  - A lithology with very high capillary pressure, nanodarcy permeability e.g. mudstones, salt, anhydrite
- Mudstones that are good seals have low acoustic velocity (ITT > 90 μs /ft)

Mechanisms of Overpressure Generation

- Disequilibrium Compaction
- Fluid Expansion at Depth
  - Hydrocarbon cracking / gas generation
  - Thermal pressuring
  - Mineral phase transformations
  - Lateral & vertical transfer
  - Osmosis

Compaction in Normal and Abnormal Situations



Pore pressure Controls

- Loading rate
- Compaction Co-efficient
- Temperature, and
- Permeability

Hydrocarbon Cracking / Gas generation

- Volume changes occur when kerogen transforms to oil and gas and when oil cracks to gas.
- The volume changes depends on kerogen density and volume of the petroleum products generated during maturation.
- Meissener (1978): 25% during oil generation from Type II kerogen and more than 100% during dry gas maturation.

Thermal Pressuring

- Volume expansion due to change in temperature
- Rock (ignored)
- Gas (1.65% for increase in temperature of 40°C)

(Osborne and Swarbrick, 1997)

If,

Temp. gradient = 40°C/km

Sedimentation rate = 2 km/m.y.

Therefore, vol. Change = 3.3 % per m.y.

Mineral Phase Transformation

- Smectite dehydration
  - Total Vol. change = 4% in three stages of dewatering
  - 1.3% in each stages (effective)
  - 1st two stages at depth below 0.5 and above 1.5 km.
- Smectite transformation to Illite
  - 2.3 to 3.3 km on GoM shelf, 3.5 – 4.5 km in Niger Delta, 2.4 – 3.5 km in North Sea
  - Total vol. change recorded = 4.1 to 8.4%

Osmosis

- Salinity contrasts across semi-permeable membranes induced osmotic flow and continues till salinity contrast is maintained by recharge.

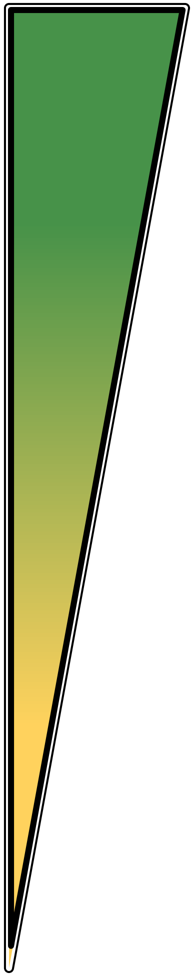
Net Result of Fluid Expansion

- An increase in pore pressure
- A reduction in effective stress
- An increase in porosity (usually small)
- Secondary porosity generation

Sources of Pressure Data

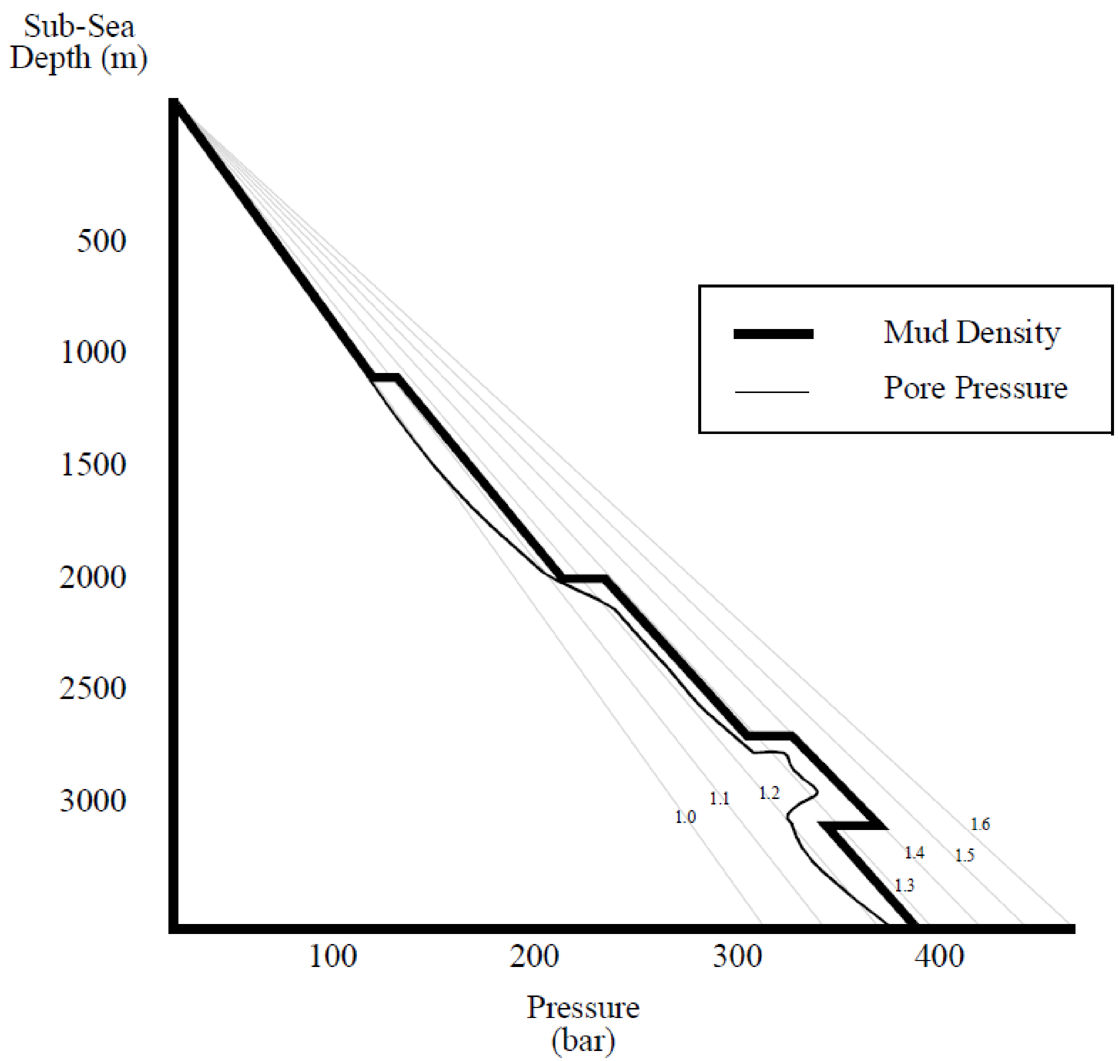
- Direct Measurement
  - Reservoir BHP measurements
  - Formation Tests (RFT, MDT, DST)
  - Kick
- Indirect Measurement
  - Petrophysical methods
  - Seismic interval velocity
  - Basin modeling
  - Gas Detection
  - Mud weight
  - Drilling parameters

Good



Poor

Example of Pore Pressure and Mud Weight



Pressure Gradient (G)

- Rate of change of pore pressure with depth
- It tells us about formation fluid density
- Pressure gradient greater than 0.53 psi/ft or 10.2 ppg or 1.22 sg suggests pressure compartmentalization

Example

- Pressure data measured using RFT are
  - 7.2981 bar @ 2990 m
  - 7.2996 bar @ 3005 m
  - 7.6501 bar @ 3015 m
  - 8.5601 bar @ 3028 m
  - 15.5000 bar @ 3125 m
  - 17.5000 bar @ 3145 m
- Compute pressure gradient (G)?
- RFT – Repeat Formation Tester. It could be MDT, DST or Production bottom-hole pressure test

Typical Values of Gradient (G)

Type	psi/ft	kPa /m	ppg	sg
Freshwater	0.42	9.49	8.1	0.97
North Sea Water	0.45	10.2	8.7	1.04
GOM water	0.465	10.4	8.9	1.07
Saturated Salt water	0.53	12.0	10.2	1.22
Oil @ 30 API	0.30	6.8	5.8	0.69
Gas	0.10	2.3	1.9	0.23
Isolated cells	1.00	20.6	19.2	2.31
Isolated cells deepwater	0.84	19	16.2	1.93

Conversions

sg = ppg/8.335 = (0.12)(ppg)

sg = g/cc /1

sg = kg/m3 / 1000

sg = psi/ft / 0.433

ppg = (psi/ft) (19.25) = psi/ft / 0.052

psi /ft = ppg / 19.25 = (ppg) (0.052)

Bars = psi / 14.5

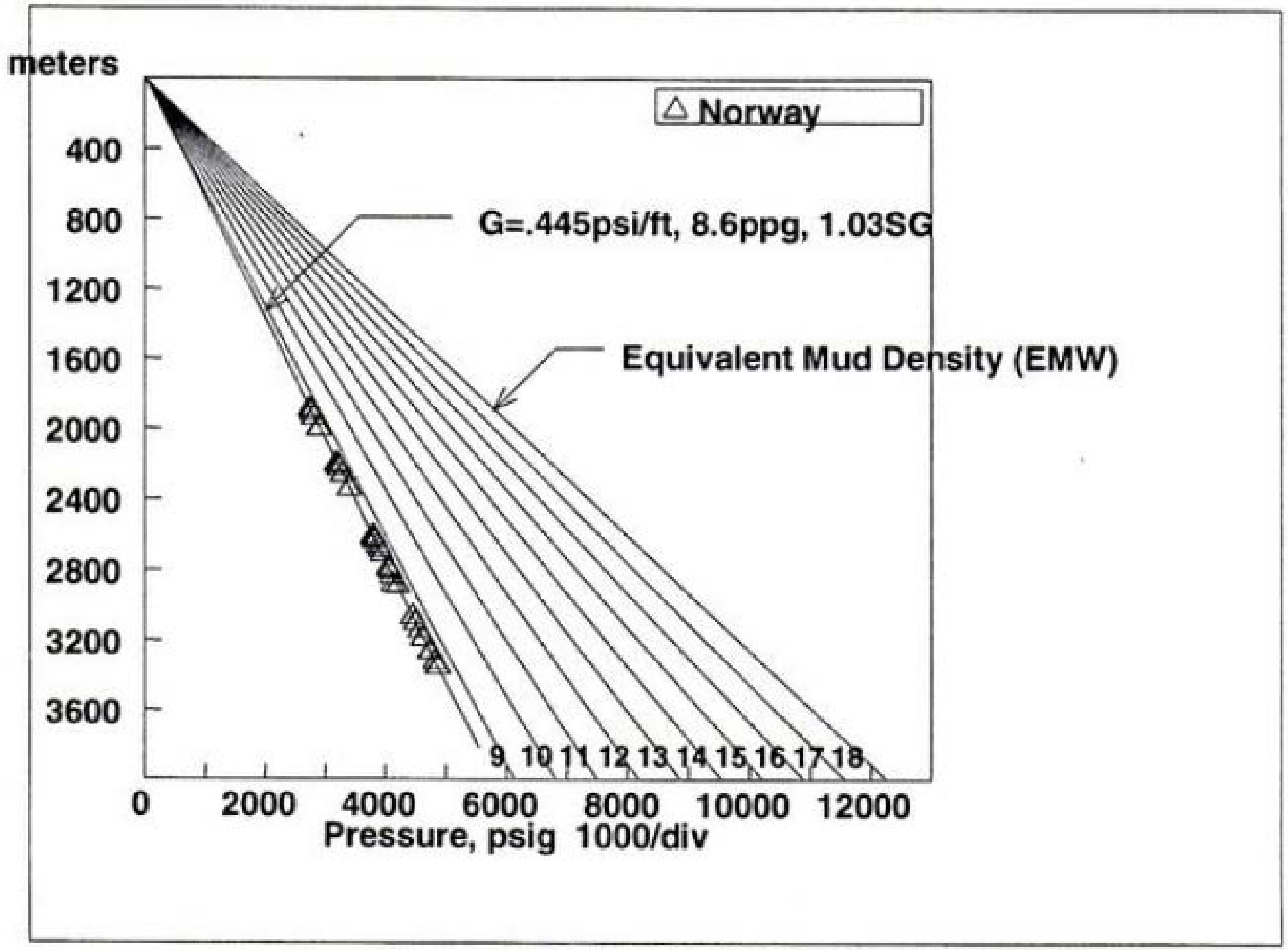
KPa = (Bars)(100)

MPa = Bars/ 10

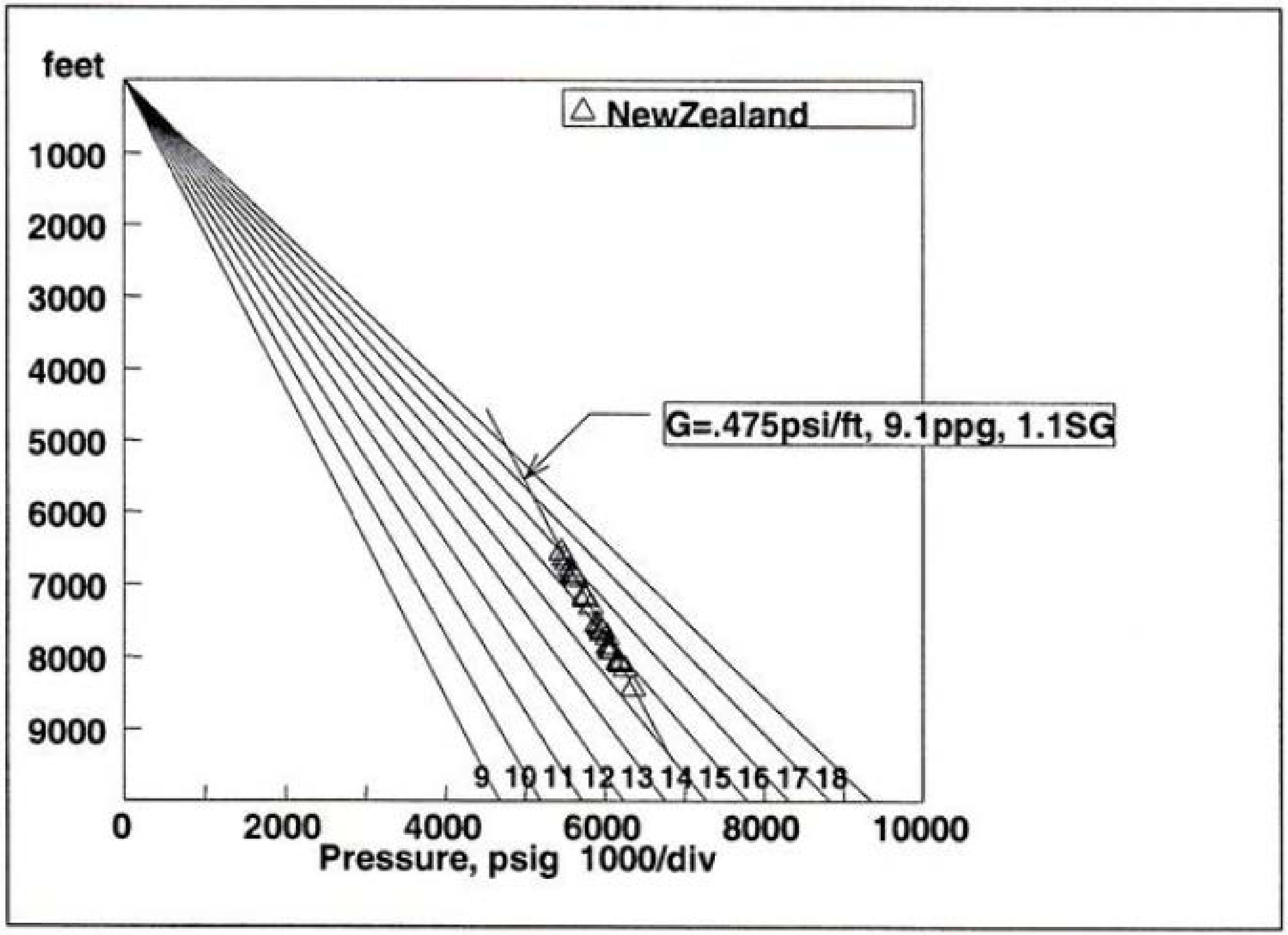
Feet = meters (3.281)

V = 10^6 / ITT

Pressure Plot - Norway



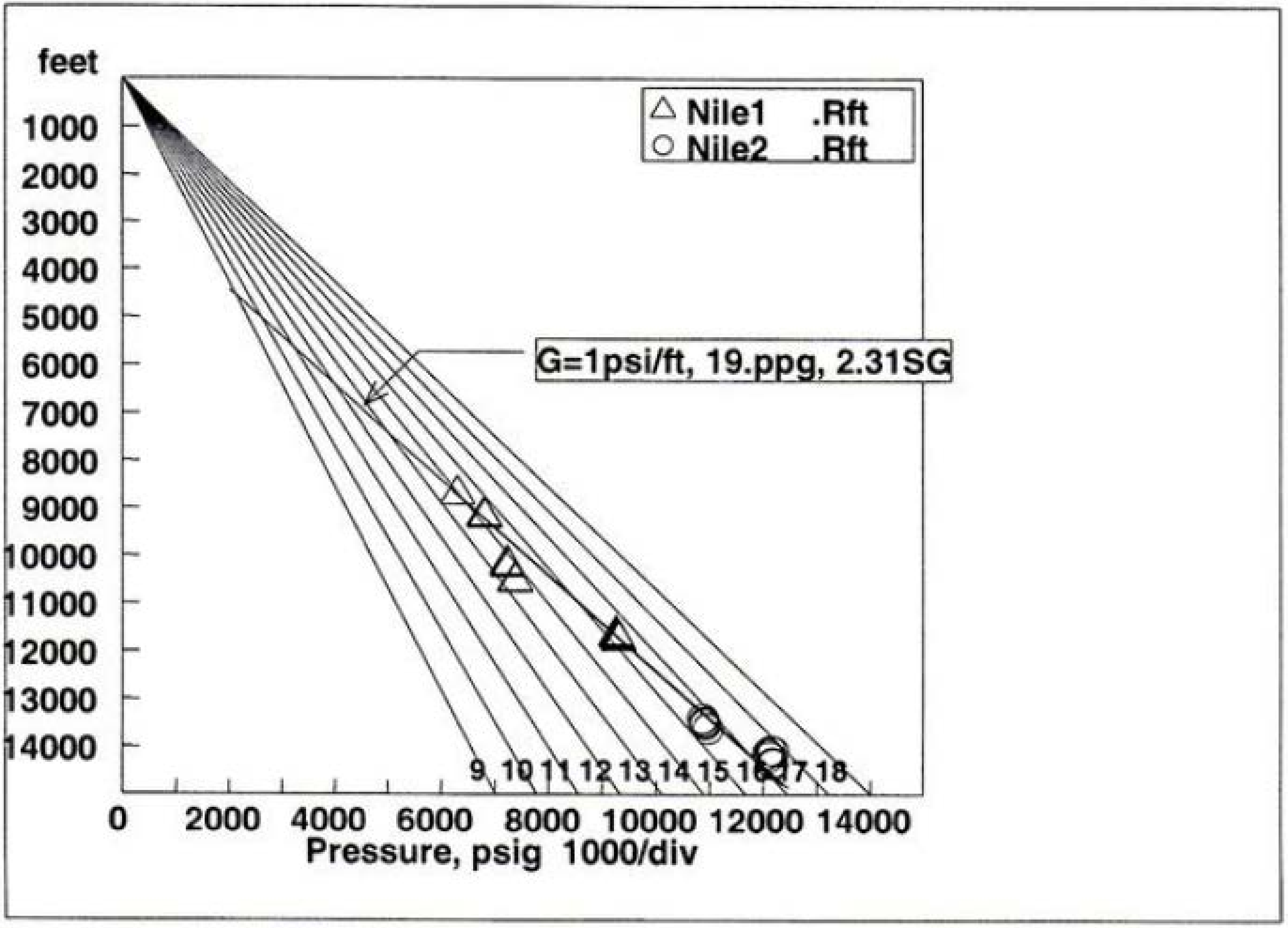
Pressure Plot – New Zealand



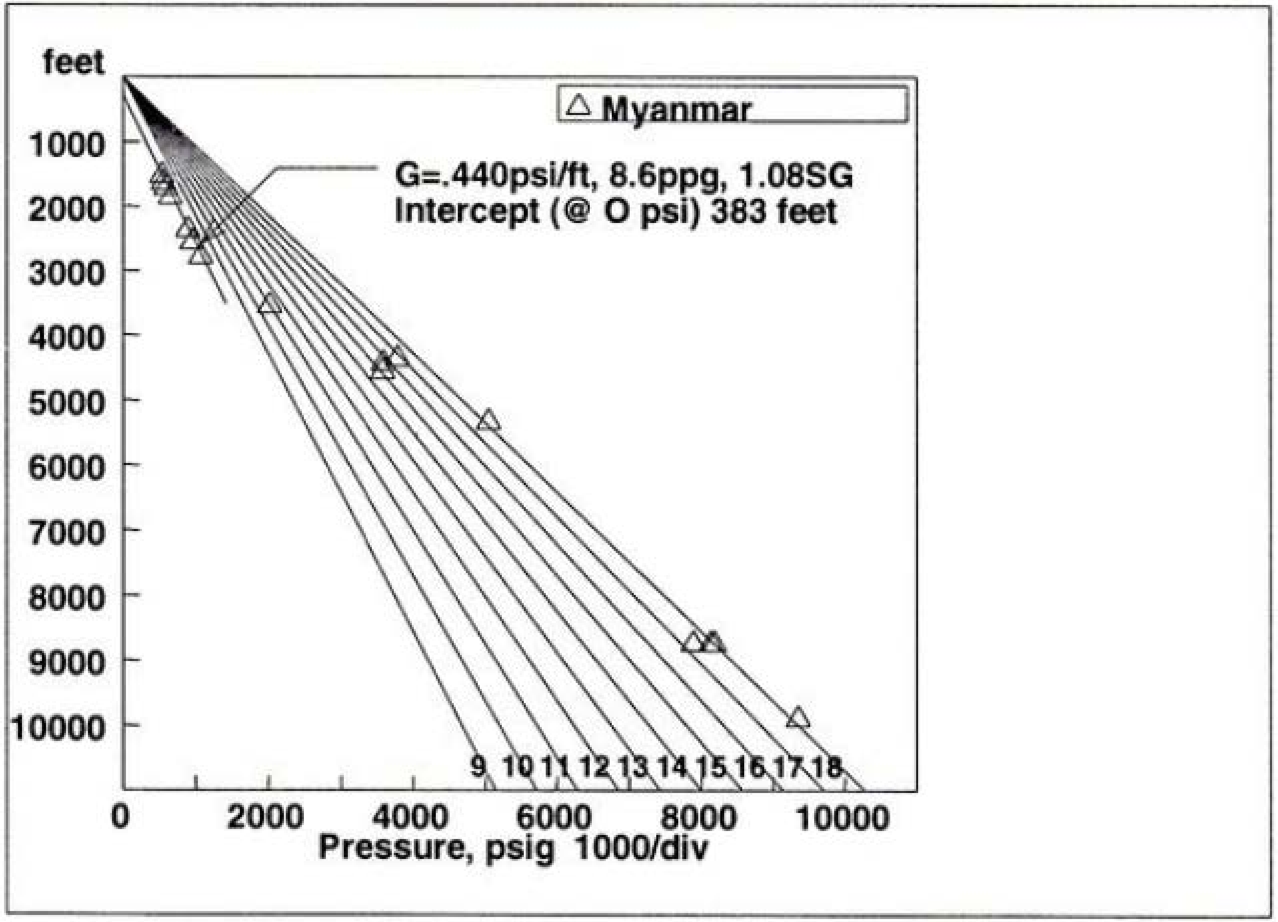
Example

- If the equivalent mud density is 14 ppg at the top of a thick gas column at a depth of 1000 m what is the equivalent mud density ahead of the bit at a depth of 1100 m.

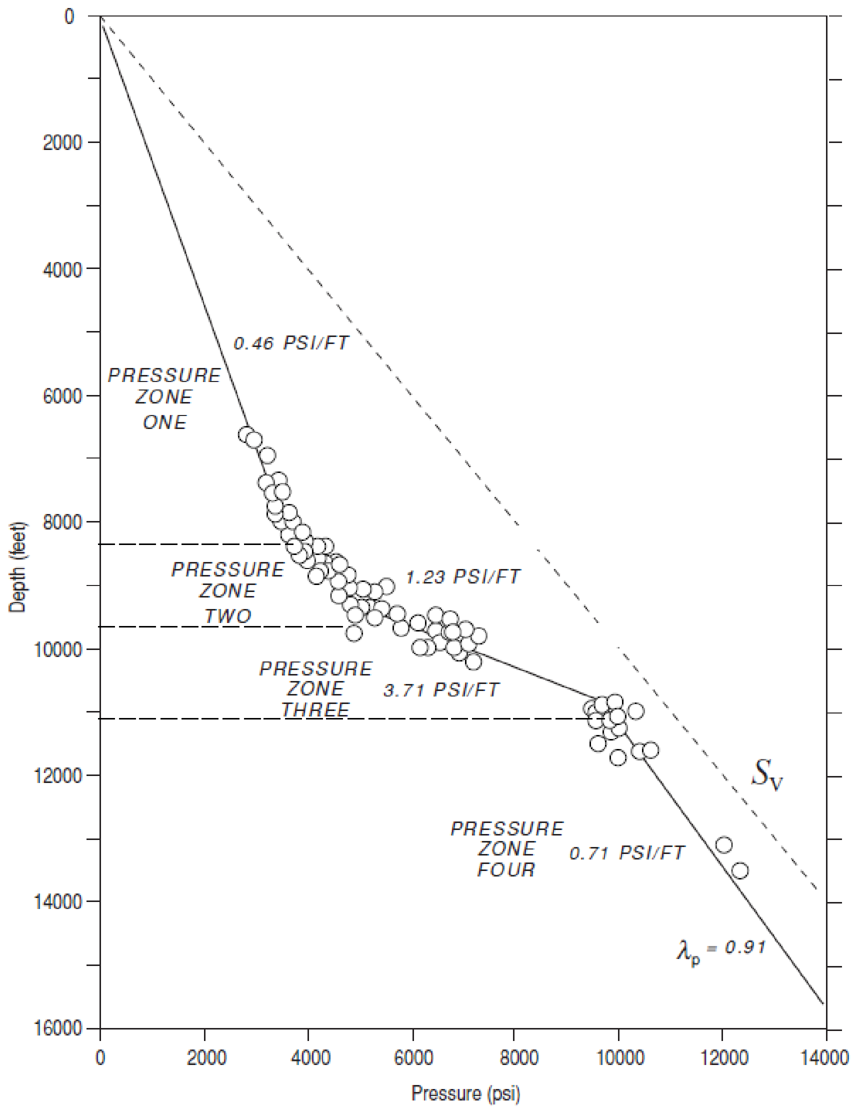
Pressure Plot – Nile Delta



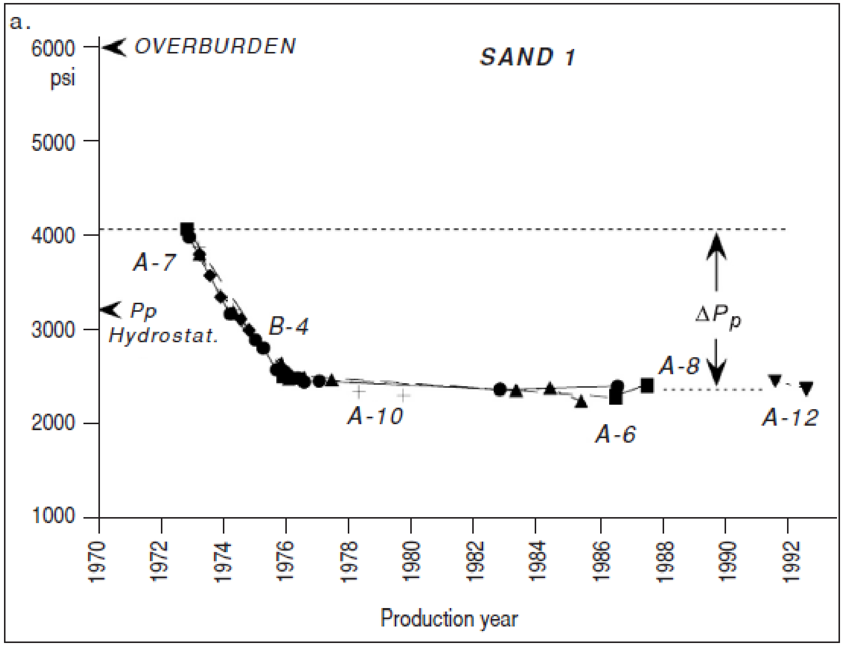
Pressure Plot - Myanmar

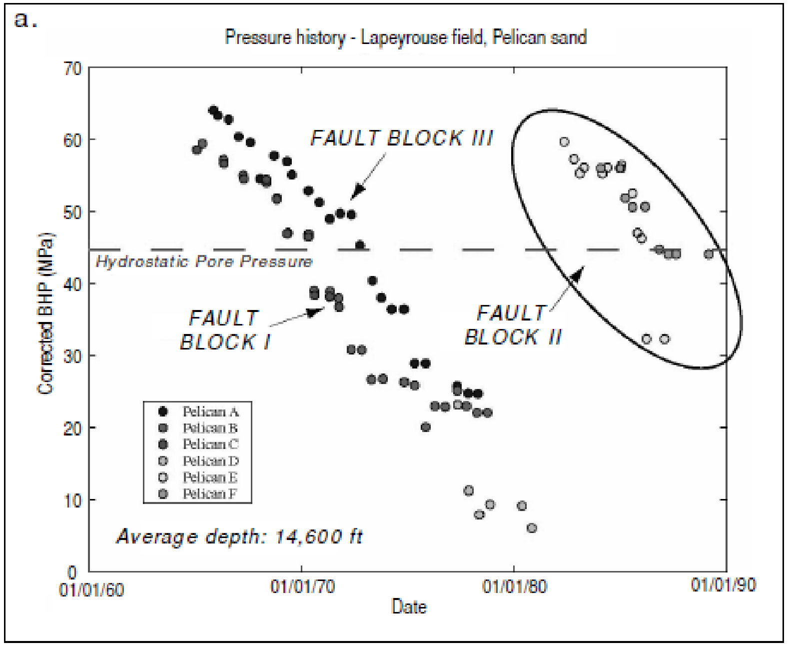


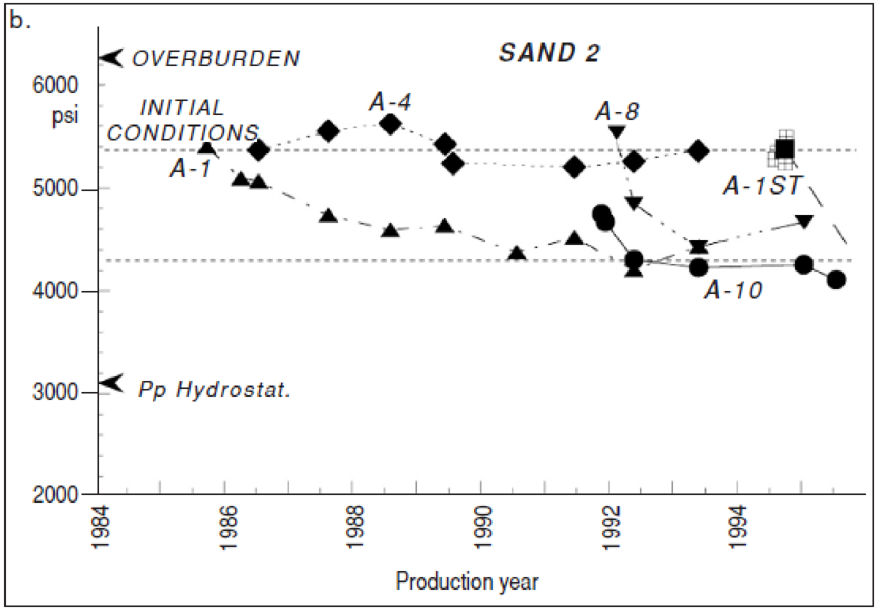
Pore Pressure



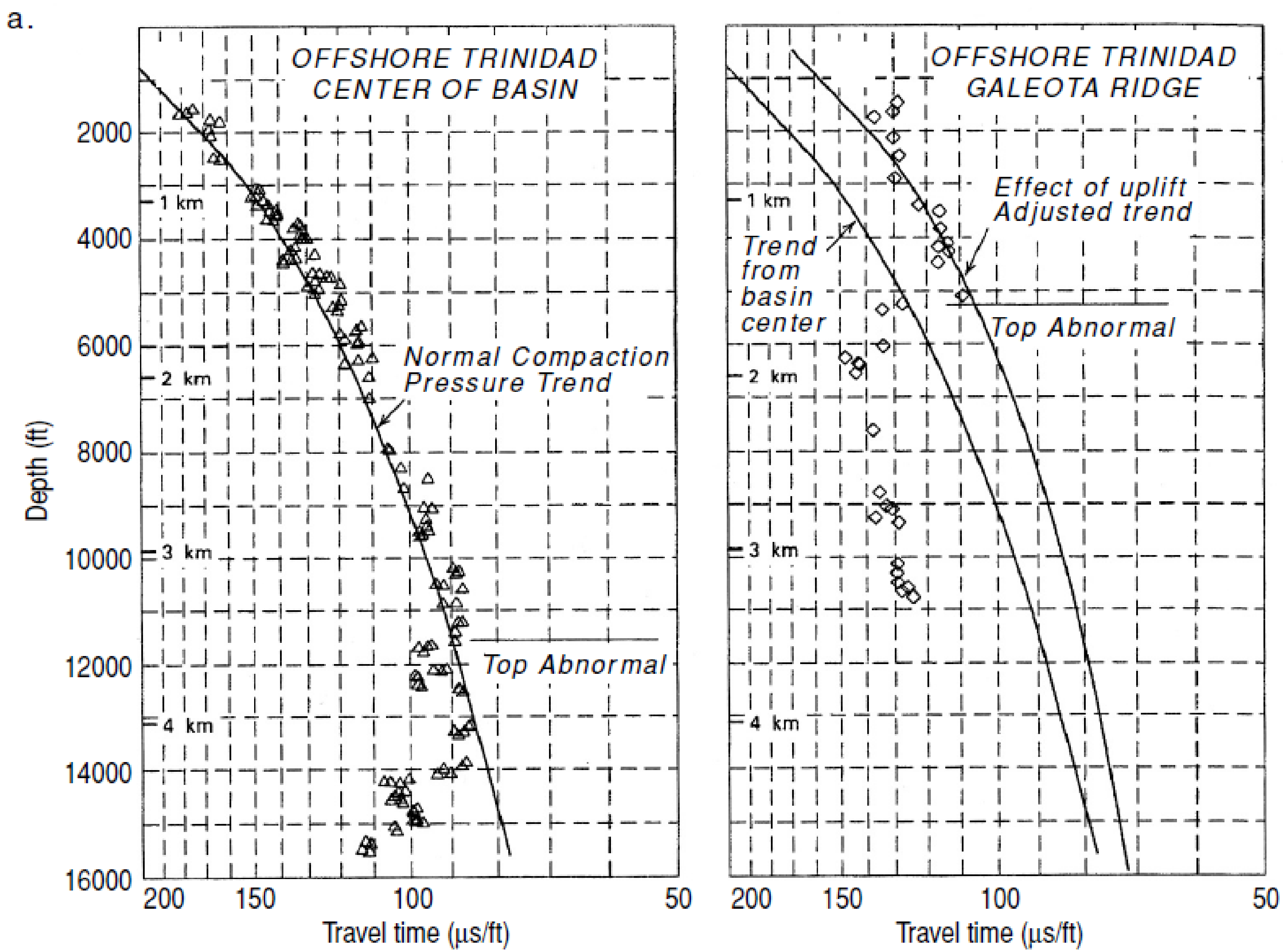
Pore Pressure Examples



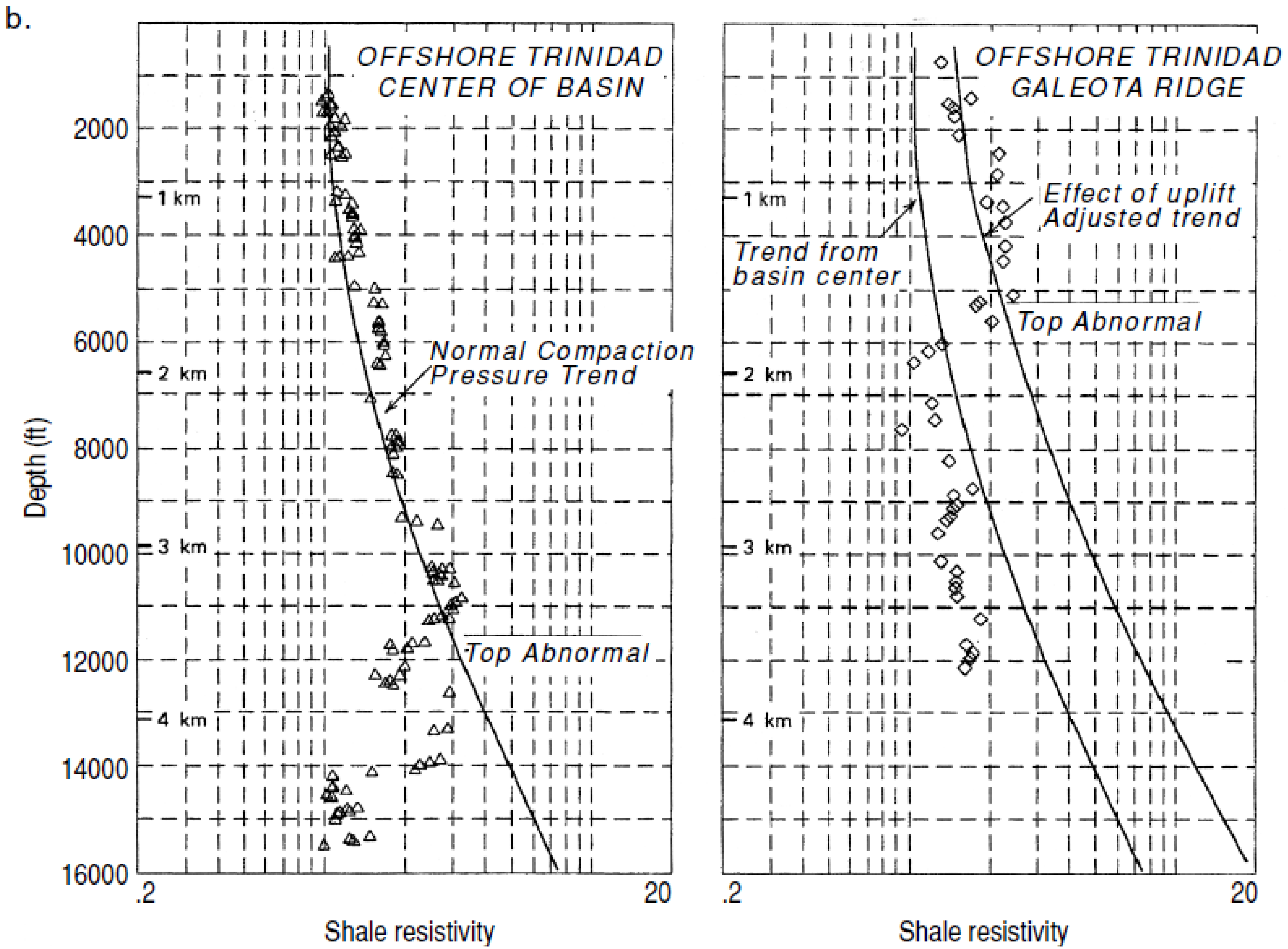




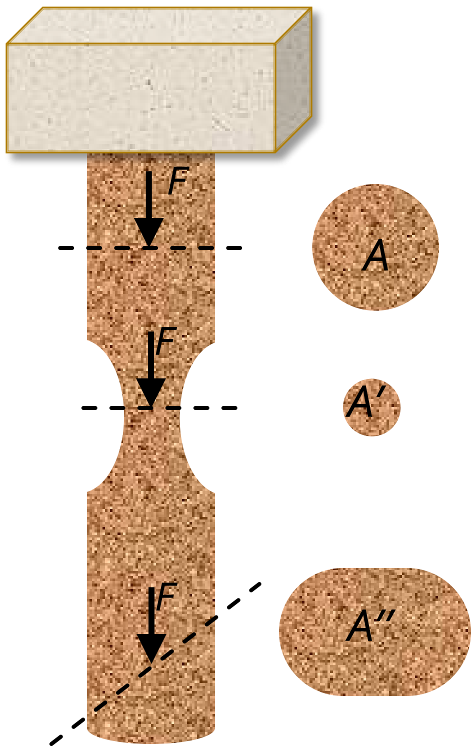
Key element – Normal Compaction Trend

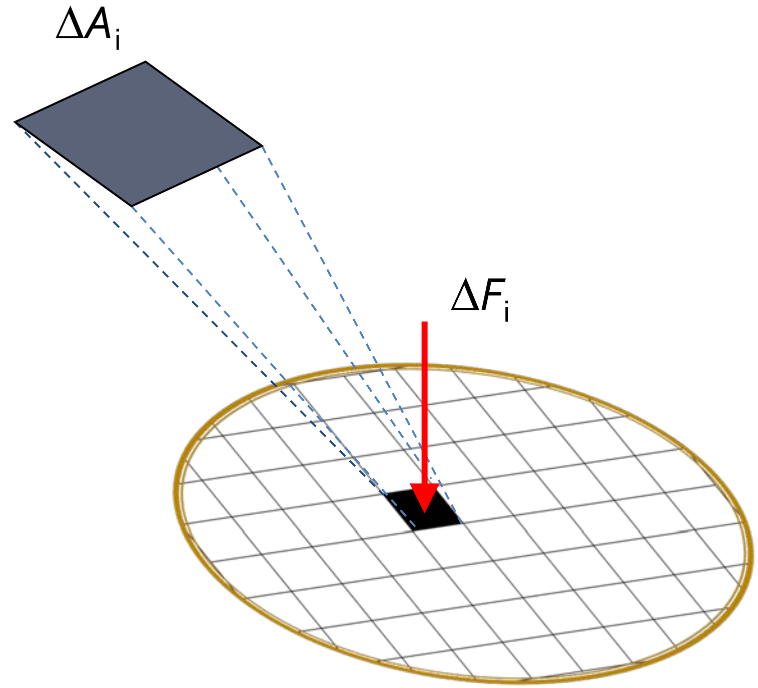


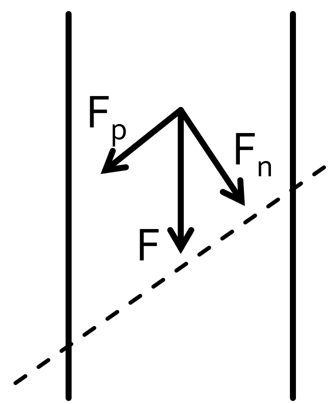
Key element – Normal Compaction Trend



Understanding Stress







$$\sigma = \frac{F_n}{A''}$$

$$\tau = \frac{F_p}{A''}$$

$$\sigma = \lim_{\Delta A_i \to 0} \frac{\Delta F_i}{\Delta A_i}$$

Stress

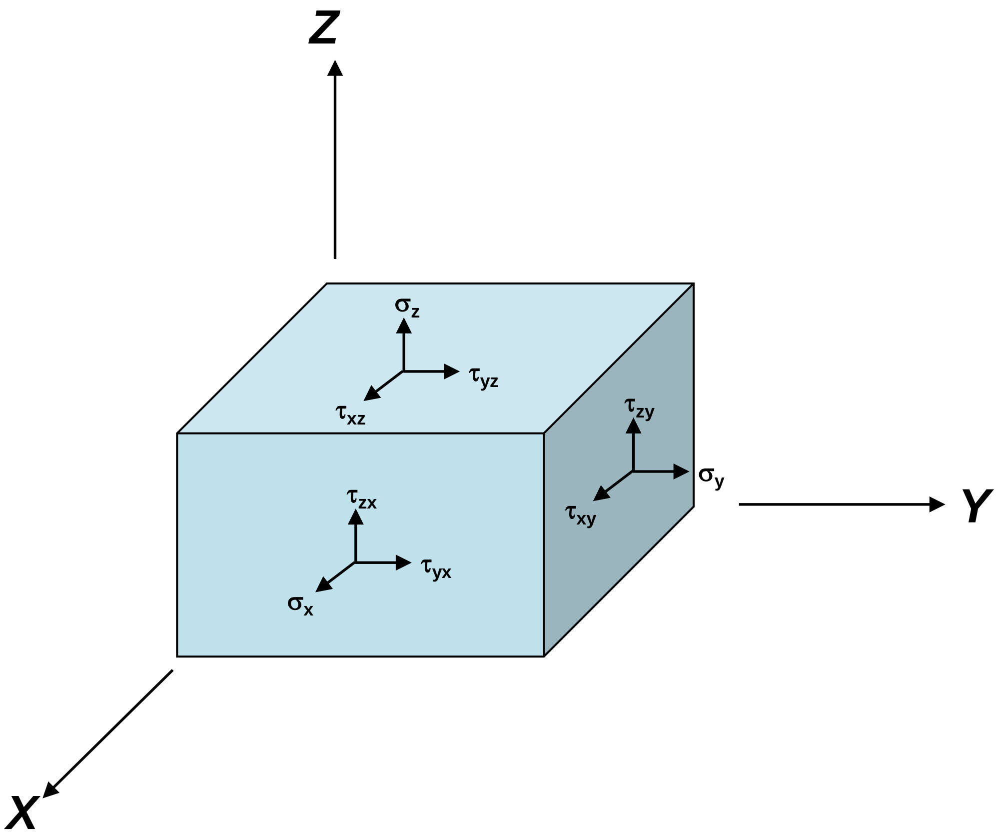
- In rock mechanics the sign convention states that compressive stresses are positive.
- we may divide the cross-section at a) into an infinite number of subsections *A, through which an infinitely* small part *F of the total force F is acting*
- the force is no longer normal to the cross-section. We may then decompose the force into one component *Fn that is* normal to the cross-section, and one component *Fp that is parallel to the section*

To convert from	To	Multiply by
atm	MPa	0.101325
bar	MPa	0.1
bbl	m^3	0.1589873
cp	Pa s	1.0×10^{-3}
Darcy	mm^2	0.9869233
$dyne/cm^2$	Pa	0.1
ft	m	0.3048
inch	m	2.54×10^{-2}
lbf	N	4.44822
lbm	kg	0.4535924
Lbm/USgal	g/cm^3	0.1198264
psi	kPa	6.894757
psi/ft	kPa/m	22.62059

Mass(Kg)	g (m/s^2)	Force(N)	A(cm^2)	Sigma (Pa)	Psi
1	9.8	9.8	10	9800	1.42

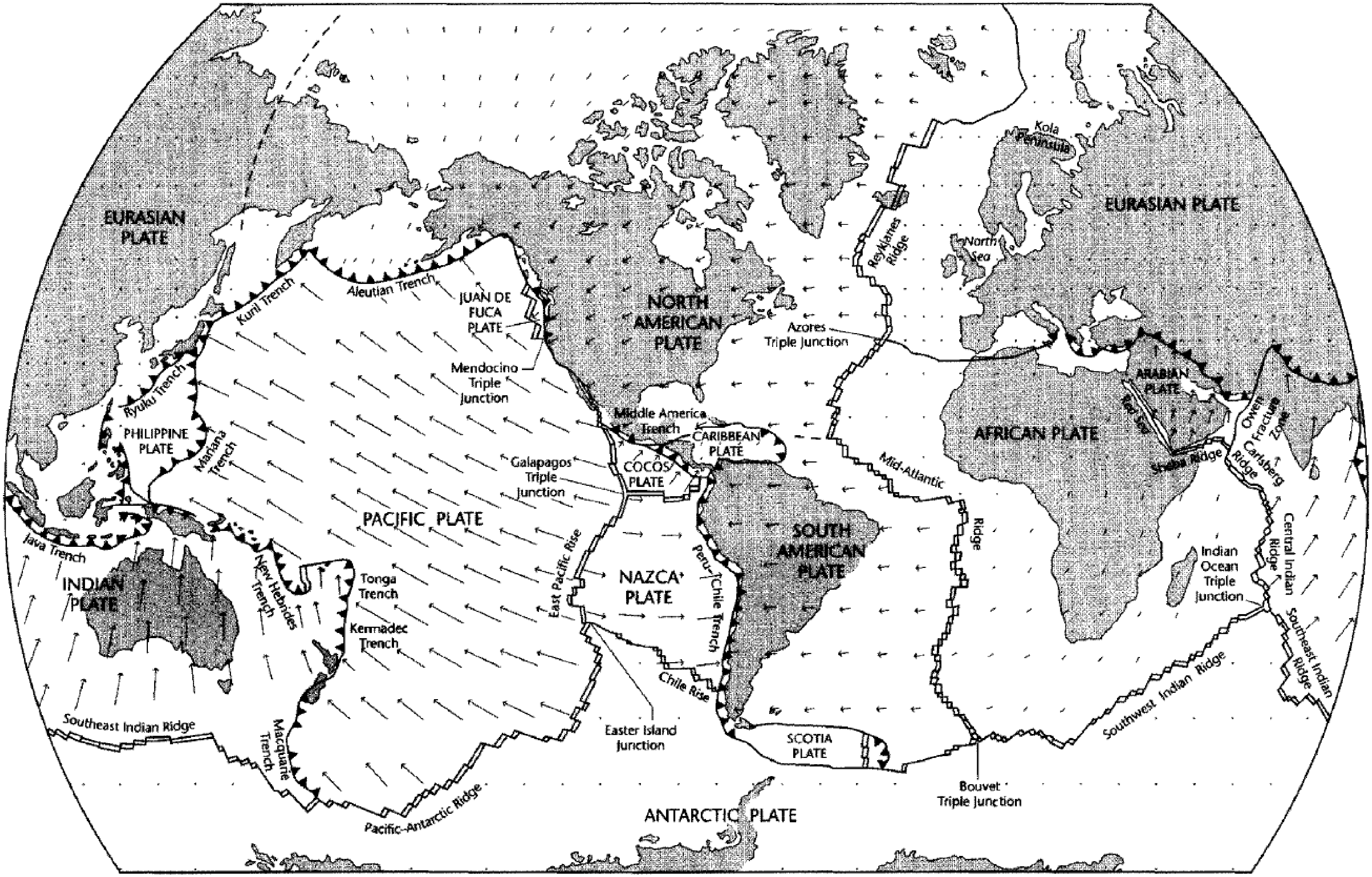
$$
\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \longrightarrow \begin{bmatrix} \sigma_{1} & 0 & 0 \\ 0 & \sigma_{2} & 0 \\ 0 & 0 & \sigma_{3} \end{bmatrix}
$$

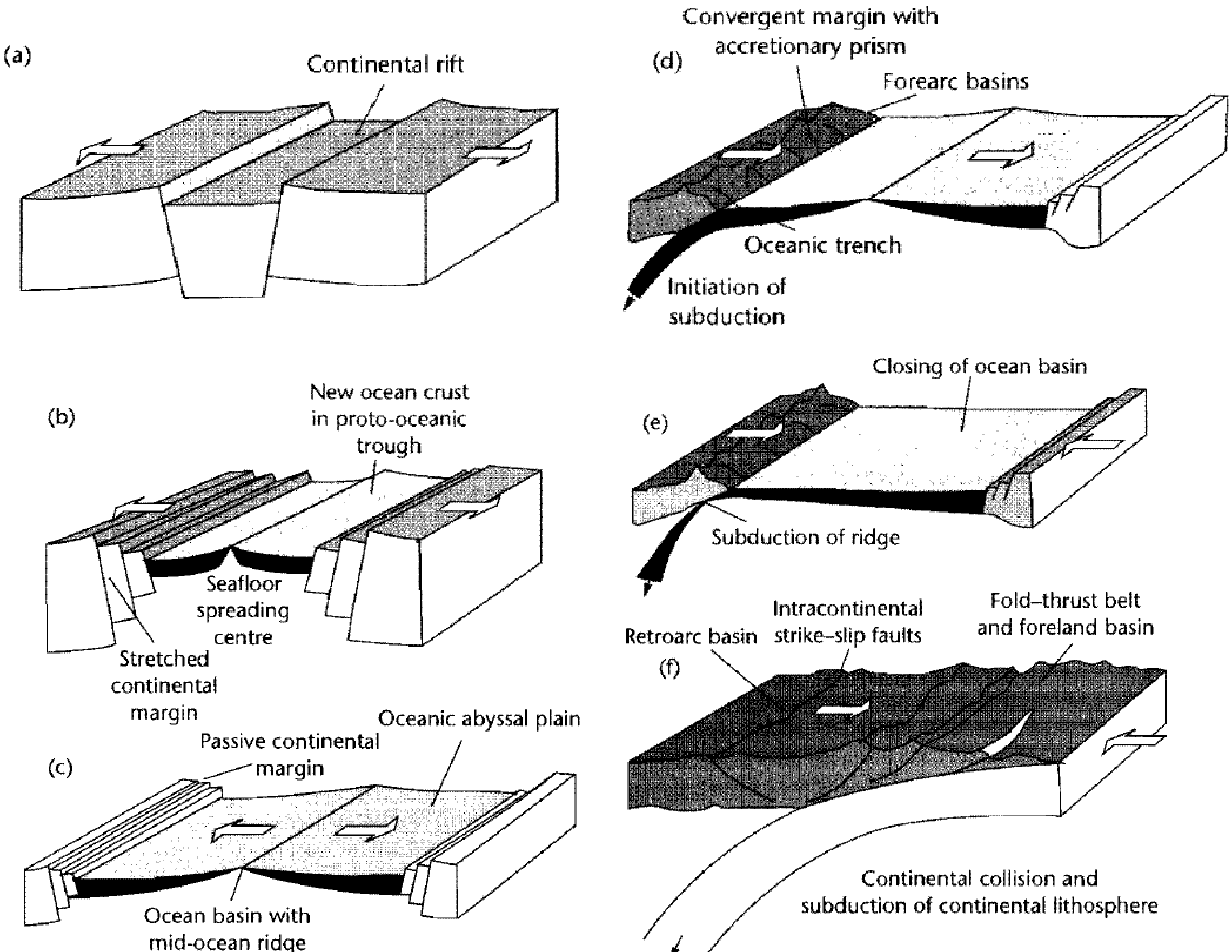
Principal stresses

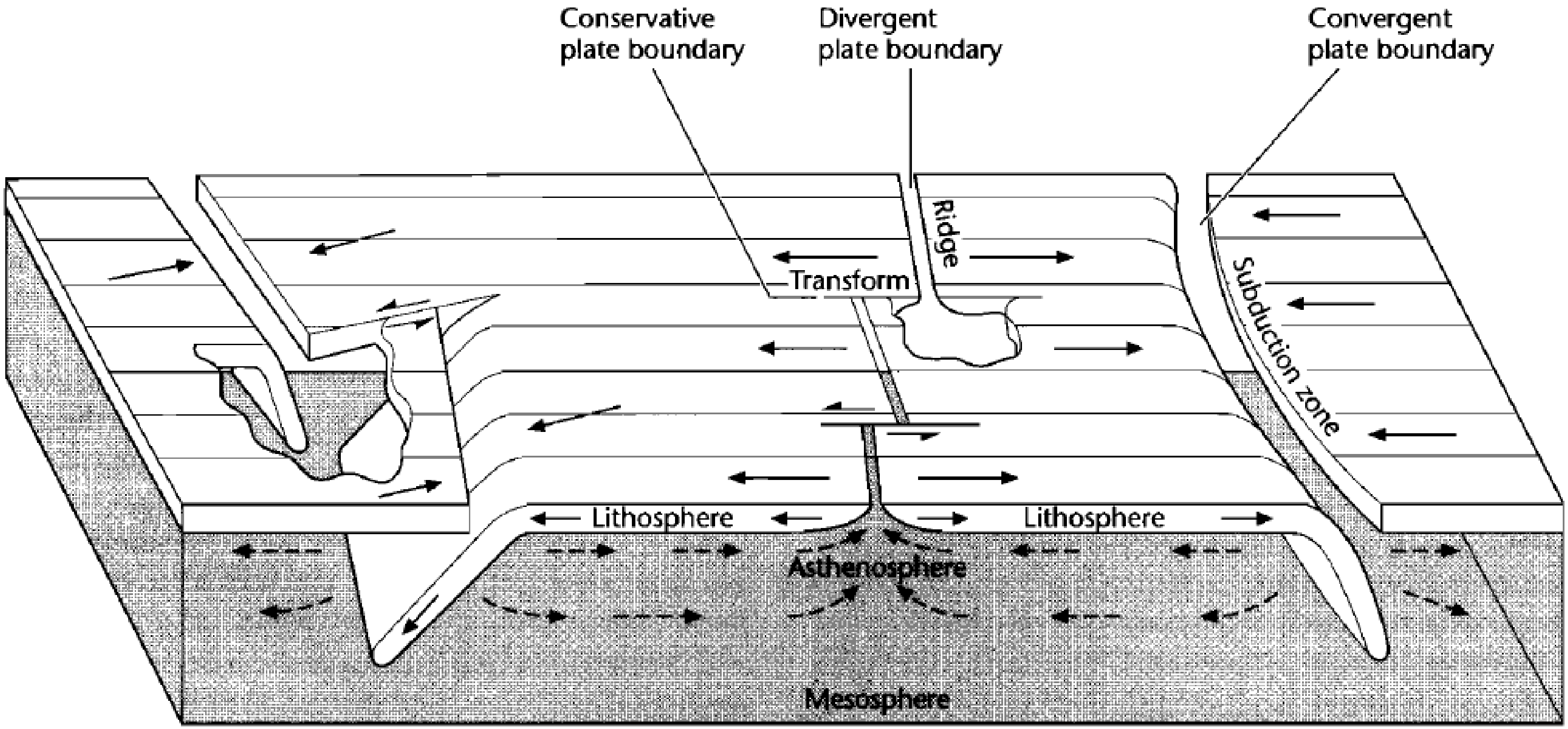


Stress Components

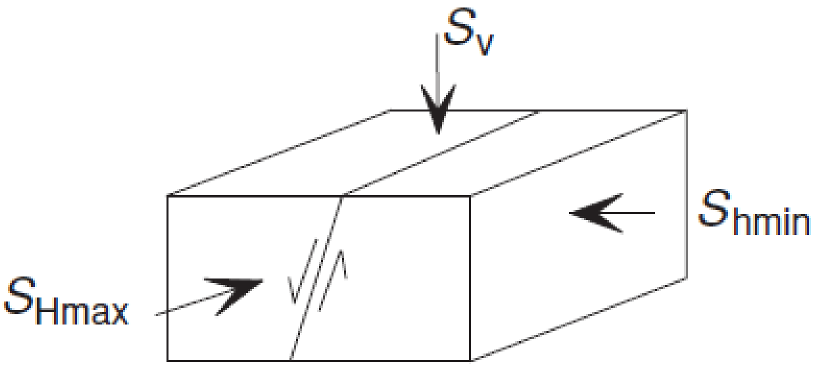
- Vertical Stress or Overburden
- Minimum horizontal stress
- Maximum horizontal stress
- Effective stress


EURASIAN PLATE
EURASIAN PLATE
Kola Peninsula
North Sea
Reykjanes Ridge
Kuril Trench
Aleutian Trench
JUAN DE FUCA PLATE
Mendocino Triple Junction
NORTH AMERICAN PLATE
Azores Triple Junction
ARABIAN PLATE
Red Sea
Owen Fracture Zone
Ryuku Trench
PHILIPPINE PLATE
Mariana Trench
Middle America Trench
CARIBBEAN PLATE
AFRICAN PLATE
Sheba Ridge
Carlsberg Ridge
Galapagos Triple Junction
COCOS PLATE
Mid-Atlantic Ridge
PACIFIC PLATE
SOUTH AMERICAN PLATE
Central Indian Ridge
Java Trench
INDIAN PLATE
New Hebrides Trench
Tonga Trench
Kermadec Trench
East Pacific Rise
NAZCA PLATE
Peru-Chile Trench
Indian Ocean Triple Junction
Southeast Indian Ridge
Chile Rise
Southwest Indian Ridge
Southeast Indian Ridge
Macquarie Trench
Easter Island Junction
SCOTIA PLATE
Bouvet Triple Junction
Pacific-Antarctic Ridge
ANTARCTIC PLATE

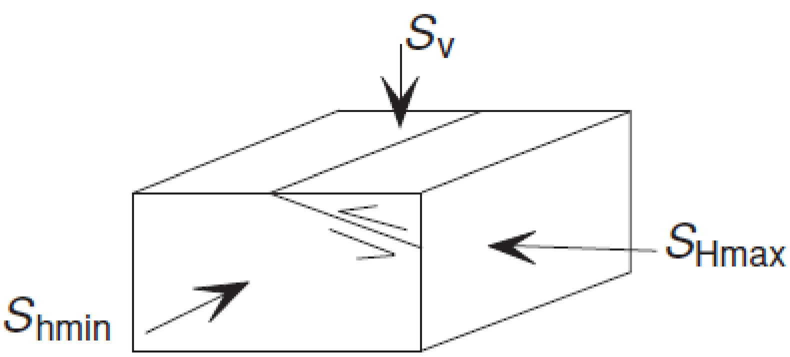

(a)
Continental rift
(b)
New ocean crust
in proto-oceanic
trough
Seafloor
spreading
centre
Stretched
continental
margin
(c)
Passive continental
margin
Oceanic abyssal plain
Ocean basin with
mid-ocean ridge
Convergent margin with
accretionary prism
(d)
Forearc basins
Oceanic trench
Initiation of
subduction
Closing of ocean basin
(e)
Subduction of ridge
Retroarc basin
Intracontinental
strike–slip faults
Fold–thrust belt
and foreland basin
(f)
Continental collision and
subduction of continental lithosphere


Conservative plate boundary
Divergent plate boundary
Convergent plate boundary
Ridge
Transform
Subduction zone
Lithosphere
Lithosphere
Asthenosphere
Mesosphere

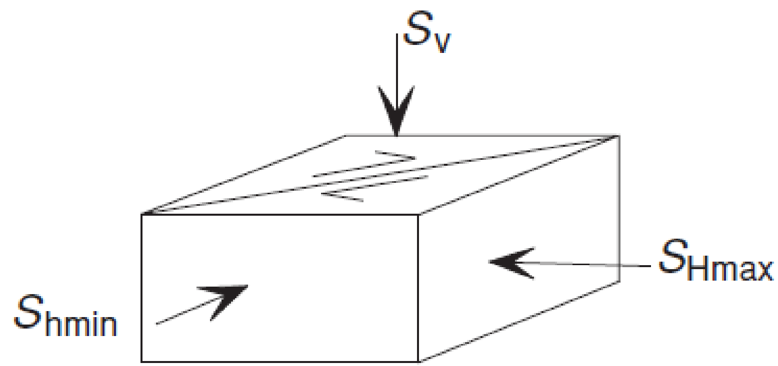
Different Stress Regimes



$S_v > S_{Hmax} > S_{hmin}$

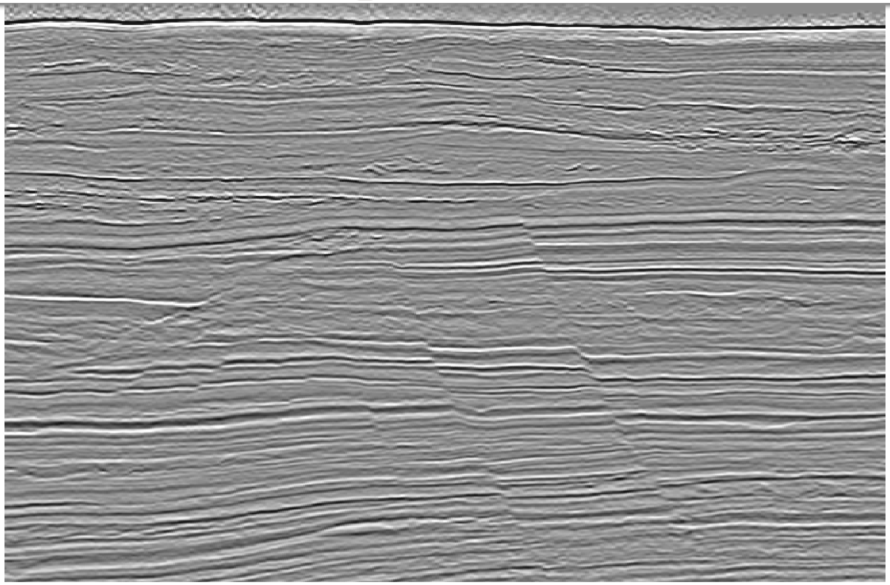


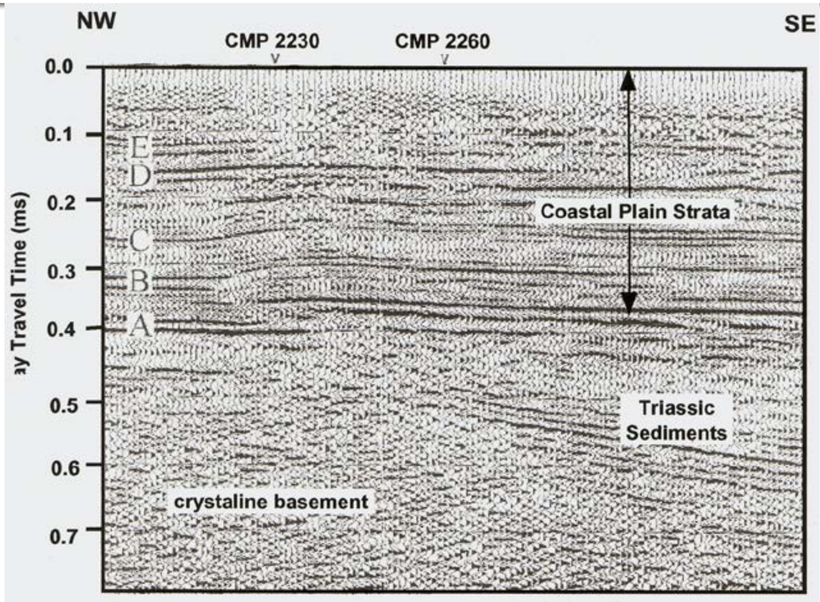
$S_{Hmax} > S_{hmin} > S_v$

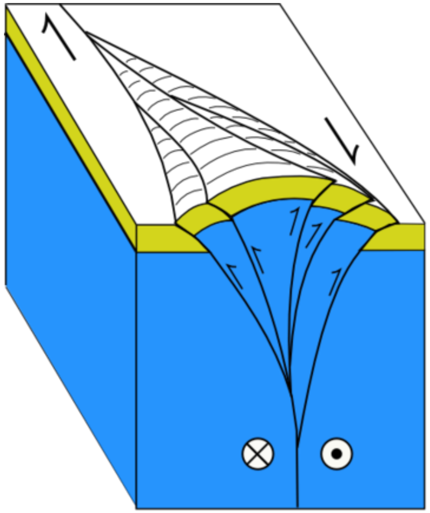


$S_{Hmax} > S_v > S_{hmin}$

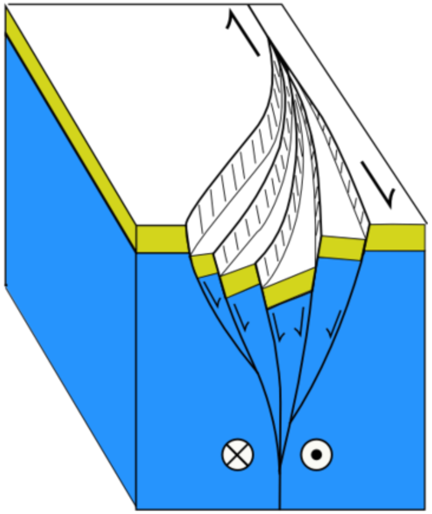
Examples





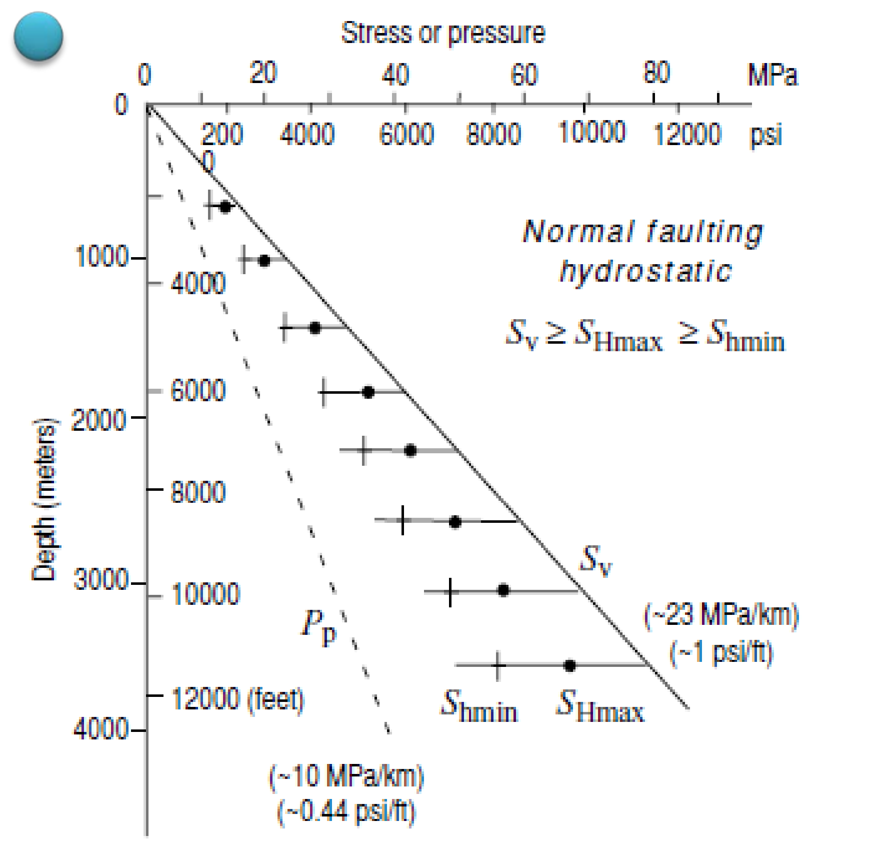


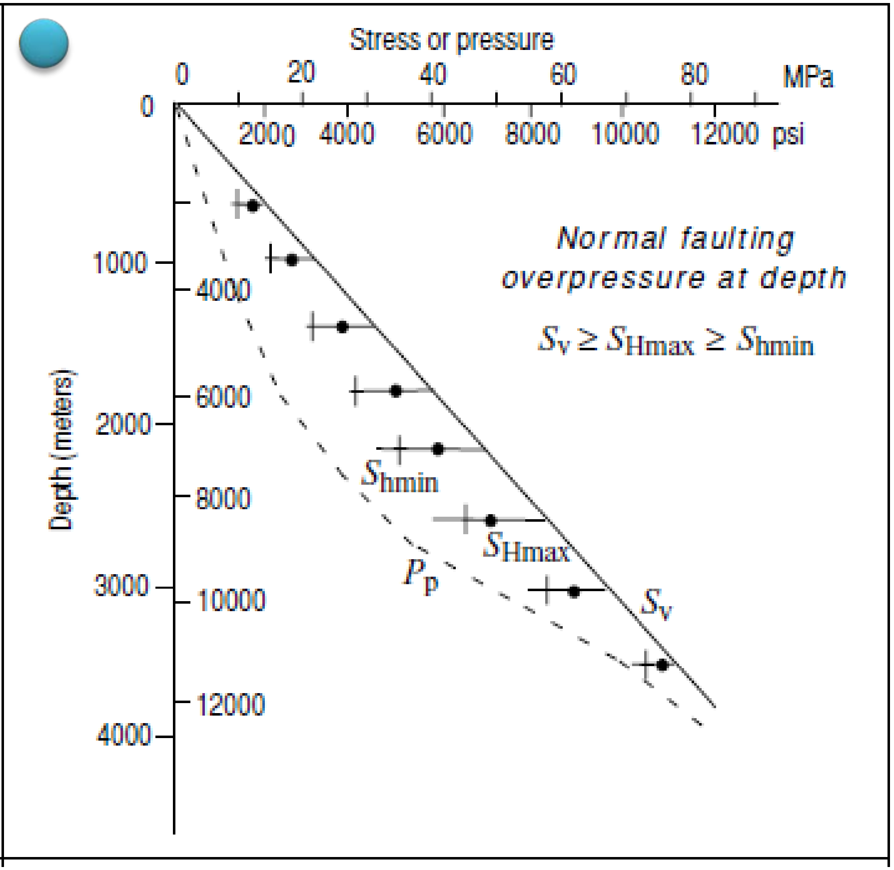
Positive Flower



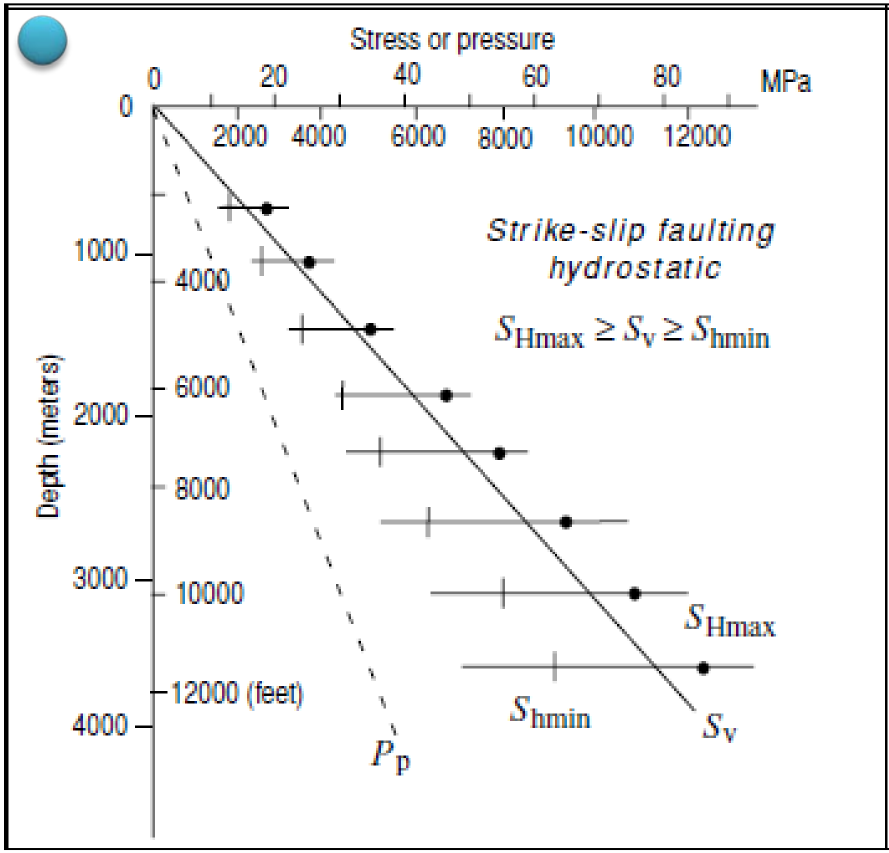
Negative Flower

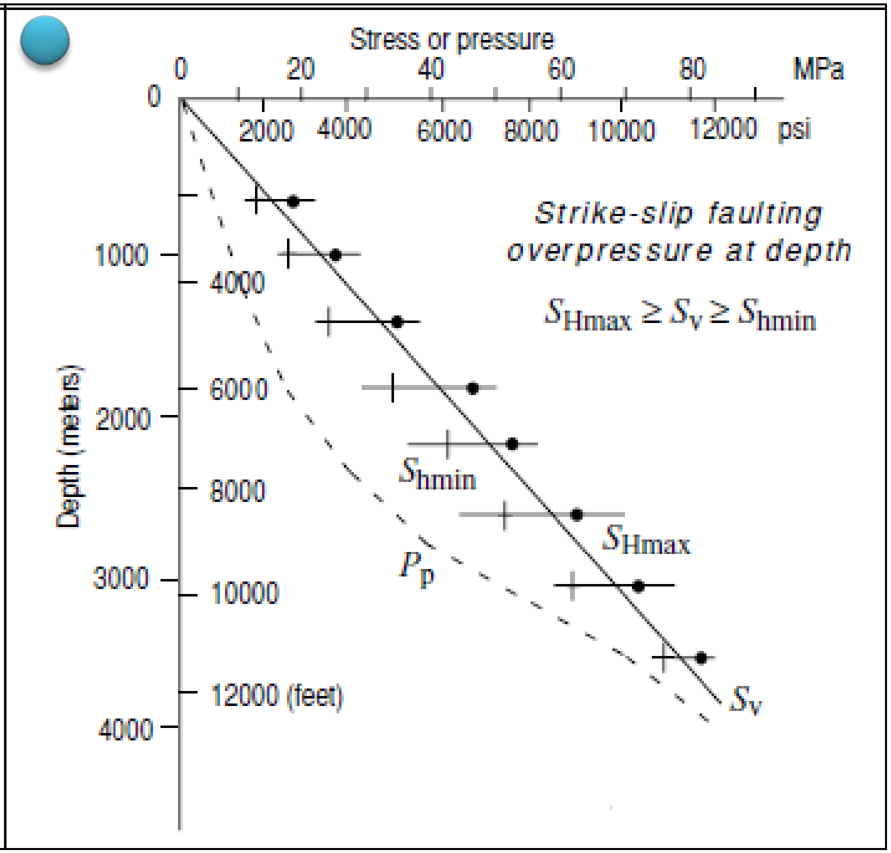
Principal Components of Stress



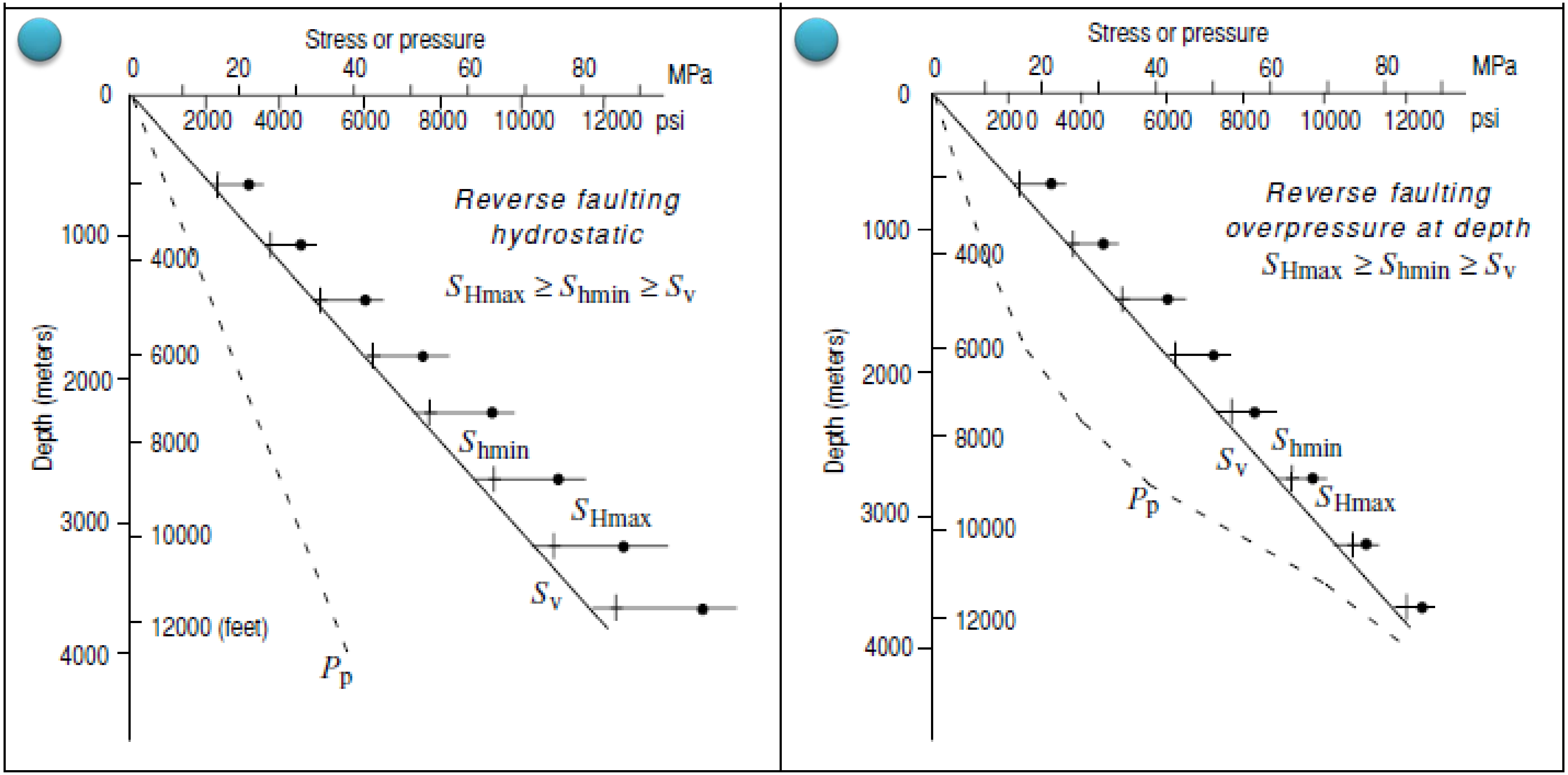


Principal Components of Stress





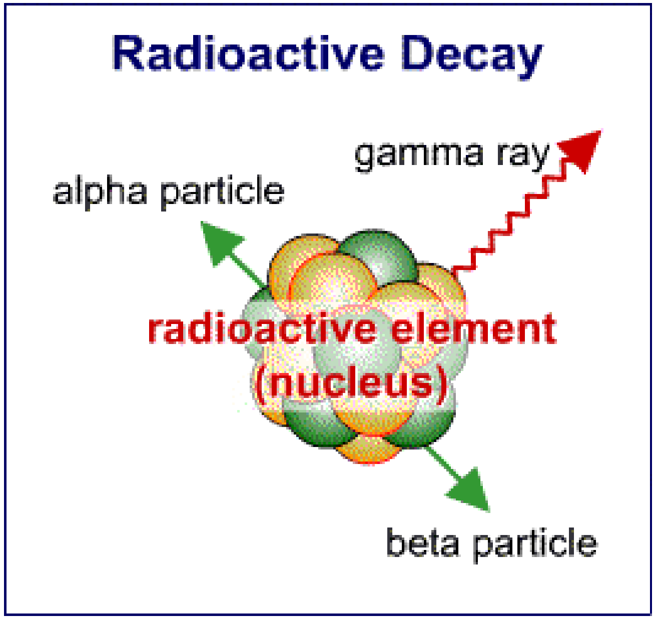
Principal Components of Stress



Well Logs used in Geomechanical Studies

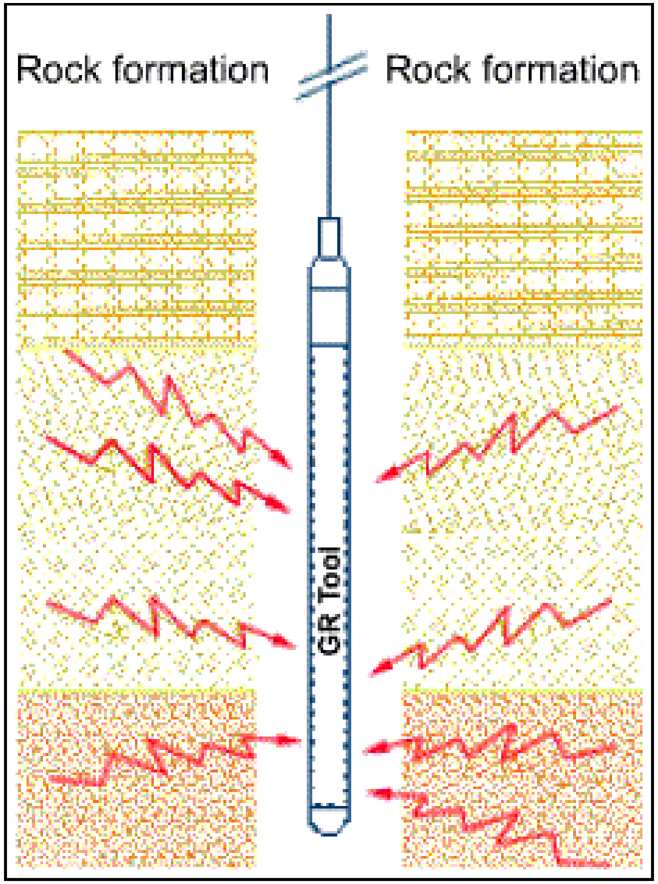
Gamma Ray Logging

GR Principles



- Alpha particles : positively charged particles that are made up of two neutrons and two protons, making it identical to the nucleus of a helium atom. Alpha particles are easily stopped by a thick cloth.
- Beta particles : either negatively or positively charged particles with the same mass and charge as an electron. Beta particles are easily stopped by a thin sheet of metal.
- Gamma rays : electromagnetic waves traveling at the speed of light having discrete energy levels. Gamma rays penetrate farther than most particles, mainly because they lack charge.

Gamma Ray Logging

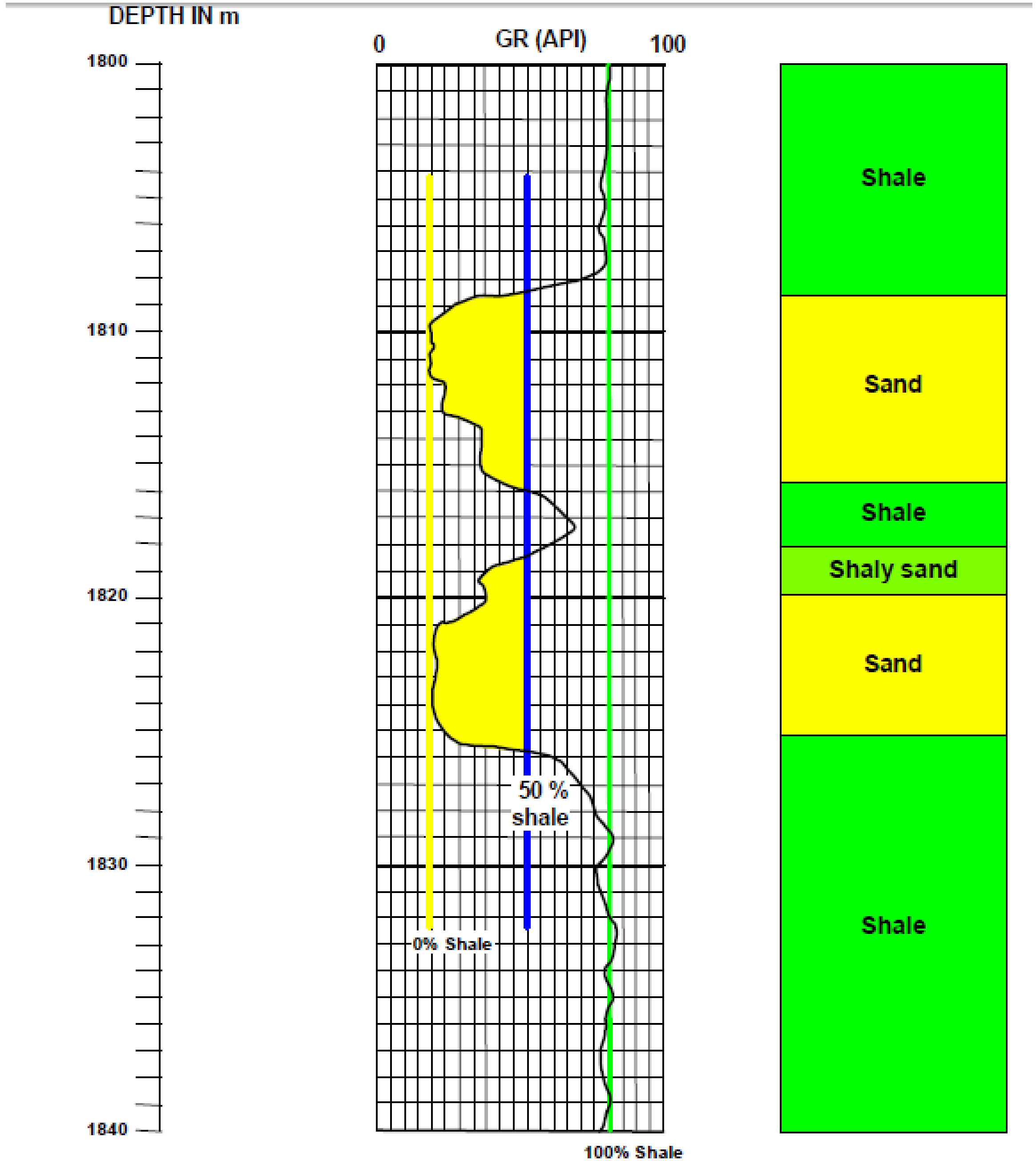


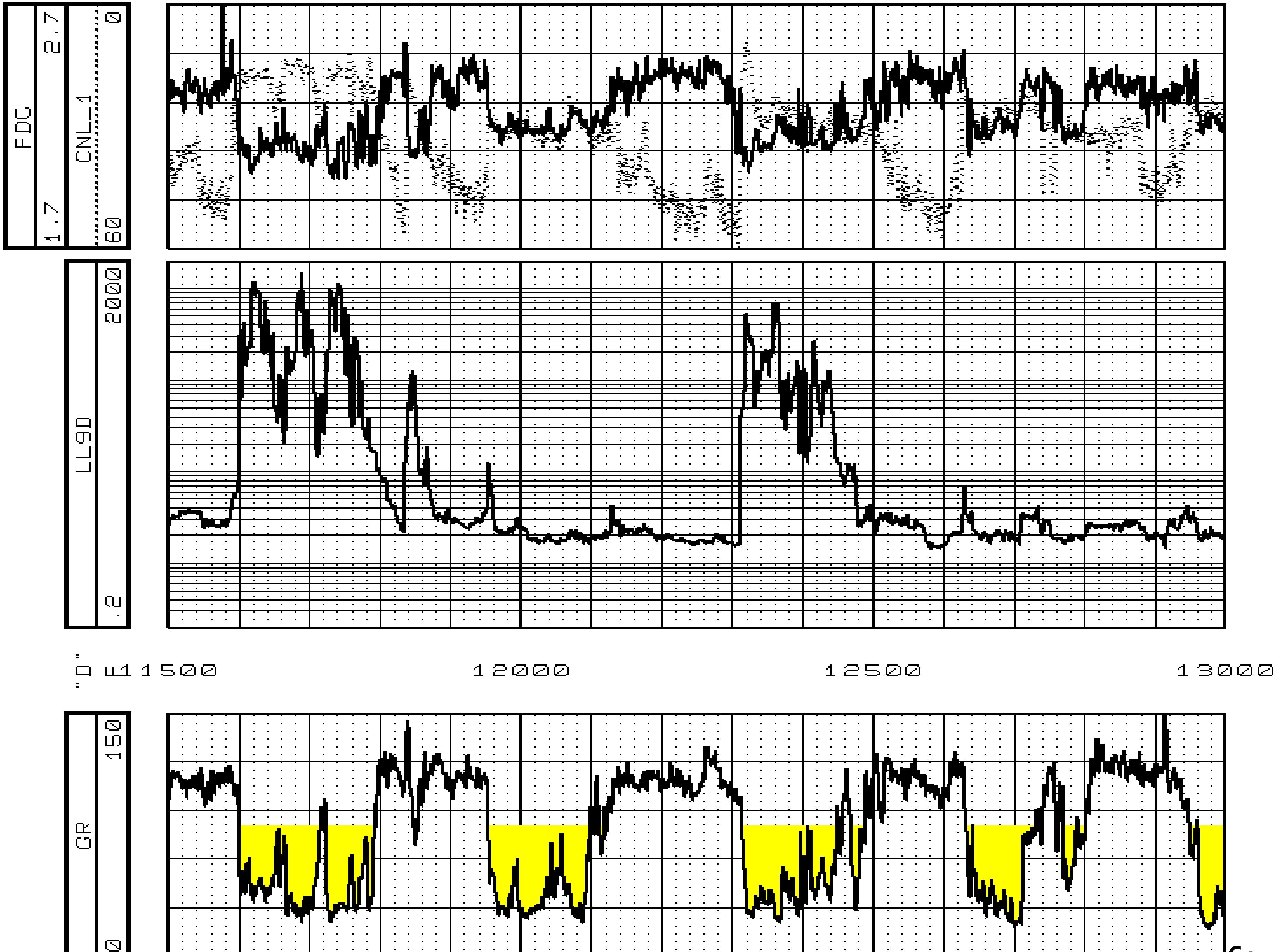
- To measure the natural gamma rays emitted from the formation, the Gamma ray (GR) tool is lowered in the borehole.
- The GR tool consists of a detector and associated electronics to measure the gamma radiation originating in the volume of formation near the tool.

GR response to lithology

- The GR log records the abundance of the radioactive isotopes of K, Th and U
- K, Th and U are usually concentrated in shales and less concentrated in sandstones and carbonates (owing to differences in mineralogy)
- Common GR readings, in API units*, are:
  - Limestones and anhydrites, 15-20 API
  - Dolomites and "clean" (shale-free) sandstones, 20-30 API
  - *Shales, average 100 API*, but can vary from 75 to 300 API
  - Other lithologies: coal, salt (halite, NaCl) and gypsum usually give low readings while volcanic ash and beds of potash salts (sylvite, KCl) give high readings
- Therefore, the GR log is a good "first-pass" indicator of lithology

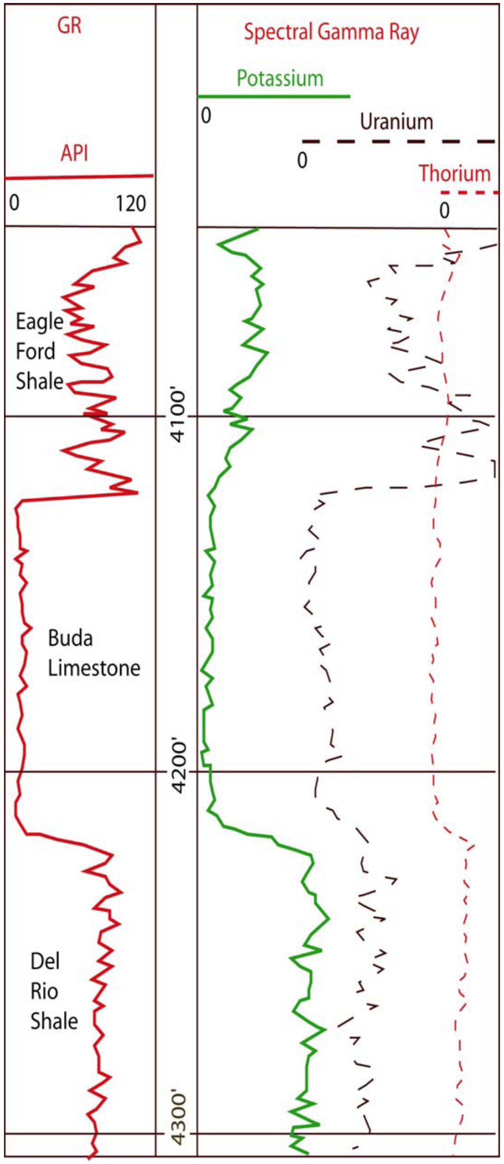
*1 API unit = 1/200th of the response generated by a calculated standard that has 2x the average radioactivity of shale with 6ppm U, 12ppm Th and 2% K


DEPTH IN m
1800
1810
1820
1830
1840
0
GR (API)
100
50 %
shale
0% Shale
100% Shale
Shale
Sand
Shale
Shaly sand
Sand
Shale

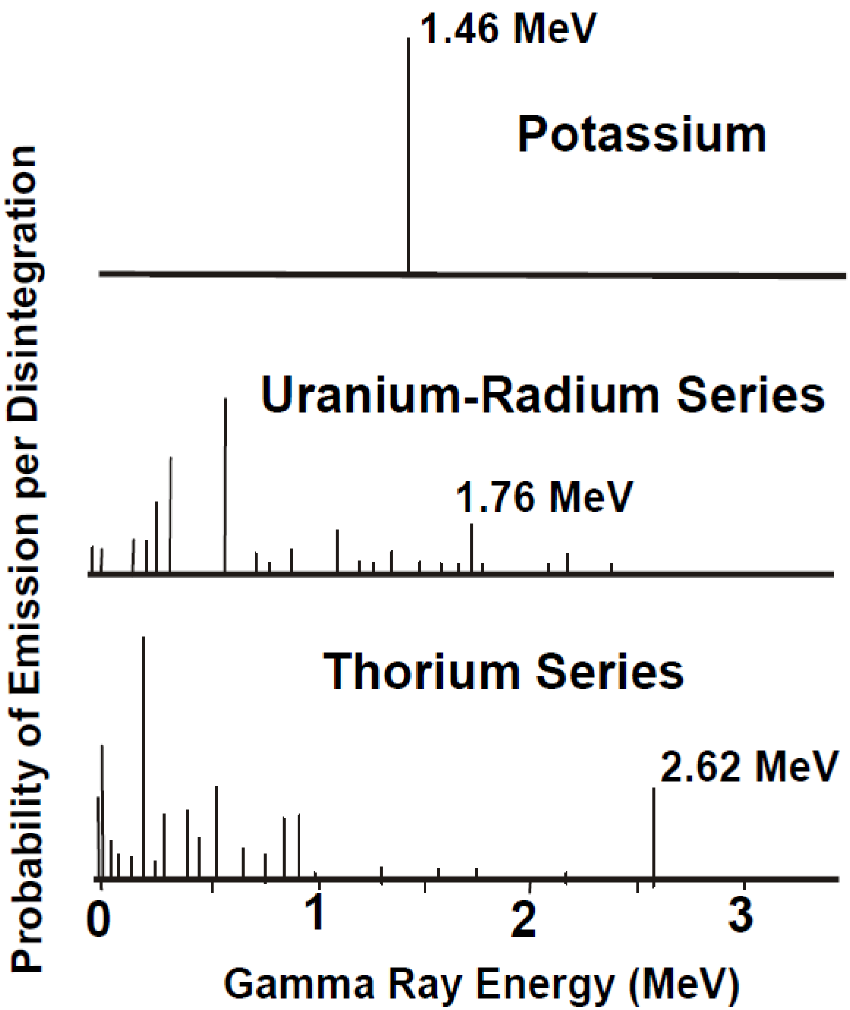

FDC
1.7
2.7
CNL_1
60
0
LL9D
.2
2000
11500
12000
12500
13000
GR
0
150

Spectral GR

- **Eagleford Fm: Shale and source rock. High U content associated with high TOC (organics)**
- **Buda Fm: Limestone. Very low radioactivity (<20 API)**
- **Del Rio Fm: Typical shale. High K content associated with illite**



Gamma Ray Emission Energy Spectra



Intensity of radiation per gram per second

U-Ra series – 26000 photons per gram per second

Th series – 12000 photons per gram per second

$_{19}K^{40}$ – 3 photons/g/s

Typical Gamma Radiation

Mineral or Lithology	Composition	Gamma Radiation (API Units)
Pure Mineral		
Calcite	$CaCO_3$	0
Dolomite	$CaMg(CO_3)_2$	0
Quartz	SiO_2	0
Lithology		
Limestone	-	5-10
Dolomite	-	10-20
Sandstone	-	10-30
Shale	-	80-140
Evaporites		
Halite	NaCl	0
Anhydrite	$CaSO_4$	0
Gypsum	$CaSO_4(H_2O)_2$	0
Sylvite	KCl	500
Carnalite	$KCl\ MgCl_2(H_20)_6$	220
Langbeinite	$K_2SO_4(MgSO_4)_2$	290
Polyhalite	$K_2SO_4MgSO_4(CaSO_4)_2(H_2O)_2$	200
Kainite	$MgSO_4KCl(H_2O)_3$	245
Others		
Sulphur	S	0
Lignite	$CH_{0.849}\ N_{0.015}\ O_{0.221}$	0
Anthracite	$CH_{0.358}\ N_{0.009}\ O_{0.022}$	0
Micas	-	200-350

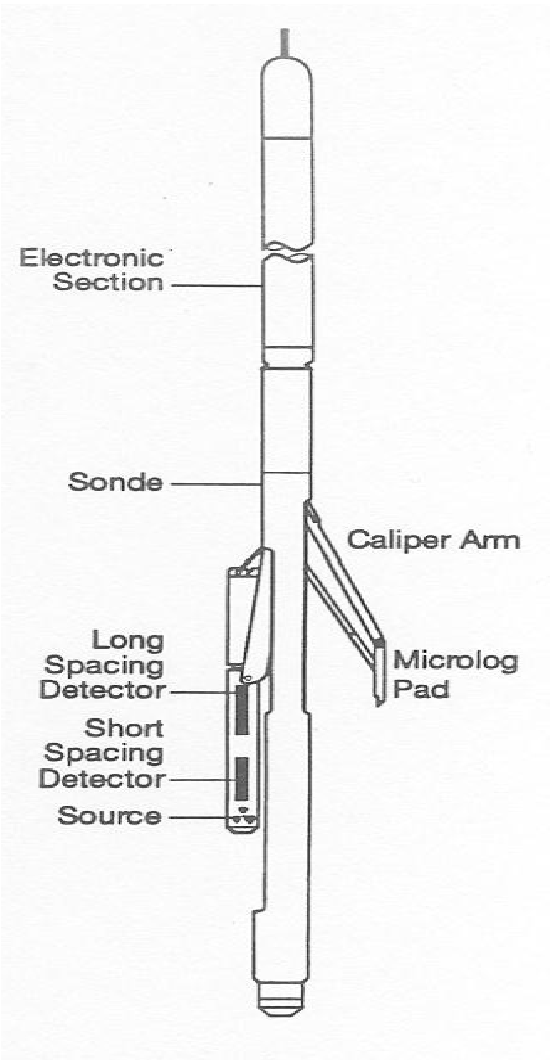
Determination of Shale content

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}}$$

I_{GR} is Gamma Ray Index

Density Log

Schematic of Density Tool



Vertical Resolution ~ 1 ft

Depth of Investigation 3 - 6”

Logging speed: 15-30 ft/min

Theory

- A radioactive source
  - caesium-137 or cobalt-60
    - Emits gamma rays in medium energy range (0.2-2 MeV)
- A short range detector
  - Placed 7 inches from the source
- A Long range detector
  - Placed 16 inches from the source

Electron Number Density (n_e)

- For a pure substance, number density is directly related to bulk density
- Atoms per mole – Avogadro Number (N)
- Electrons in a mole = NZ

  Z= Atomic number
- Number of electrons per gram = NZ/A

  A = Atomic mass number
- Number of electrons per vol (n_e) = (NZ/A) ρ_b

Electron Density as proxy for density

- Effective electron density $\rho_e = 2n_e/N$
- $\rho_e = (2Z/A)\ \rho_b$

Element	*Z*	*A*	*Z/A*	2*Z/A*
H	1	1.0079	0.99215	1.9843
C	6	12.0111	0.4995	0.999
O	8	15.9994	0.5	1.000
Na	11	22.9898	0.47845	0.9569
Mg	12	24.3120	0.4936	0.9872
Al	13	26.9815	0.4818	0.9636
Si	14	28.086	0.49845	0.9969
S	16	32.064	0.499	0.9980
Cl	17	35.453	0.4795	0.9590
K	19	39.102	0.4859	0.9718
Ca	20	40.080	0.499	0.9980

Calibration

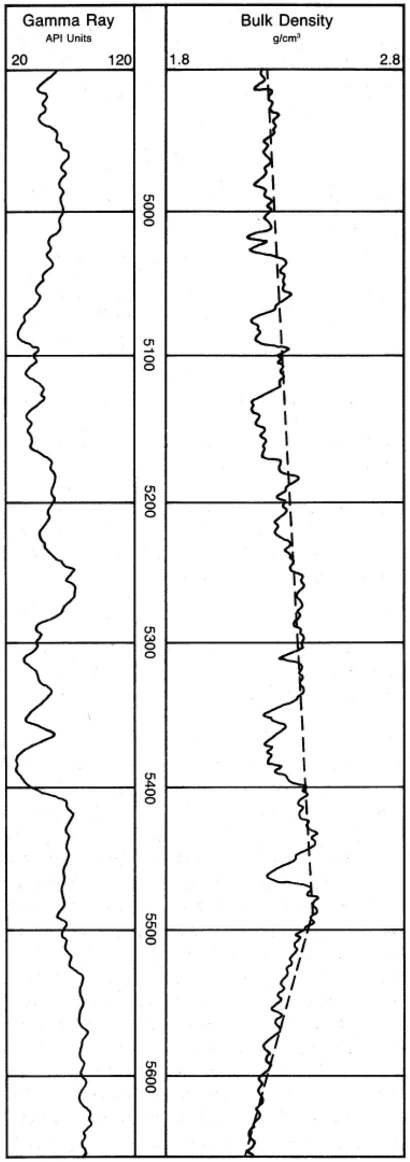
- Calibrated in freshwater filled limestone

$$\rho_{ba} = 1.0704\rho_e - 0.1883$$

Actual Density vs. Apparent Bulk Density

Compound	Composition	Actual Bulk Density, ρ_b	2 Z/A	Effective Electron Density, ρ_e	Apparent Bulk Density, ρ_a
Quartz	SiO_2	2.654	0.9985	2.650	2.648
Calcite	$CaCO_3$	2.710	0.9991	2.708	2.710
Dolomite	$CaCO_3.MgCO_3$	2.870	0.9977	2.863	2.876
Anhydrite	$CaSO_4$	2.960	0.9990	2.957	2.977
Sylvite	KCL	1.984	0.9657	1.916	1.863
Halite	NaCl	2.165	0.9581	2.074	2.032
Gypsum	$CaSO_4.2H_2O$	2.320	1.0222	2.372	2.351
Anthracite (low)		1.400	1.030	1.442	1.355
Anthracite (high)		1.800	1.030	1.852	1.796
Coal (Bituminous)		1.200	1.060	1.272	1.173
Coal		1.500	1.060	1.590	1.514
Pure Water	H_2O	1.000	1.1101	1.110	1.000
Salt Water	200,000 ppm NaCl	1.146	1.0797	1.237	1.135
Oil	$(CH_2)_n$	0.850	1.1407	0.970	0.850
Methane	CH_4	ρ_m	1.247	$1.247\rho_m$	$1.335\rho_m$-0.188
Gas	$C_{1.1}H_{4.2}$	ρ_g	1.238	$1.238\rho_g$	$1.325\rho_g$-0.188

Density Log

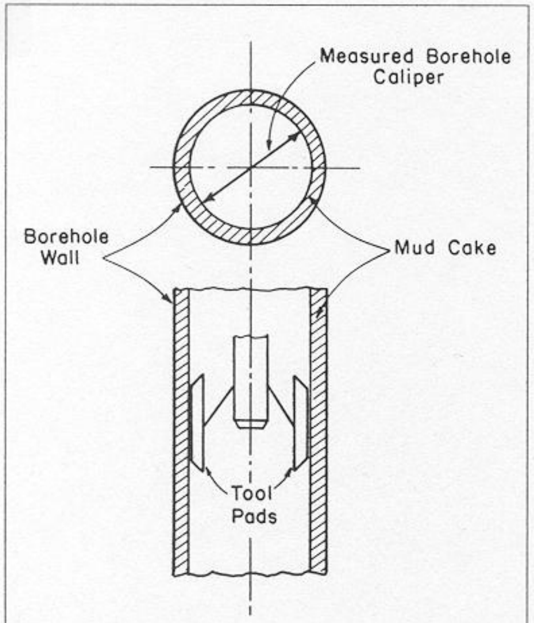


Gamma Ray
API Units
20
120
Bulk Density
g/cm³
1.8
2.8
5000
5100
5200
5300
5400
5500
5600

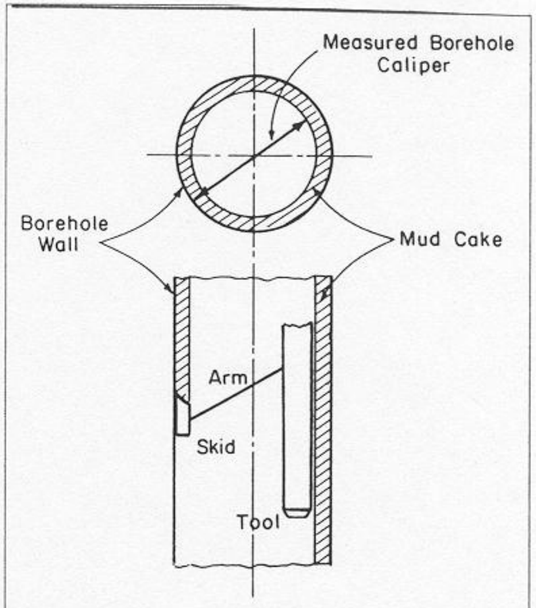
Caliper Logging

- Evaluate the borehole environment of logging measurements
- Identification of mudcake deposition
- Estimate hole volume to determine cement volume requirements
- Determine competent formations to set packers
- Provide position data for dipmeter interpretation
- Methods
  - Acoustic
  - Electromagnetic
  - Mechanical

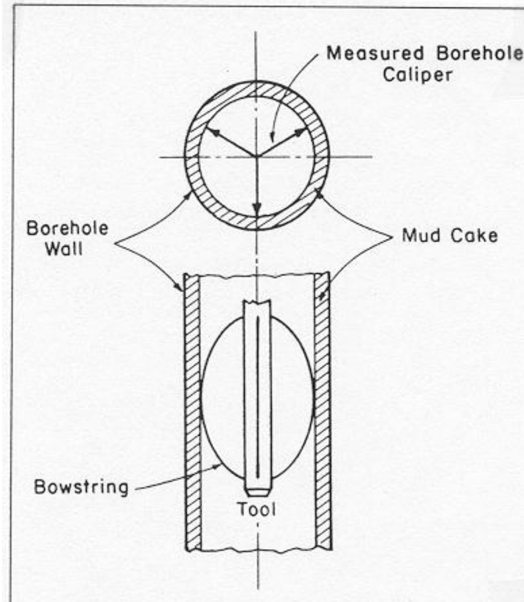
Caliper Logging



—Schematic of microresistivity log caliper.



—Schematic of density and pad-type neutron log caliper.

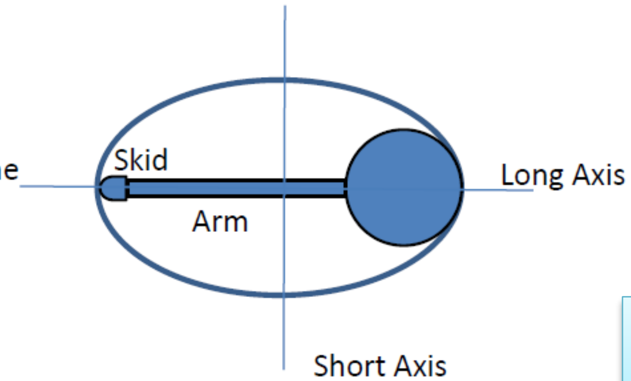


—Schematic of sonic log tool caliper.

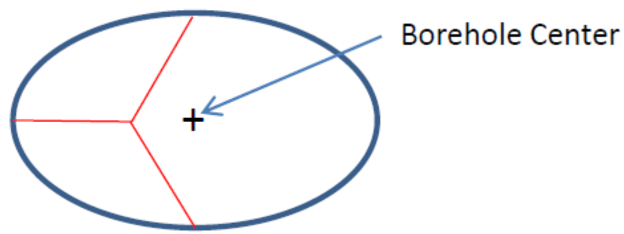
Pad-type devices

Elliptical Boreholes

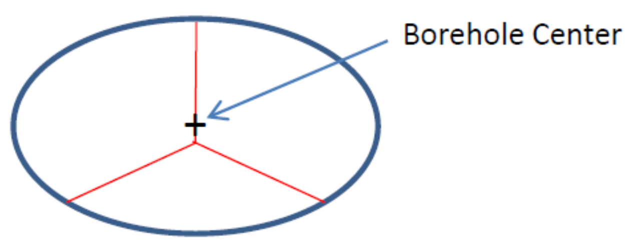
Schematic of elliptical borehole showing the preferential position of a pad-type device



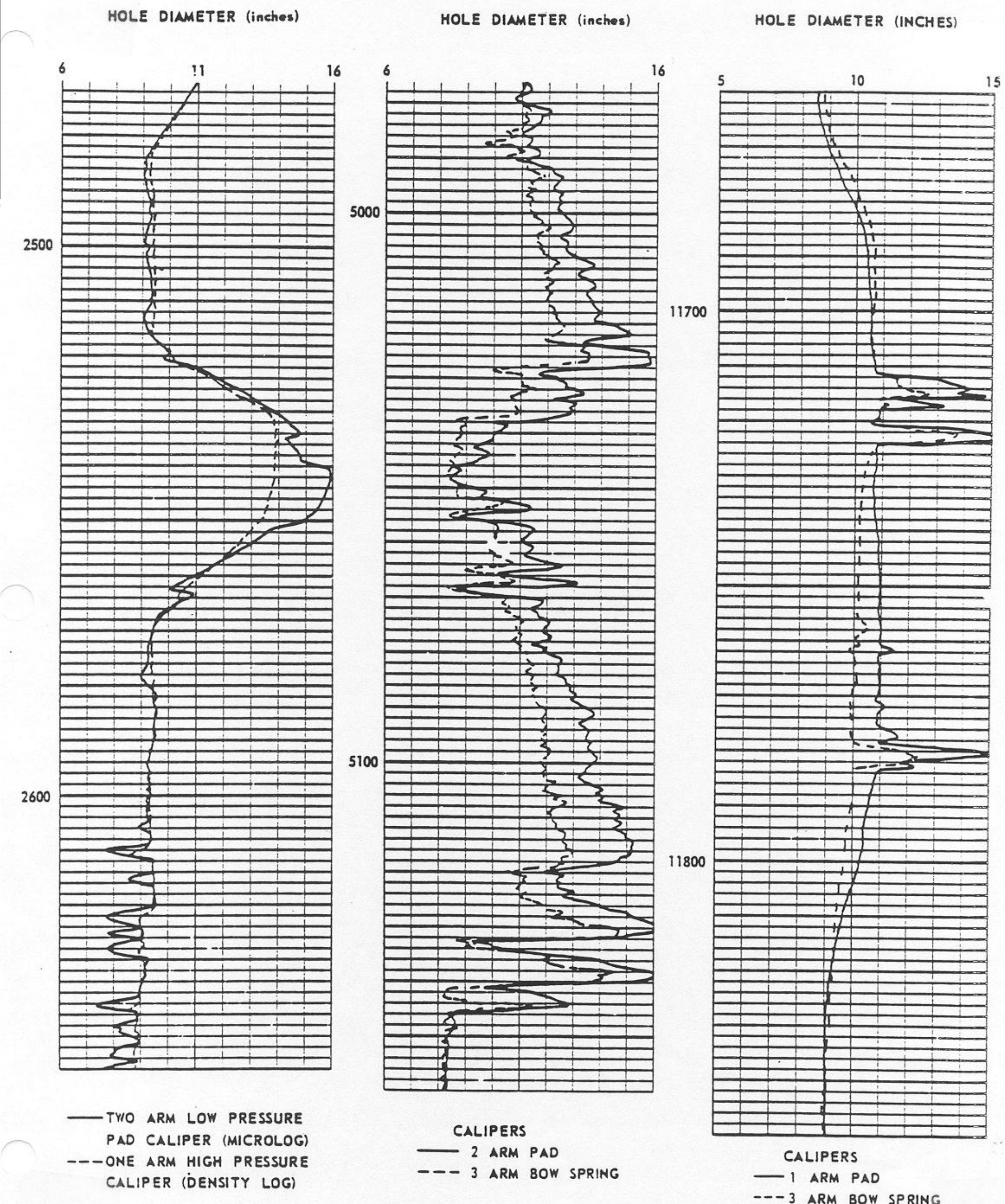
Due to anisotropic mechanical properties of the formations



Most probable positions assumed by a Three-arm caliper in an elliptical borehole



Caliper Log

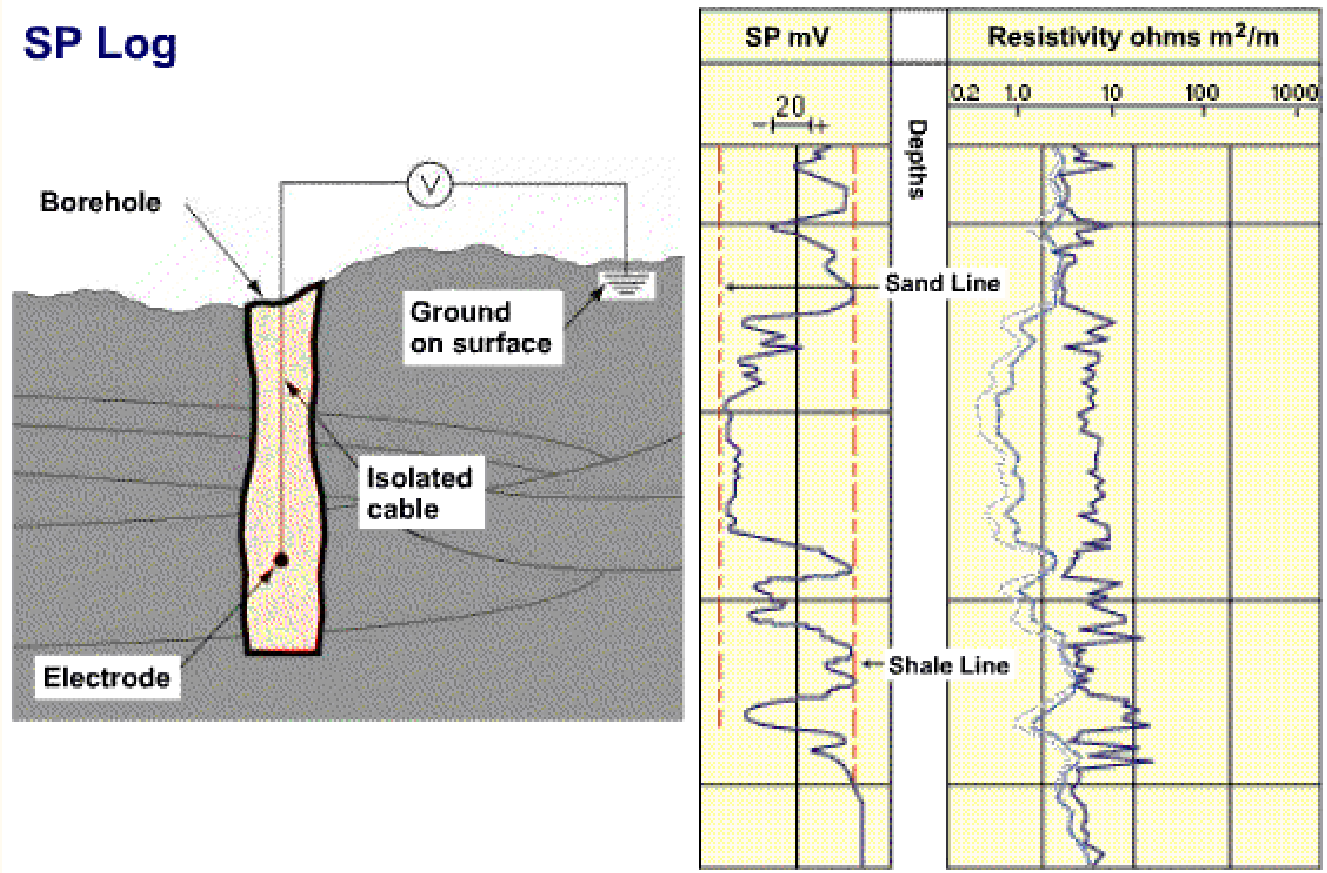

HOLE DIAMETER (inches)
6
11
16
2500
2600
—TWO ARM LOW PRESSURE PAD CALIPER (MICROLOG)
---ONE ARM HIGH PRESSURE CALIPER (DENSITY LOG)
HOLE DIAMETER (inches)
6
16
5000
5100
CALIPERS
— 2 ARM PAD
--- 3 ARM BOW SPRING
HOLE DIAMETER (INCHES)
5
10
15
11700
11800
CALIPERS
— 1 ARM PAD
--- 3 ARM BOW SPRING

SP LOG

SP Log

- The SP log measures the difference in electrical potential between a fixed electrode at the surface and a movable electrode in the borehole
  - The hole must be filled with conductive mud
  - No SP can be measured in oil based mud, empty holes or cased holes
  - The scale of the SP in in millivolts (MV). There is no absolute zero: only changes in potential are recorded
  - Vertical resolution ≈ $1/\Phi$ or
    - At 30% porosity, resolution = 3 ft
    - At 3% porosity, resolution = 30 ft

Schematic of SP Logging



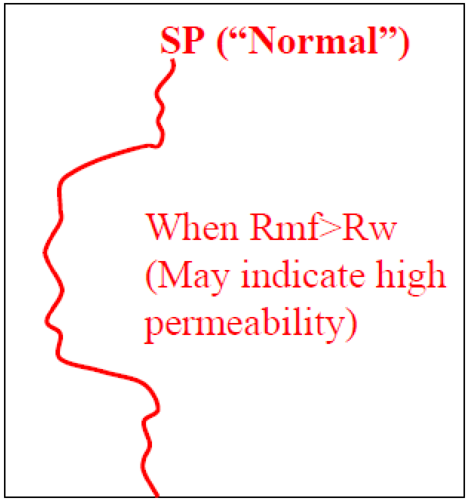
The SP log is recorded by placing a movable electrode in the borehole and measuring the difference between the electrical potential of this movable electrode and the electrical potential of a fixed surface electrode.

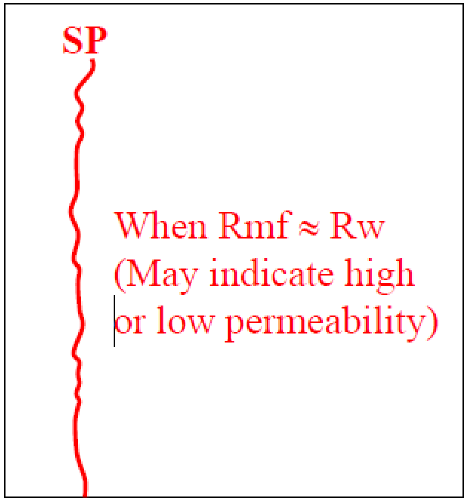
Requirements for SP recording

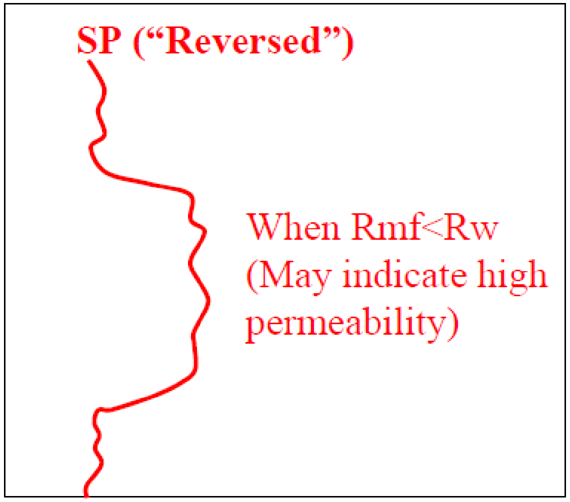
- Three requirements for the existence of and SP current
  - A conductive borehole fluid
  - A sandwich of a porous and permeable formation between low porosity and impermeable formations
  - Difference in salinity between mud and formation fluid

Limitations of the SP Logs

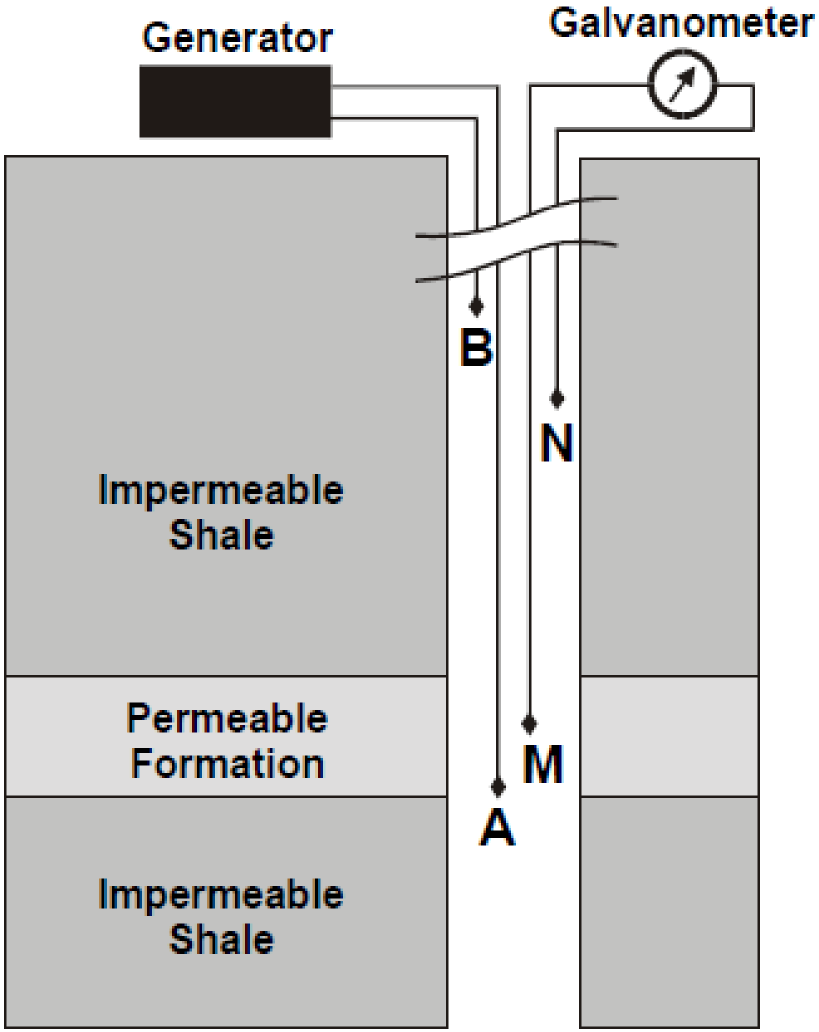
- SP logs delineate permeable beds well in relatively thick, porous sand and shale sequences but resolve beds poorly in thinly bedded and low permeability formations
- The SP log measures differences in the ionic activities (relative saltiness) of the drilling mud and the formation waters. In salt muds, the SP is often useless because the SP magnitudes at depths of interest are small (Rmf ≈ Rw) and because boundary definition with low resistivity mud and high resistivity formations is very poor
- The SP curve can reverse under certain circumstances



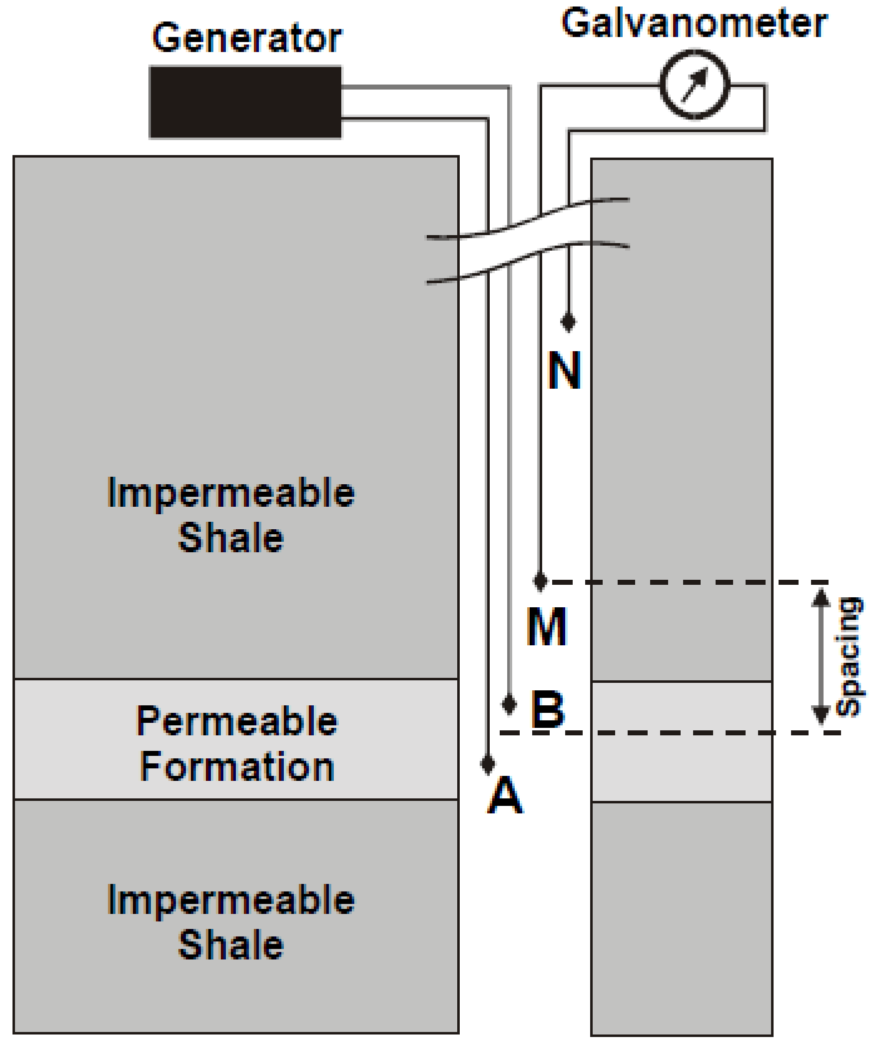




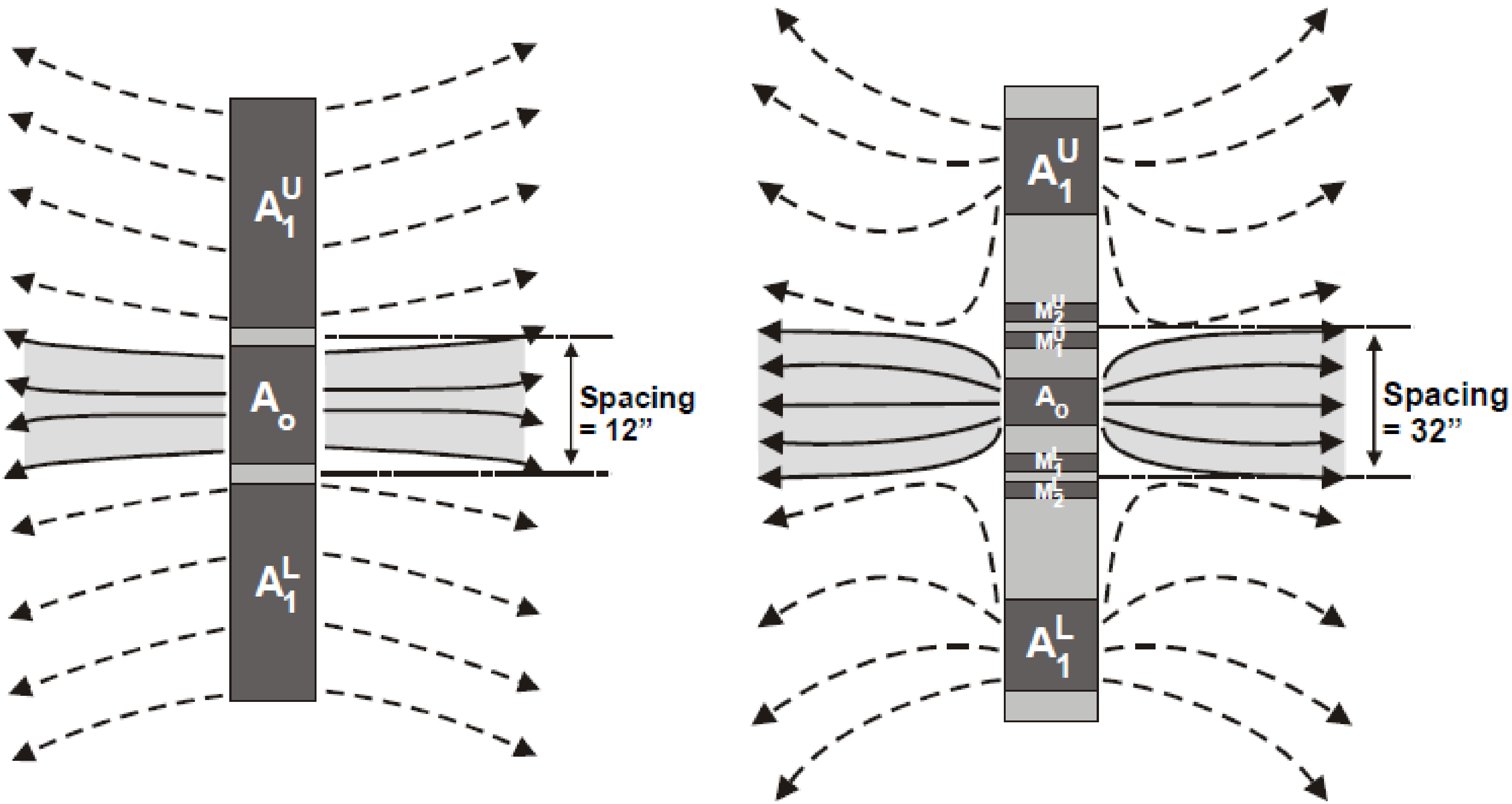
Resistivity Logs



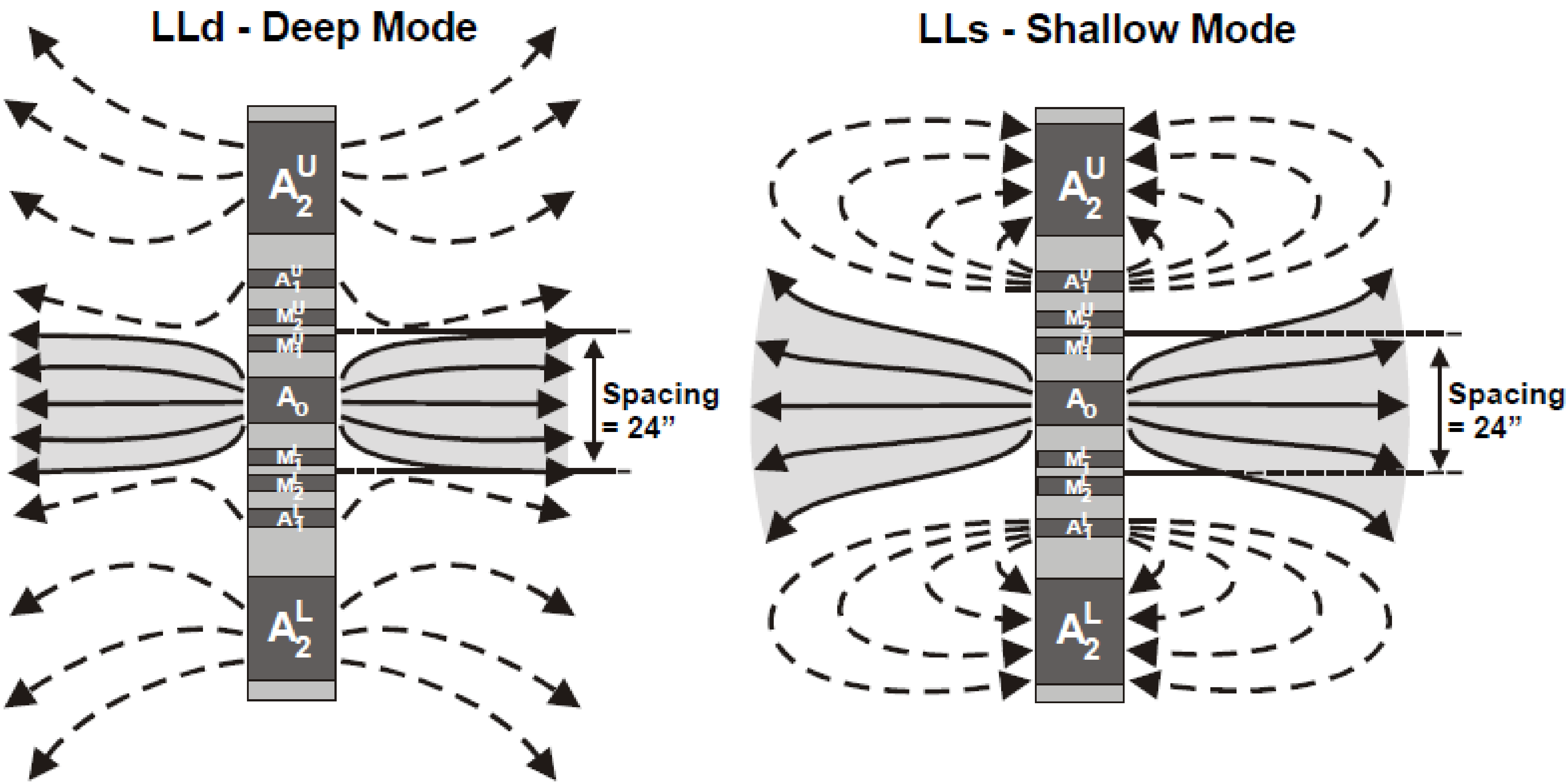
The standard normal configuration



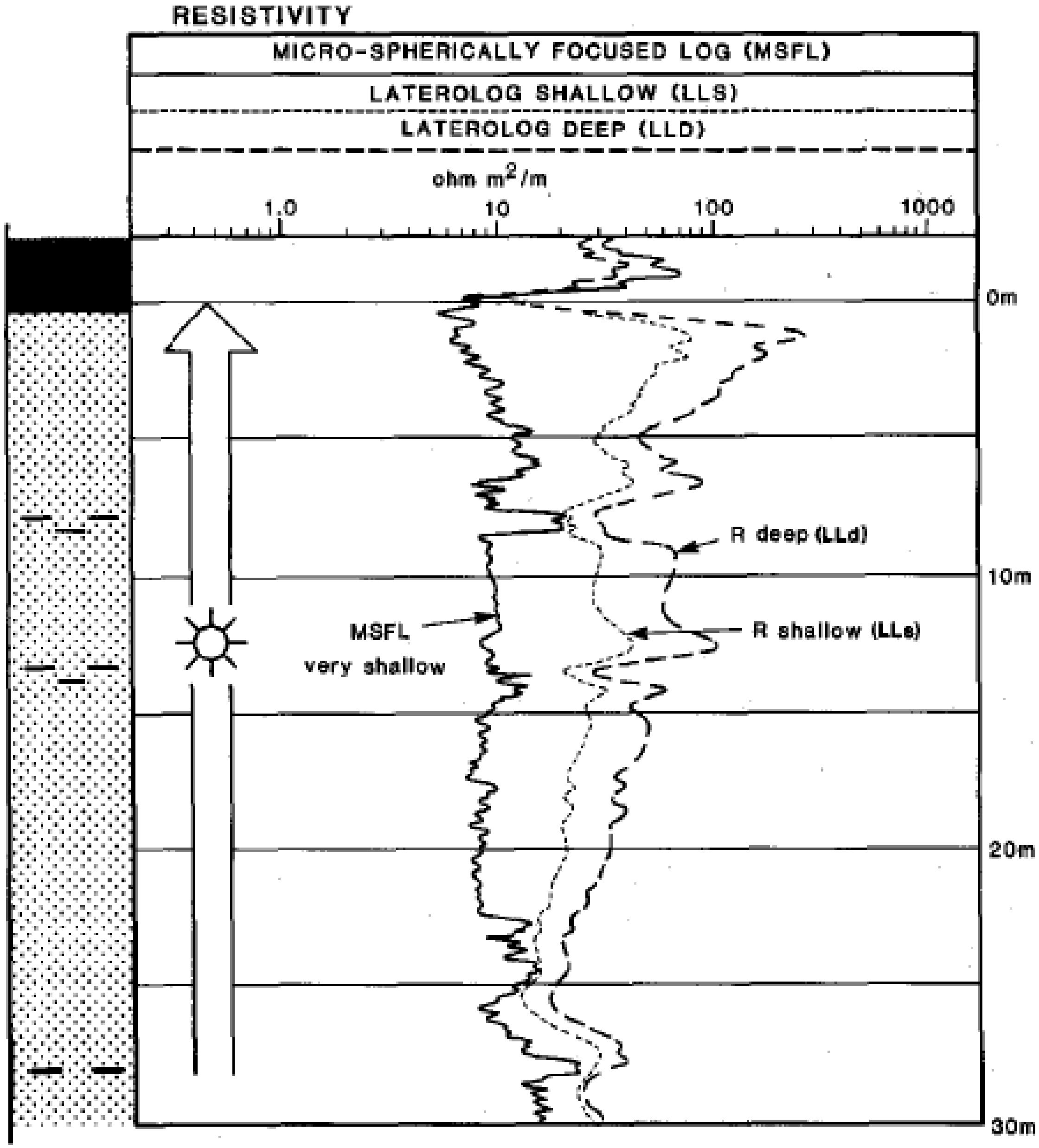
The standard lateral configuration



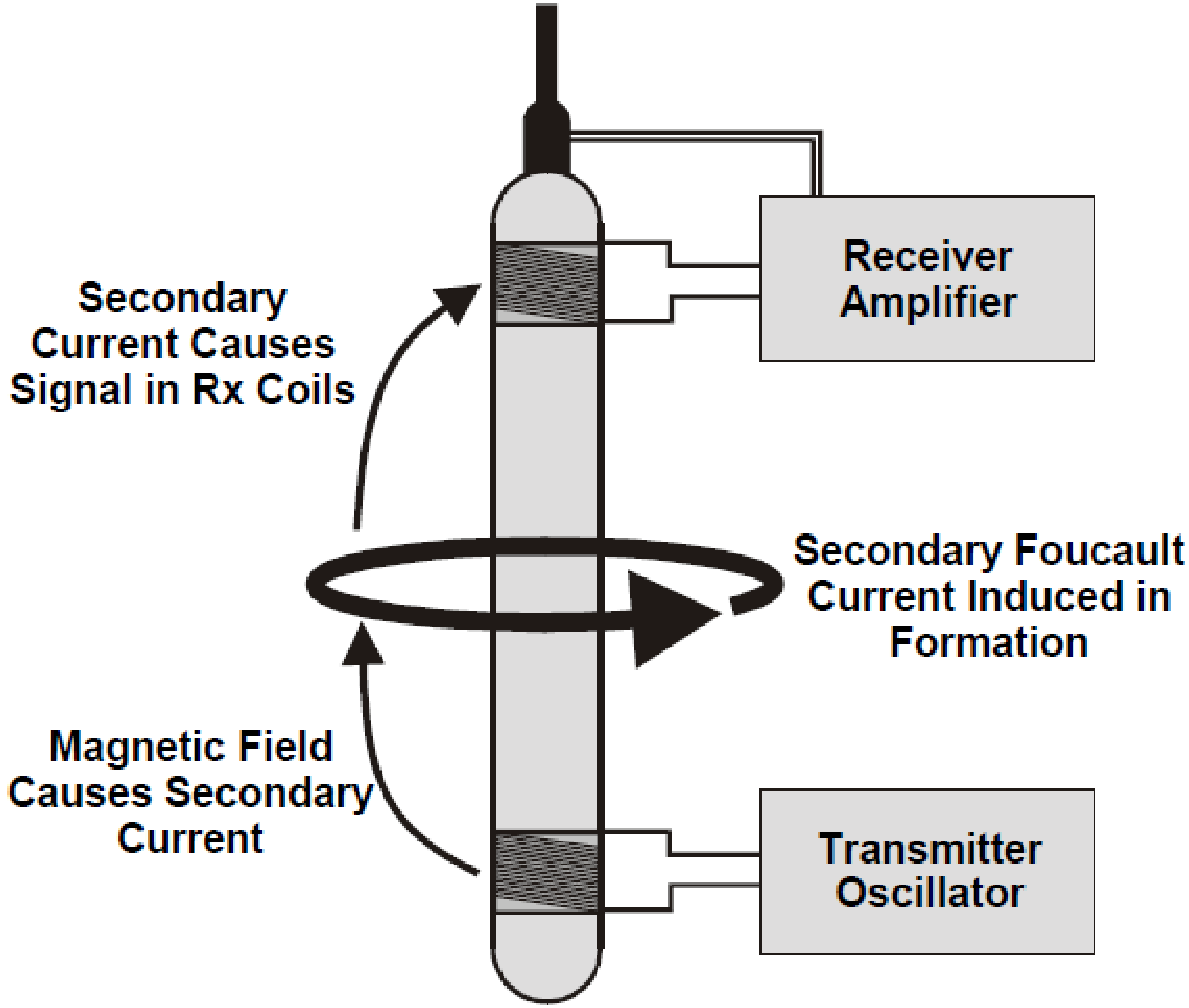
The LL3 and LL7 tool electrode configurations



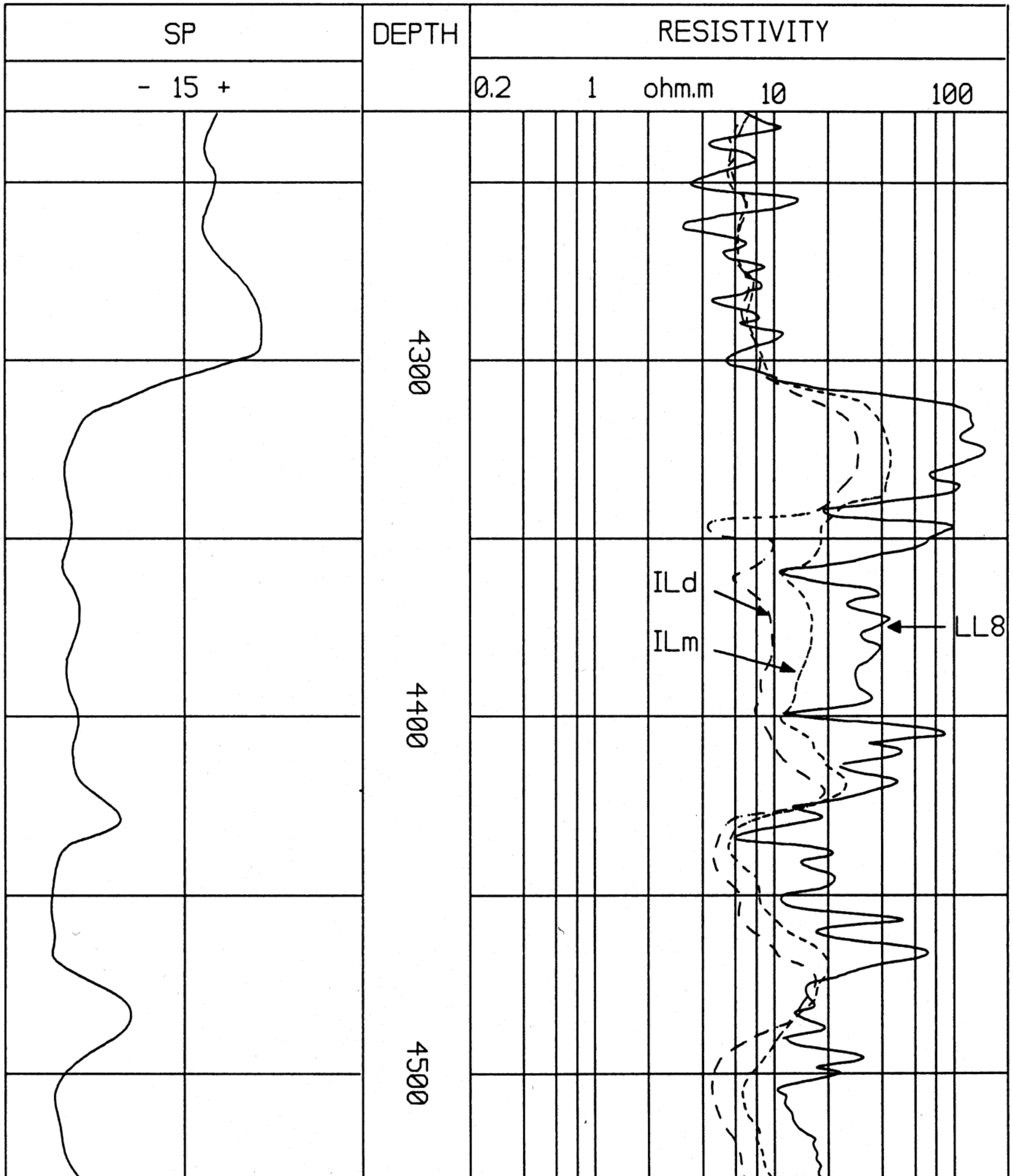
The DLL electrode configuration in both the LLd and LLs modes



Resistivity Log in Gas Zone

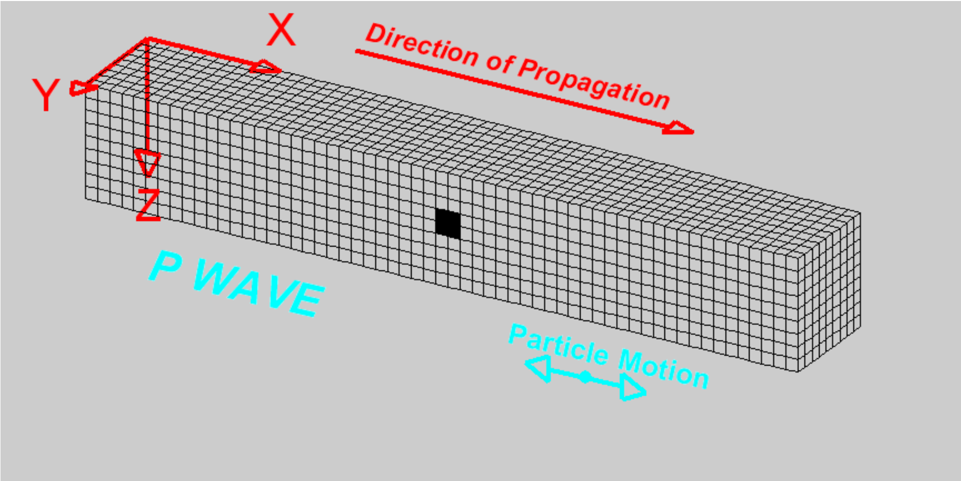


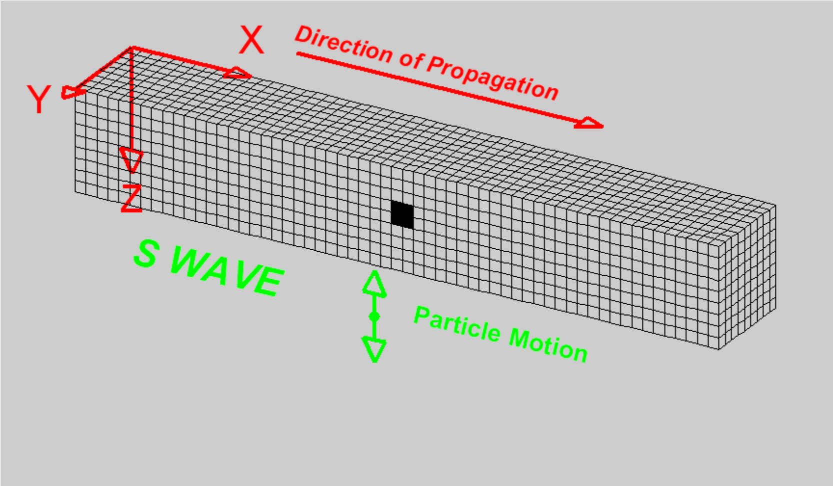
Induction Log


SP
- 15 +
DEPTH
4300
4400
4500
RESISTIVITY
0.2
1
ohm.m
10
100
ILd
ILm
LL8

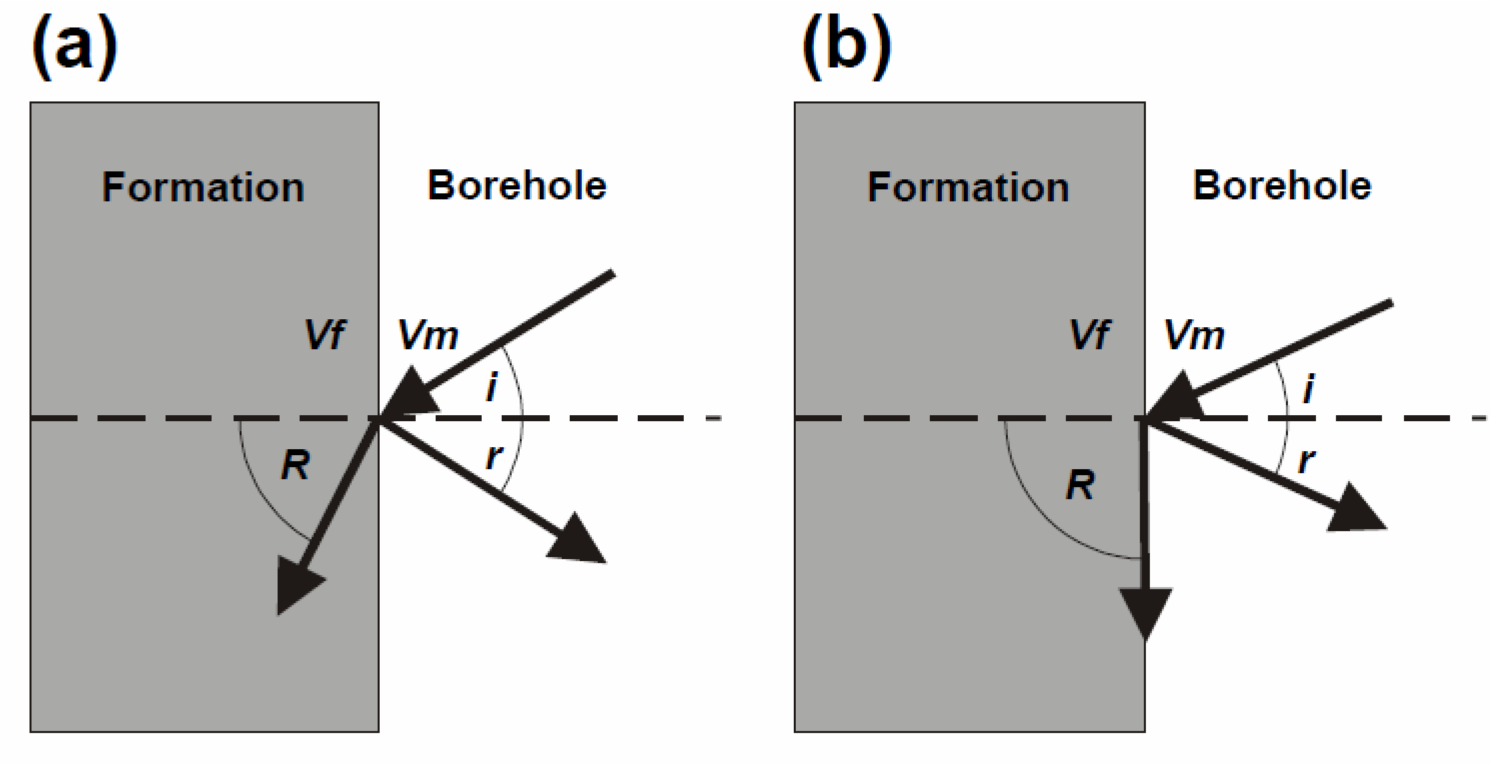
Sonic Log

P and S wave propagation

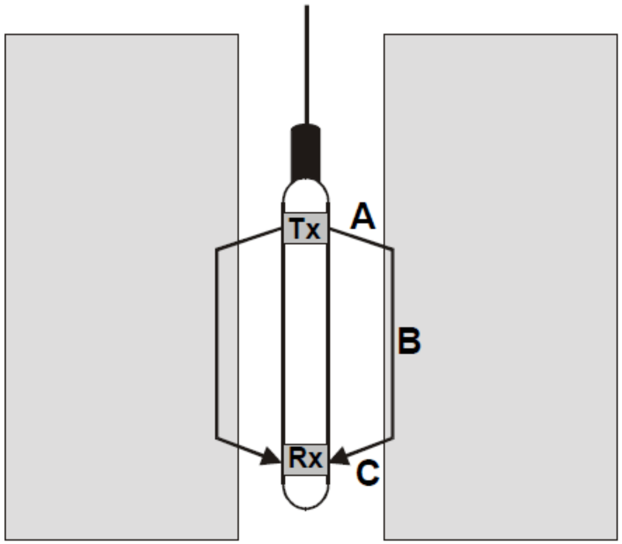




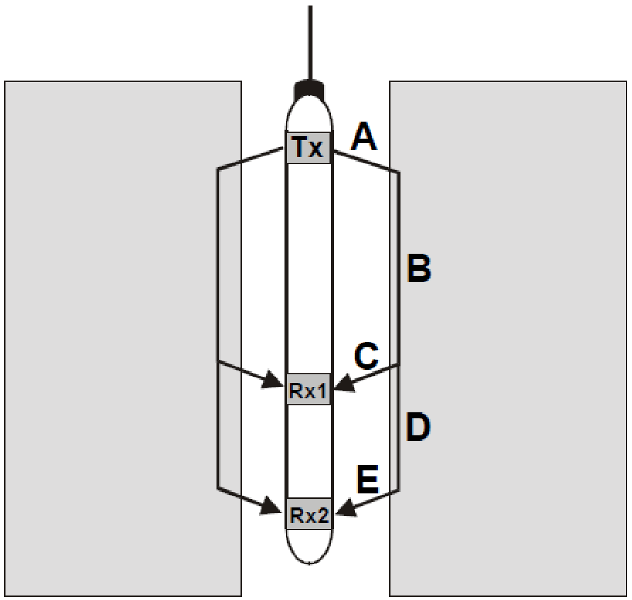
Reflection and Refraction



SONIC LOG CONFIGURATIONS

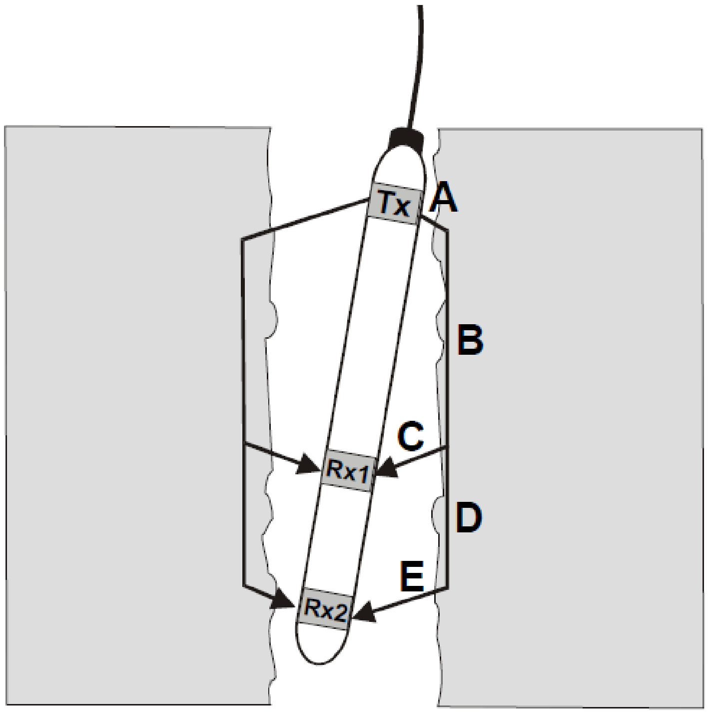


Early Sonic Tools

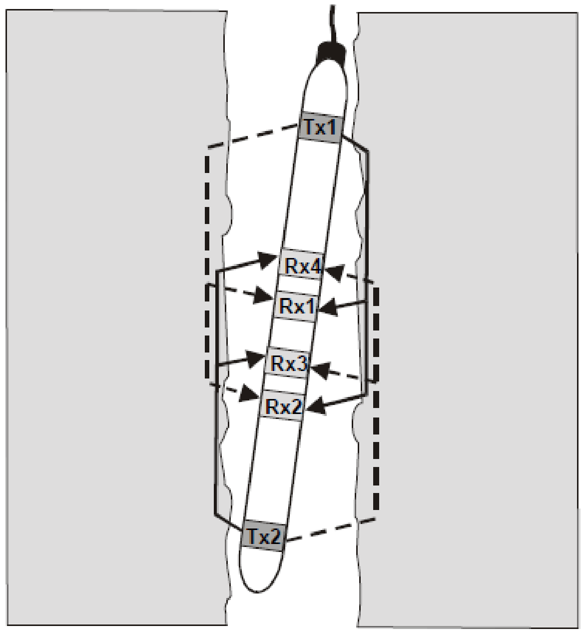


Dual Receiver Sonic Tools

SONIC LOG CONFIGURATIONS



Misalignment of the tool in the borehole



Borehole Compensated Tool

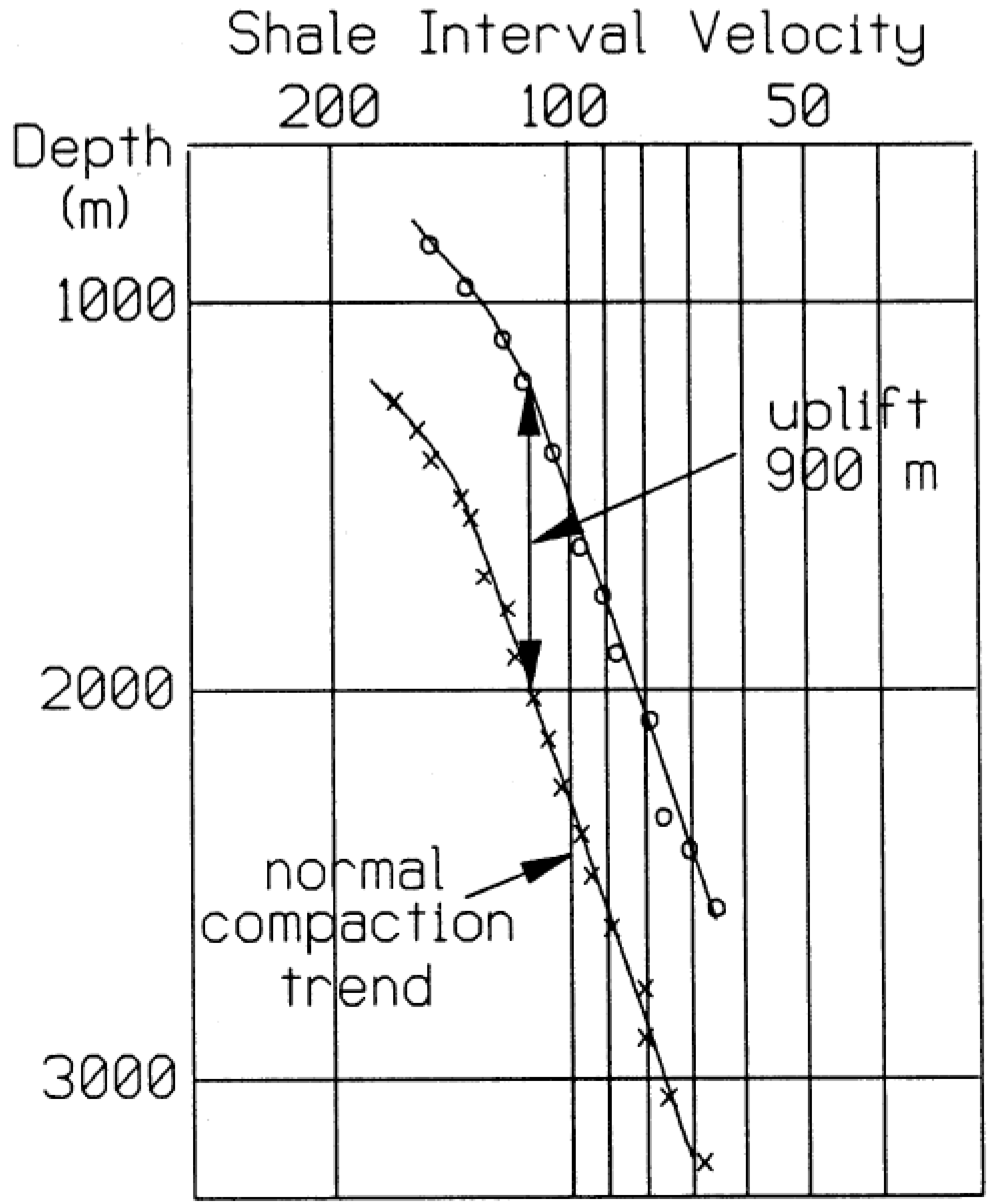
Sonic logging tools

Tool	Mnemonic	Company
Compensated sonic sonde	CSS	BPB
Long spaced compensated sonic	LCS	
Borehole compensated sonde	BCS	Halliburton
Long spaced sonic	LSS	
Borehole compensated sonic	BHC	Schlumberger
Long spaced sonic	LSS	
Array sonic (standard mode)	DTCO	
Borehole compensated acoustilog	AC	Western Atlas
Long-spaced BHC acoustilog	ACL	

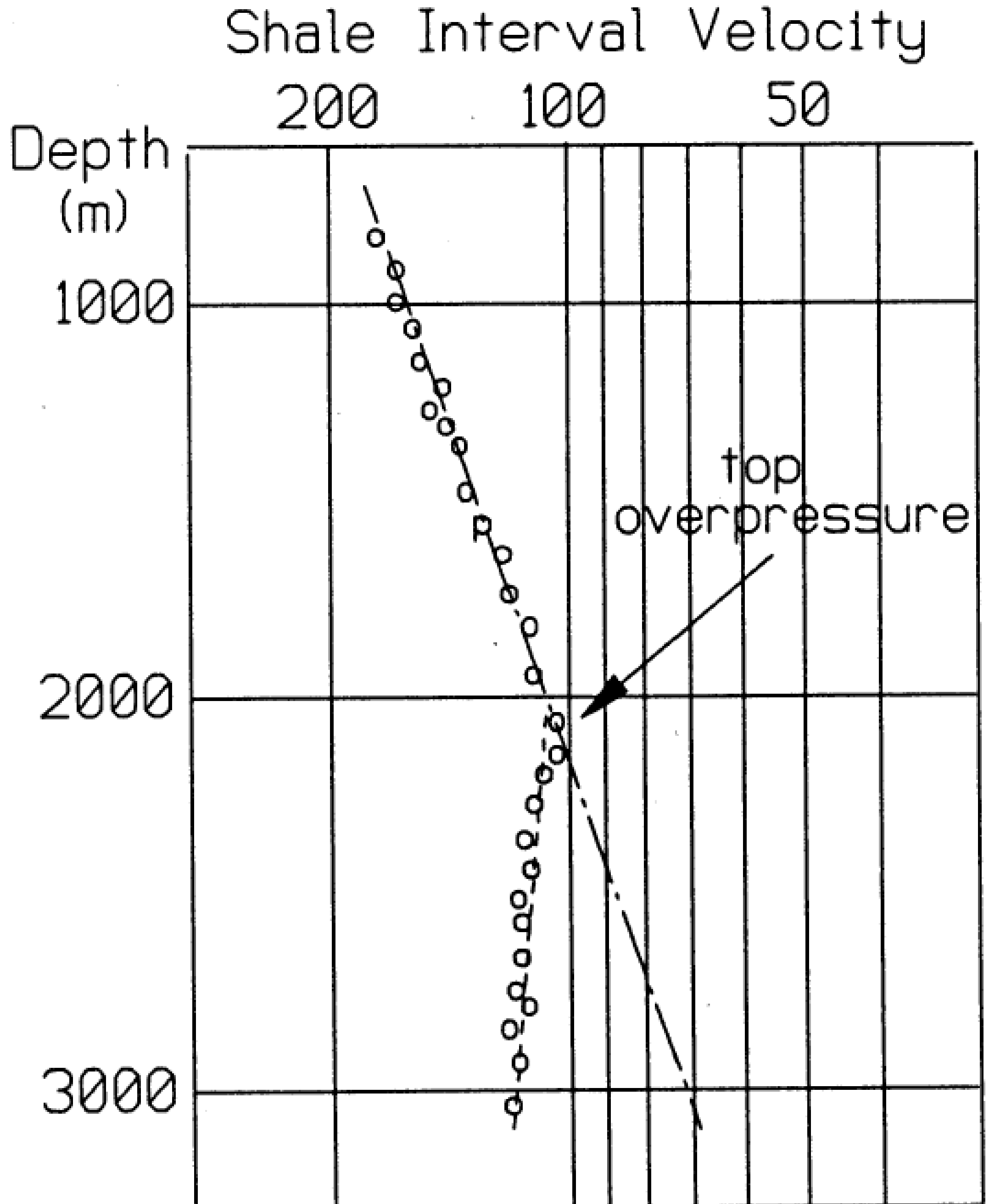
Callibration

- The data is presented as a *slowness* or the travel time per foot traveled through the formation, which is called *delta t* (Dt or DT), and is usually measured in µs/ft.

- The tool is calibrated inside the borehole opposite beds of pure and known lithology, such as anhydrite (50.0 µs/ft.), salt (66.7 µs/ft.), or inside the casing (57.1 µs/ft.).



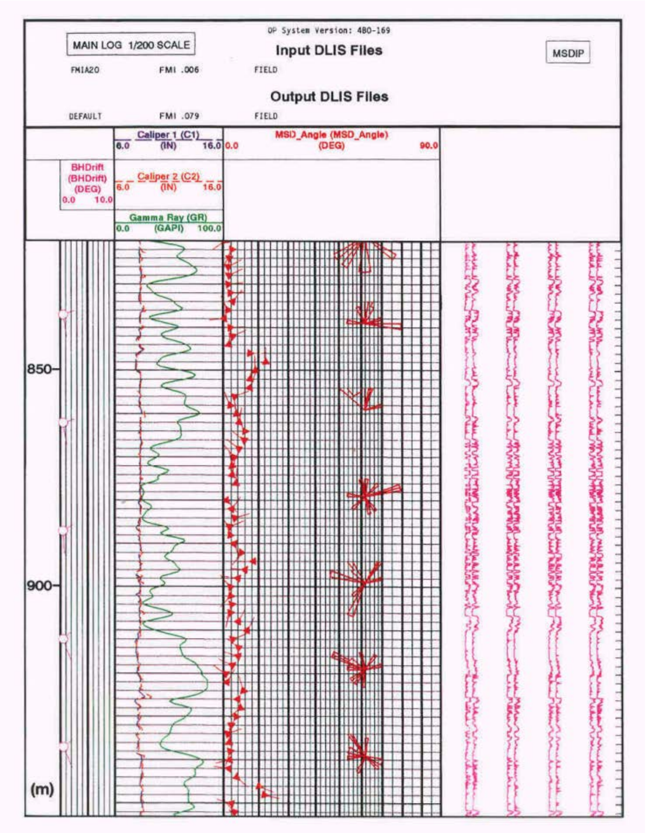
Shale Interval Velocity
200
100
50
Depth
(m)
1000
2000
3000
uplift
900 m
normal
compaction
trend

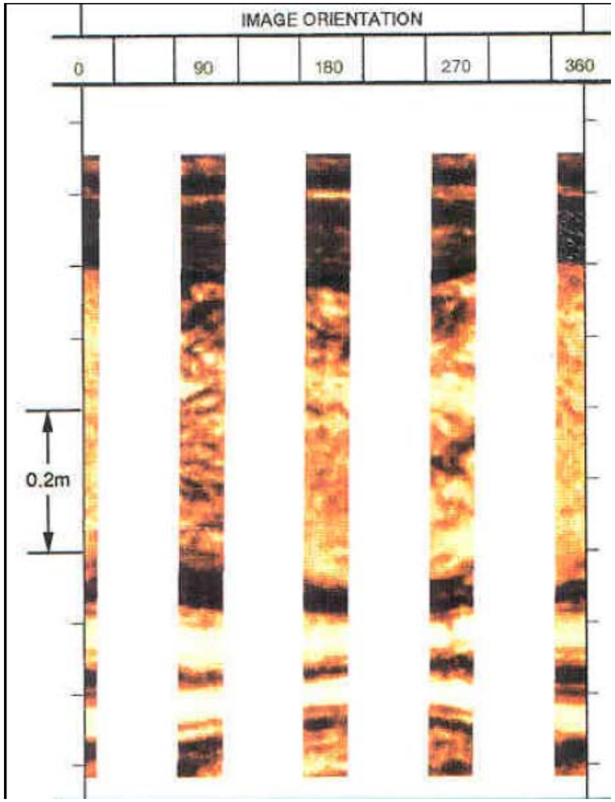


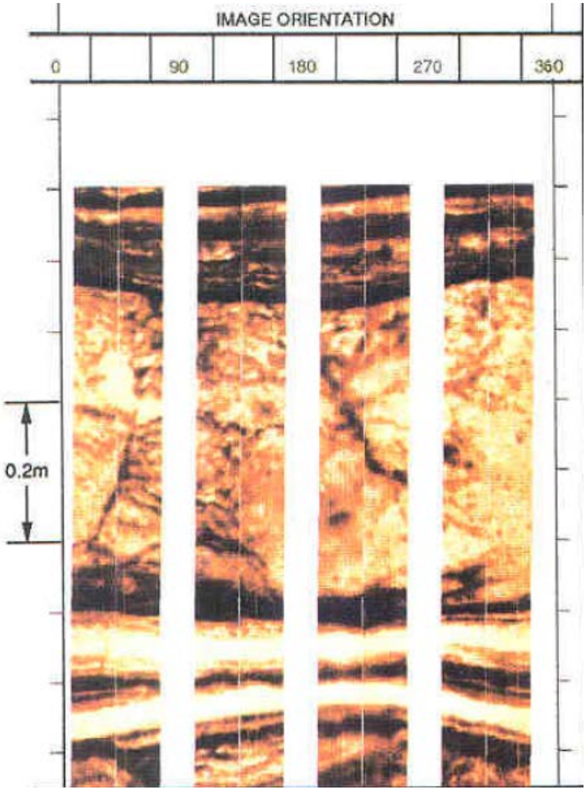
Shale Interval Velocity
200
100
50
Depth (m)
1000
2000
3000
top overpressure

Image logs

Image Logs





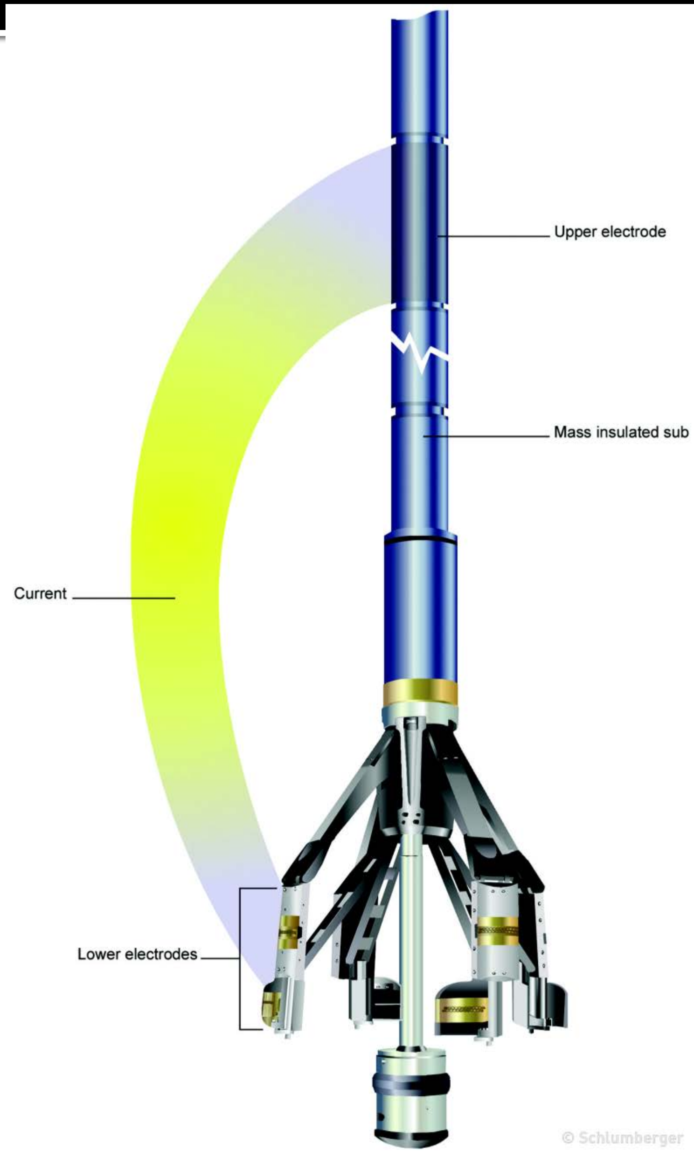


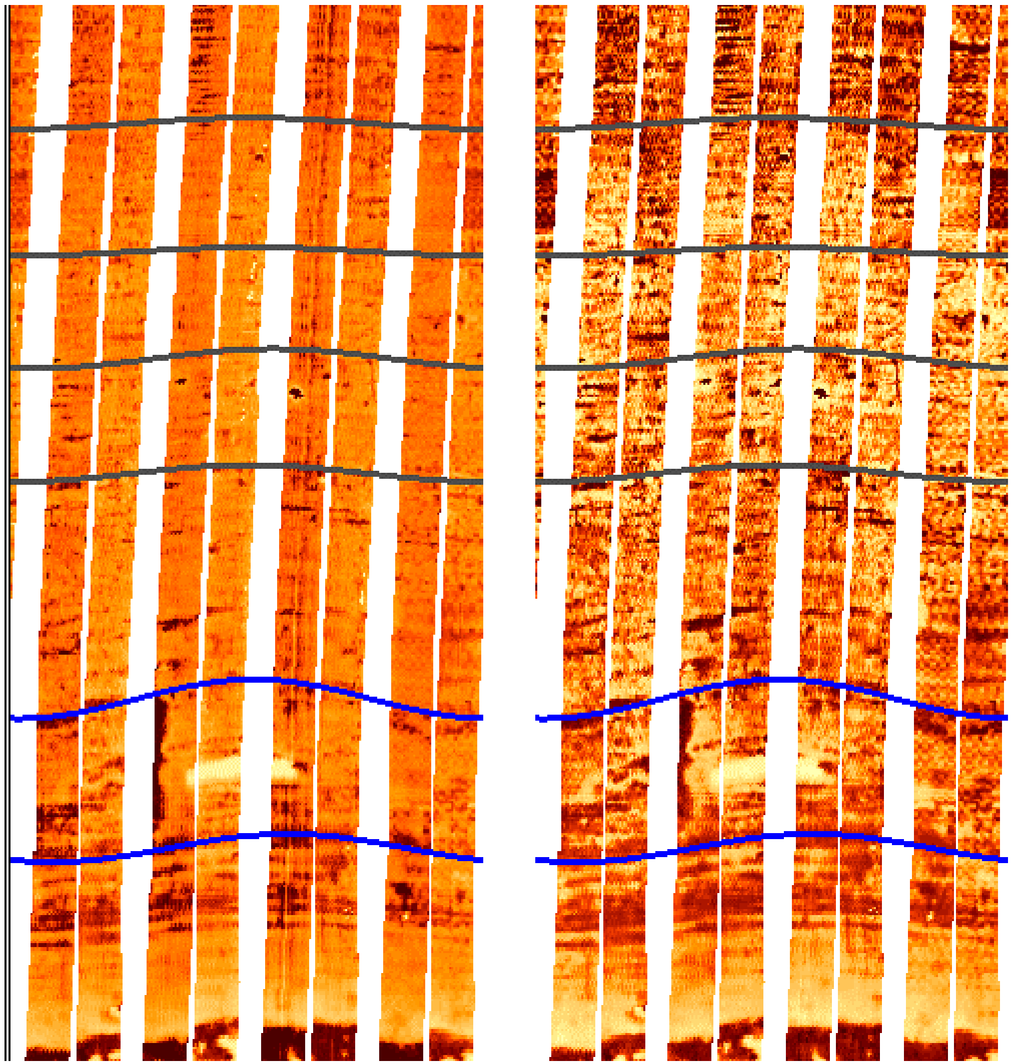
SHDT
8 Sensors

FMS
64 sensors

FMI
192 sensors

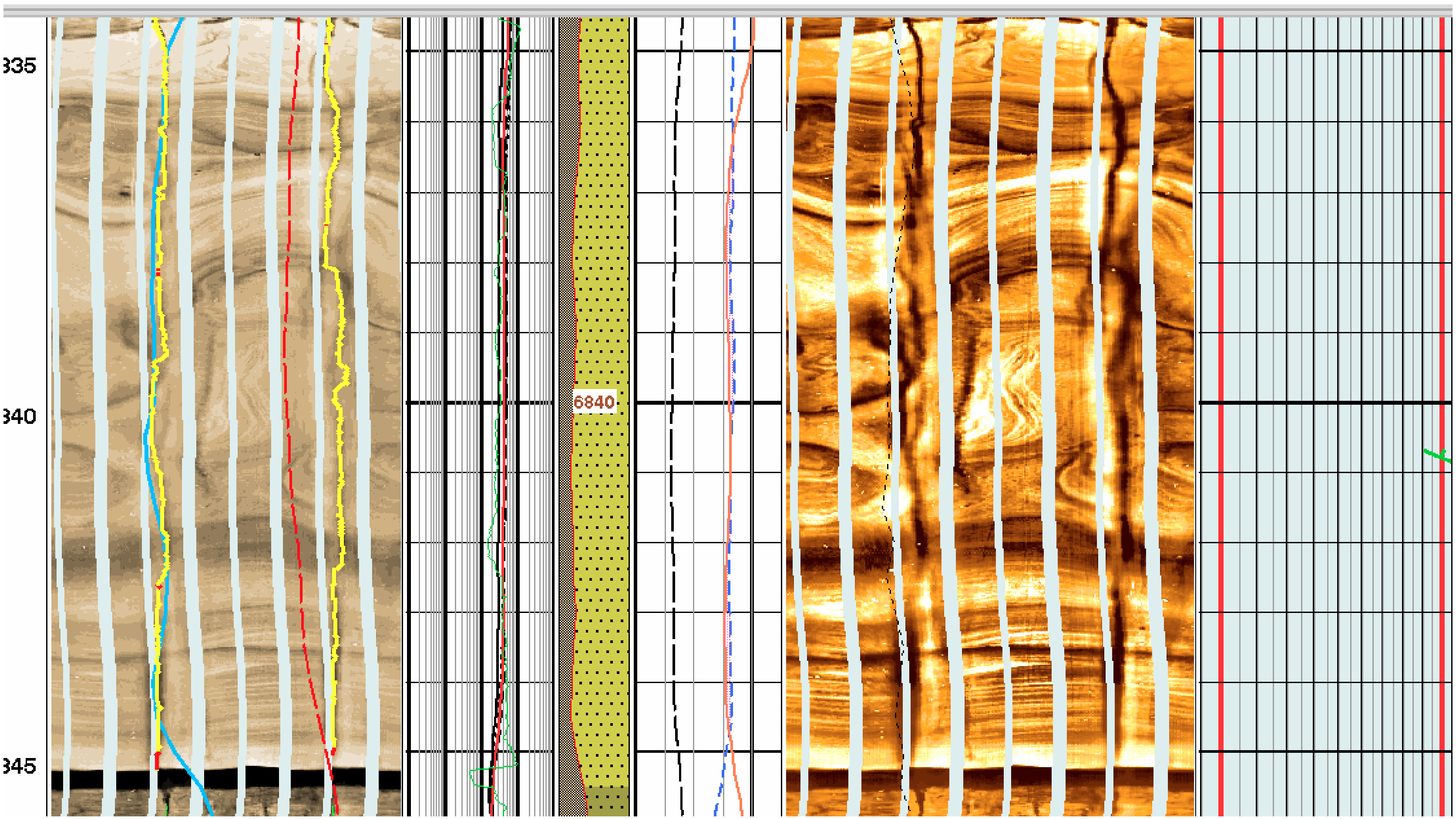
FMI Tool





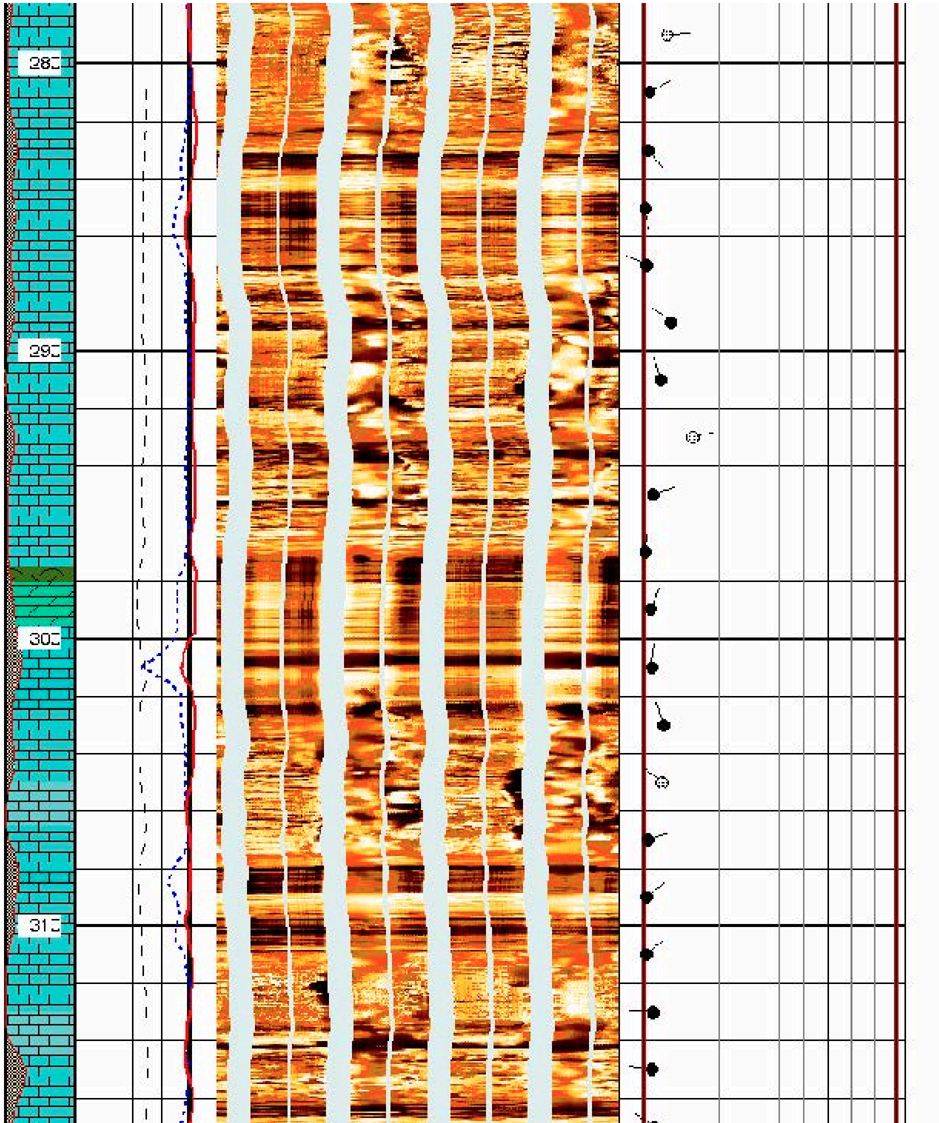
Courtesy : Schlumberger

Drilling Induced Fractures



Courtesy : Schlumberger

Borehole Breakouts

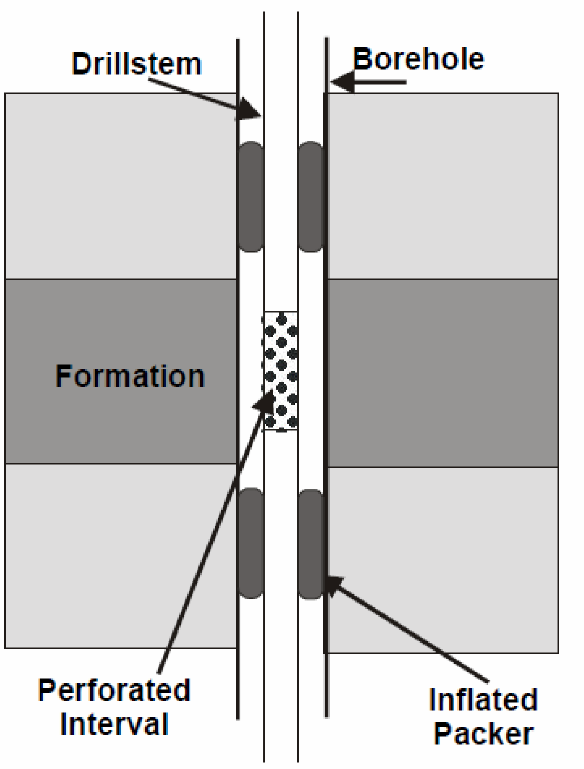


Borehole Image Tools

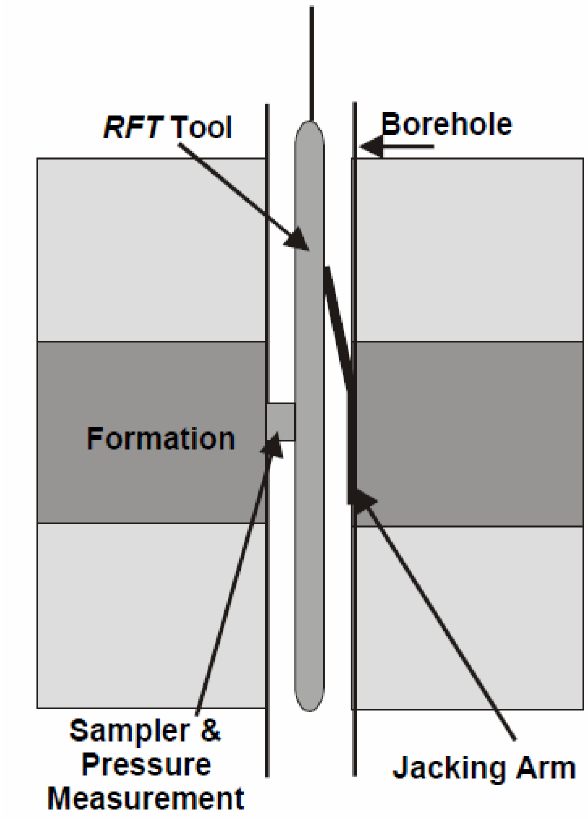
- Resistivity based: FMI / FMS / EMI / STAR
- Acoustic based: CBIL / UBI / CAST / AST

Pressure Tools

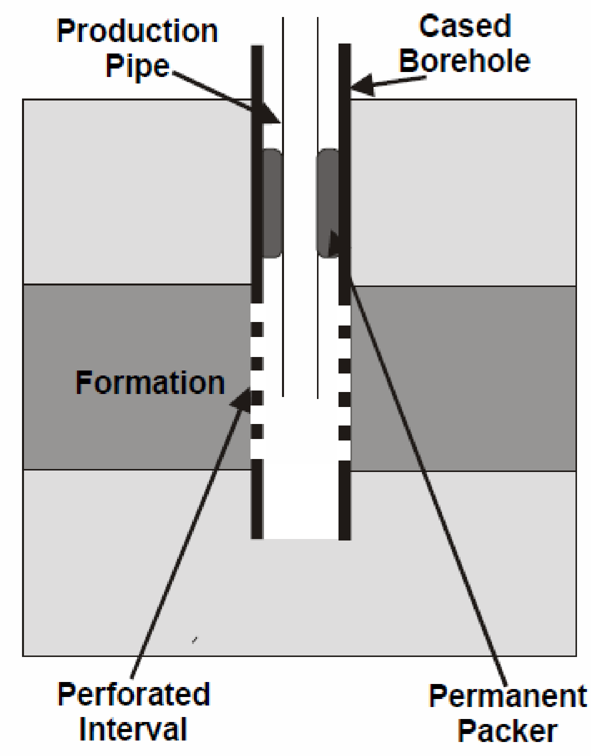
Three generic types of test



Drill Stem Testing

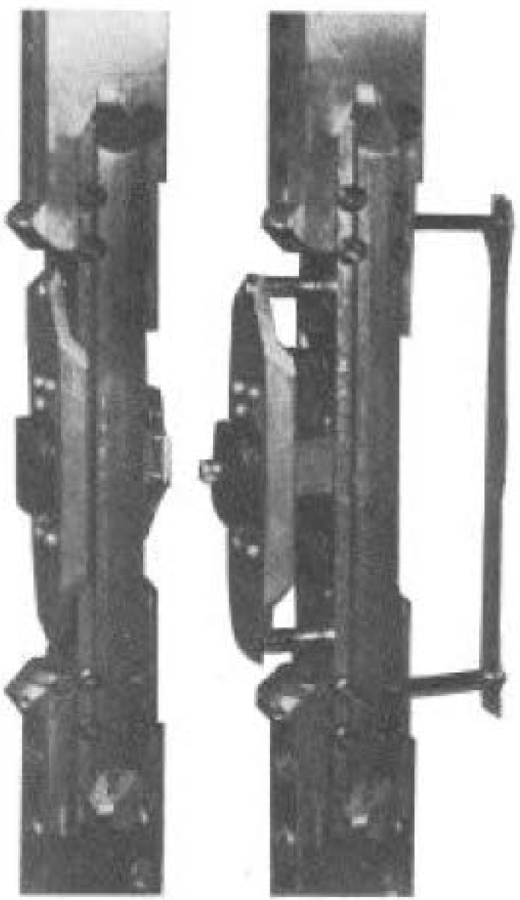


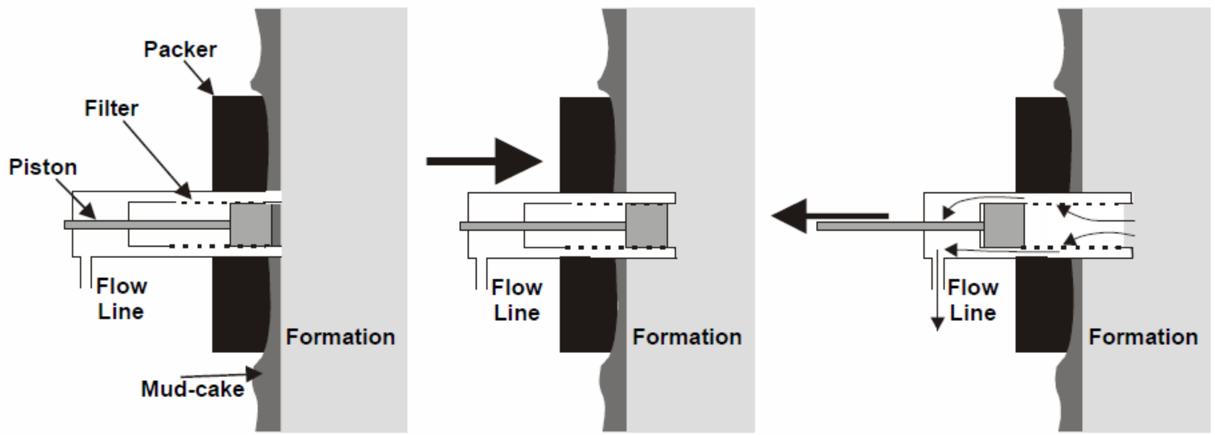
Wireline Formation Testing



Production Testing

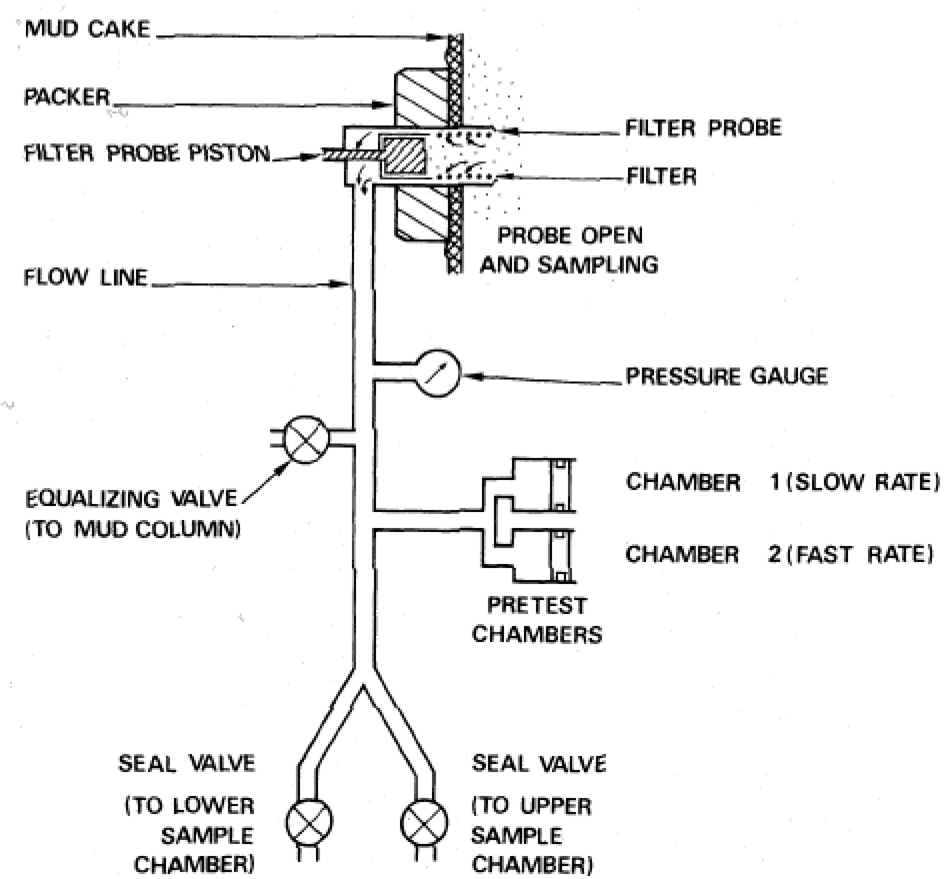
RFT Tool



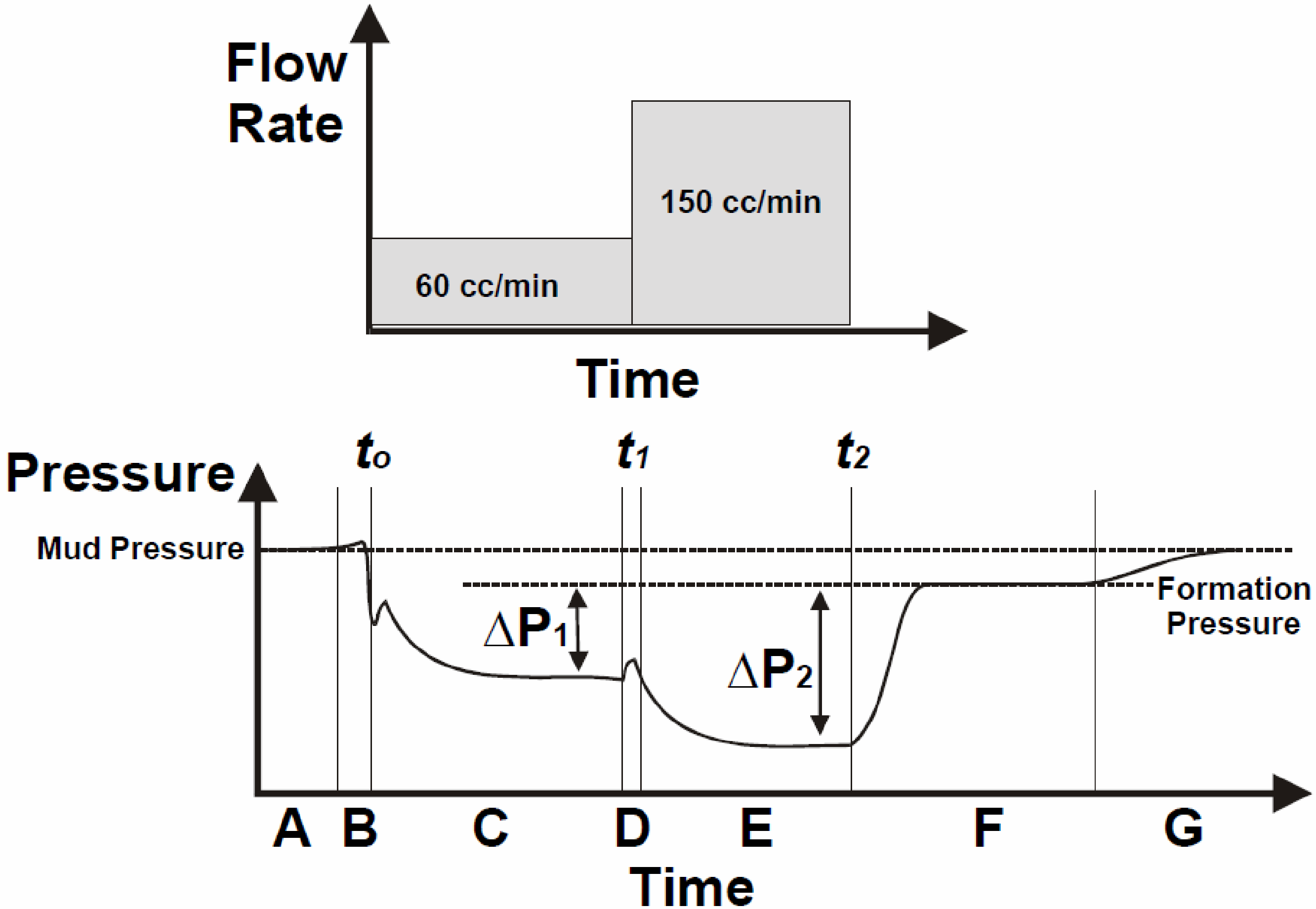


Courtesy of Schlumberger

RFT Tool

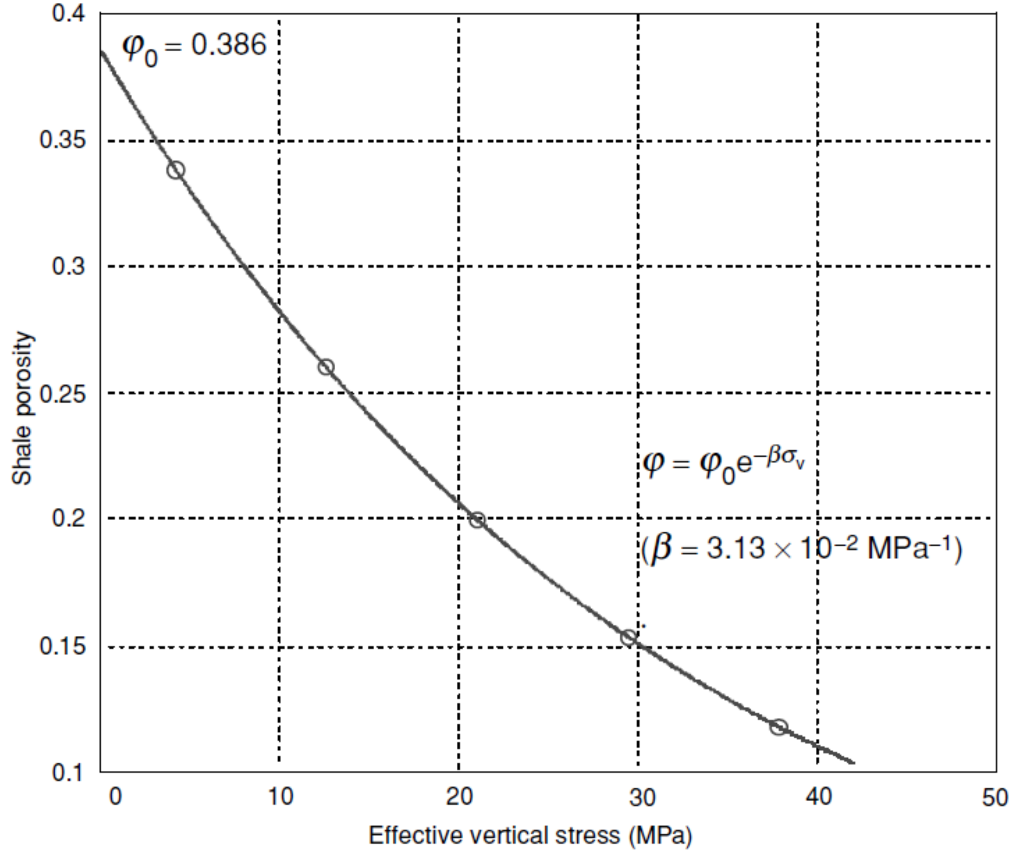

MUD CAKE
PACKER
FILTER PROBE PISTON
FILTER PROBE
FILTER
PROBE OPEN
AND SAMPLING
FLOW LINE
PRESSURE GAUGE
EQUALIZING VALVE
(TO MUD COLUMN)
CHAMBER 1 (SLOW RATE)
CHAMBER 2 (FAST RATE)
PRETEST
CHAMBERS
SEAL VALVE
(TO LOWER
SAMPLE
CHAMBER)
SEAL VALVE
(TO UPPER
SAMPLE
CHAMBER)

RFT Pressure Data



Pore Pressure and Fracture Gradient

Normal Compaction Trend



Normal Compaction Trend

$$R_n = R_0 \exp(bz)$$

R_o is shale resistivity at mudline

$$\Delta T_n = \Delta T_m + (\Delta T_{ml} - \Delta T_m)\exp(-cz)$$

ΔT_m is for shale matrix
ΔT_{ml} is for mudline

Pore Pressure Estimation

Eaton's Method

- Using Resistivity Data

$$P_p = S - (S - P_{hydro})(R_{\log} / R_n)^{1.2}$$

- Using Sonic Data

$$P_p = S - (S - P_{hydro})(\Delta T_n / \Delta T_{\log})^3$$

Reservoir Pressure or Pore Pressure

- Pressure transient techniques, e.g., wireline formation tester
- MWD/LWD
- Drilling and mud-logging
- Completion engineering

Vertical (Overburden) Stress

- Bulk Density Wireling Log
- Gravity Meters
- Seismic Velocity Analysis
- Rule of Thumb

Vertical Stress Calculation

$$\sigma_{Vertical} = \int \rho(z) g dz = \bar{\rho} g z$$

Water Depth Consideration:

$$\sigma_{Vertical} = \rho_w g z_w + \int \rho(z) g dz = \bar{\rho} g z$$

Effective Horizontal Compressive Stress

$$\sigma_h = \frac{\nu}{1-\nu}(\sigma_v - \beta P_0) + \beta P_0$$

Example

- For an oil field in the south of Texas, USA, where a vertical well is drilled to a maximum depth of 10,000 ft, the average specific gravity and pore pressure gradient are given as 2.3 and 0.38 psi/ft, respectively. Assuming the Biot's constant and Poisson's ratio as 1 and 0.28, respectively, calculate the overburden and horizontal in-situ stresses for the surrounding rock formation at the bottom of the vertical well.

Methods of measuring or estimating in-situ stresses

Measurement Element	Type of Stress	Measurement Technique	Estimation Technique
Stress Magnitude	σ_v	• Density Log	
	σ_H		• Breakout • Mud Weight • Observation of Wellbore Failure
	σ_h	• Hydraulic Fracturing	• Leak-off (LOT) Test • Formation Integrity Test • Lost Circulation • Drilling Induced Fracs
Stress Orientation	σ_H or σ_h	• Cross Dipole • Mini-frac • Hydraulic Fracture Test • Drilling Induced Fracs • Breakout	• Fault Direction • Natural Frac Direction
Formation Pore Pressure	P_o	• Drillstem Test (DST) • Repeat Formation Test • Modular Formation Dynamics Test • Logging While Drilling (LWD) • Measured Direct Tests (MDT)	• Density Log • Sonic Log • Seismic Velocity • Mud Weight Used

Maximum Allowable Mud Weight from LOT data

- ppg = (leak off pressure, psi) ÷ 0.052 ÷ (Casing shoe. TVD (ft))÷ Mud Weight (ppg)

e.g. LOT pressure = 1140 psi
Casing shoe TVD = 4000 ft
Mud weight = 10.0 ppg

ppg = 15.48

Fracture Gradient

- Hubbert and Willis Method

$$G_f = \tfrac{1}{3}\left(\frac{\sigma_v}{d} + 2\frac{P_0}{d}\right)$$

  - G_f is the formation fracture gradient (psi/ft) representing minimum calculated value
  - σ_v is in psi and depth of formation *d* is in ft

$$G_f = \tfrac{1}{2}\left(\frac{\sigma_v}{d} + \frac{P_0}{d}\right)$$

  - Maximum fracture gradient
  - Predicts higher gradient in abnormal pressure and lower pressure gradient in subnormal formation

Fracture Gradient

Matthews and Kelly method

$$G_f = f_e\left(\frac{\sigma_v}{d} - \frac{P_0}{d}\right) + \frac{P_0}{d}$$

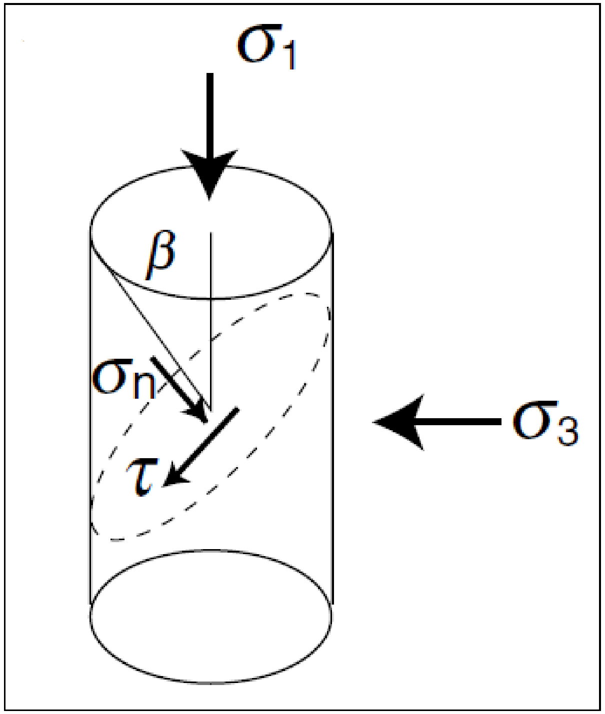
f_e is effective stress coefficient and is found from the actual fracture data of a nearby well

Fracture Gradient

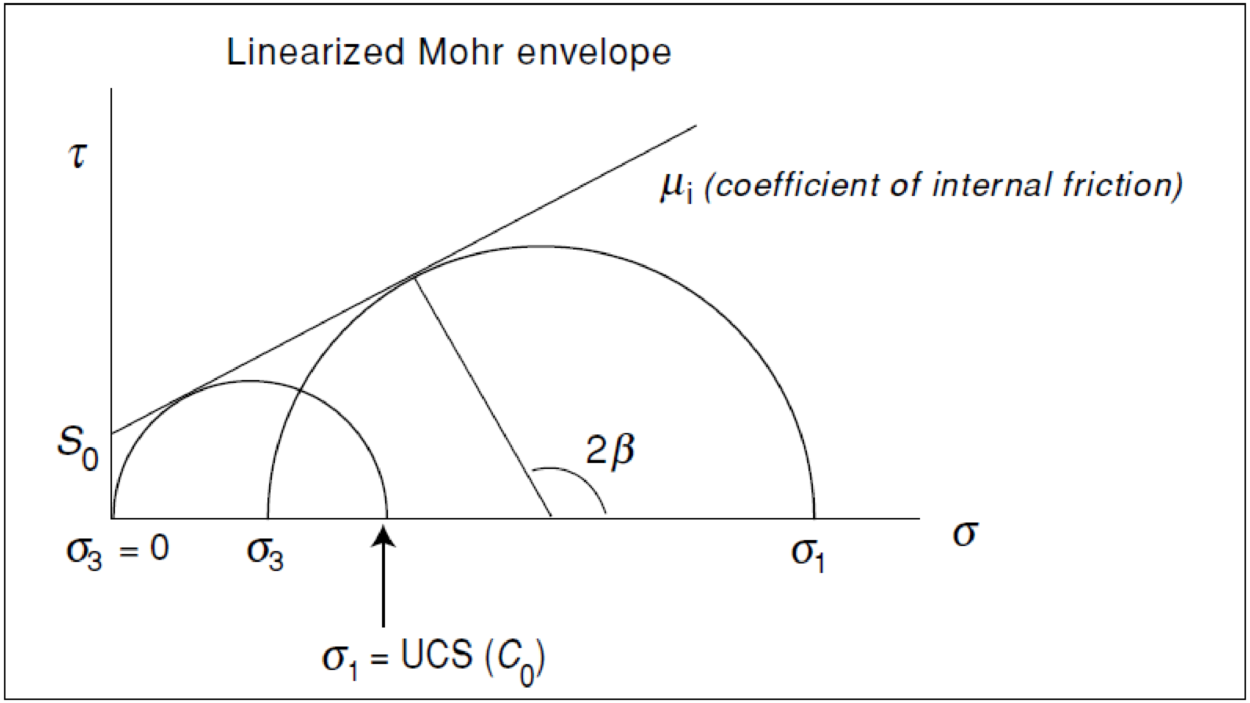
Eaton Method

$$G_f = \left(\frac{\nu}{1-\nu}\right)\left(\frac{\sigma_v}{d} - \frac{P_0}{d}\right) + \frac{P_0}{d}$$

Mohr Circle

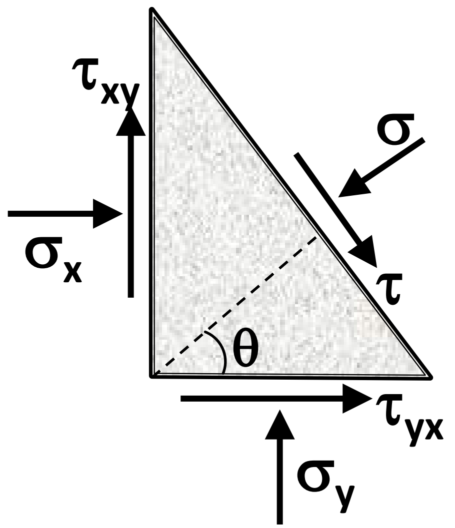


σ1
β
σn
τ
σ3



Linearized Mohr envelope
τ
μi (coefficient of internal friction)
S0
2β
σ3 = 0
σ3
σ1
σ
σ1 = UCS (C0)

Normal and Shear Stress



$$\sigma = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + \sigma_z \sin\theta\cos\theta$$

$$= \frac{1}{2}(\sigma_x + \sigma_y) + \frac{1}{2}(\sigma_x - \sigma_y)\cos 2\theta + \tau_{xy}\sin 2\theta$$

$$\tau = \sigma_y \sin\theta\cos\theta - \sigma_x \sin\theta\cos\theta + \tau_{xy}\cos\theta\cos\theta - \tau_{yx}\sin\theta\sin\theta$$

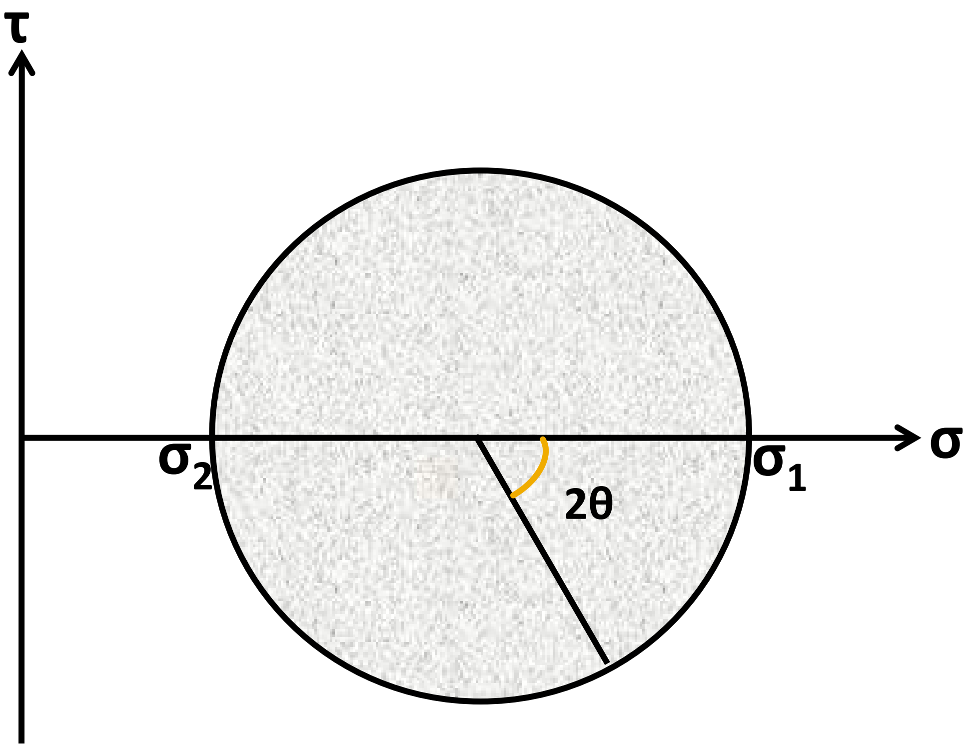
$$= \frac{1}{2}(\sigma_y - \sigma_x)\sin 2\theta + \tau_{xy}\cos 2\theta$$

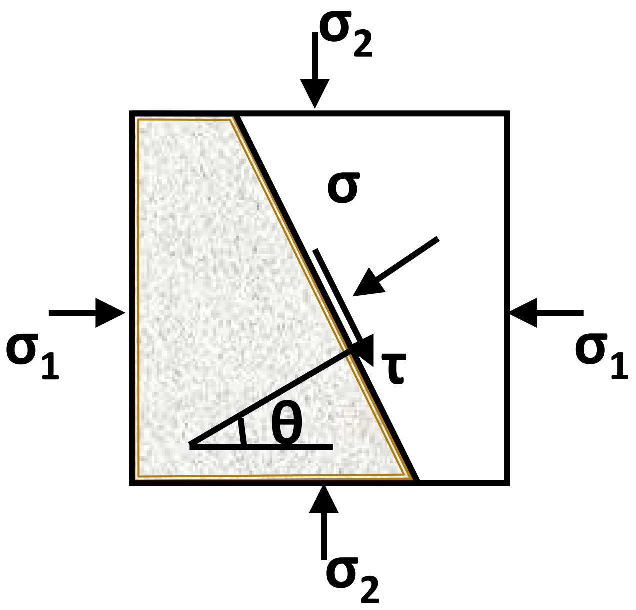
$$\sigma_1 = \frac{1}{2}(\sigma_x + \sigma_y) + \sqrt{\tau_{xy}^2 + \frac{1}{4}(\sigma_x + \sigma_y)^2}$$

$$\sigma_2 = \frac{1}{2}(\sigma_x + \sigma_y) - \sqrt{\tau_{xy}^2 + \frac{1}{4}(\sigma_x + \sigma_y)^2}$$

$$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_x - \sigma_y}$$

Mohr Circle

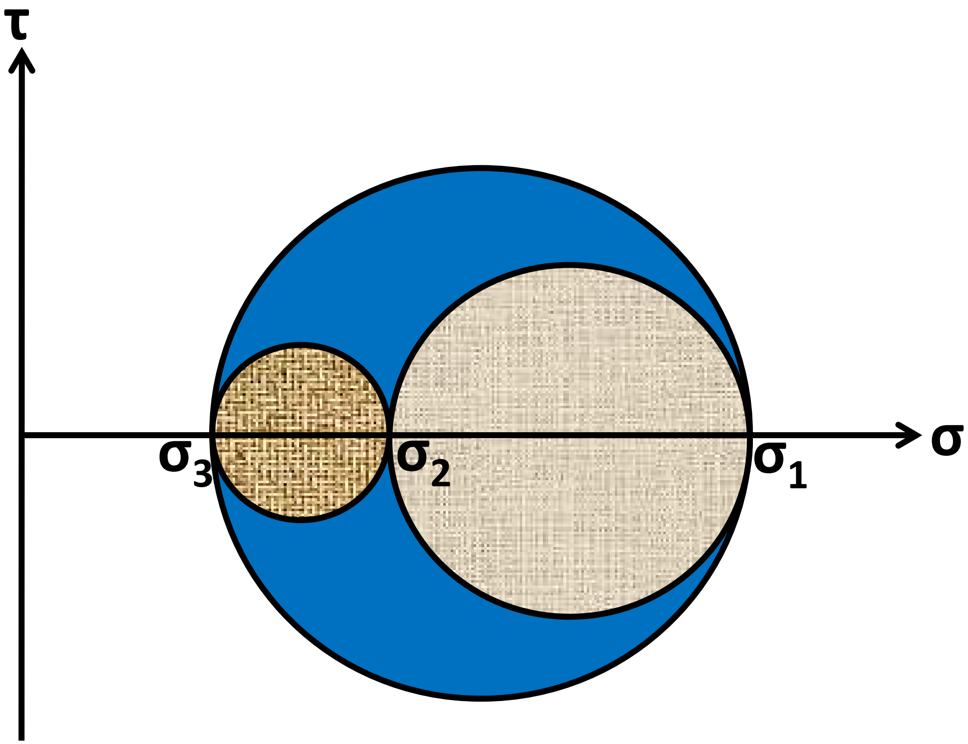




$$\sigma = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2)\cos 2\theta$$

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_2)\sin 2\theta$$

Mohr Circle in 3D



$$l_1^2\sigma_1 + l_2^2\sigma_2 + l_3^2\sigma_3 = \sigma$$

$$l_1^2\sigma_1^2 + l_2^2\sigma_2^2 + l_3^2\sigma_3^2 = \sigma^2 + \tau^2$$

Stress Invariants

$$\overline{\sigma} = (\sigma_x + \sigma_y + \sigma_z)/3$$

$$I_1 = \sigma_x + \sigma_y + \sigma_z$$

$$I_2 = -(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x) + \tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2$$

$$I_3 = \sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{xz} - \sigma_z\tau_{xy}^2 - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2$$

Deviatoric Stress

$$\begin{pmatrix} s_x & s_{xy} & s_{xz} \\ s_{xy} & s_y & s_{yz} \\ s_{xz} & s_{yz} & s_z \end{pmatrix} = \begin{pmatrix} \sigma_x - \bar{\sigma} & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y - \bar{\sigma} & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z - \bar{\sigma} \end{pmatrix}$$

$$J_1 = s_x + s_y + s_z = 0$$

$$J_2 = -(s_x s_y + s_y s_z + s_z s_x) + s_{xy}^2 + s_{yz}^2 + s_{xz}^2$$

$$J_3 = s_x s_y s_z + 2 s_{xy} s_{yz} s_{xz} - s_z s_{xy}^2 - s_x s_{yz}^2 - s_y s_{xz}^2$$

$$q = \sqrt{3J_2} = \sqrt{\frac{3}{2}\left[(\sigma_1 - \bar{\sigma})^2 + (\sigma_2 - \bar{\sigma})^2 + (\sigma_3 - \bar{\sigma})^2\right]}$$

$$r = \sqrt[3]{\frac{27 J_3}{2}} = \sqrt[3]{\frac{27}{2}(\sigma_1 - \bar{\sigma})(\sigma_2 - \bar{\sigma})(\sigma_3 - \bar{\sigma})}$$

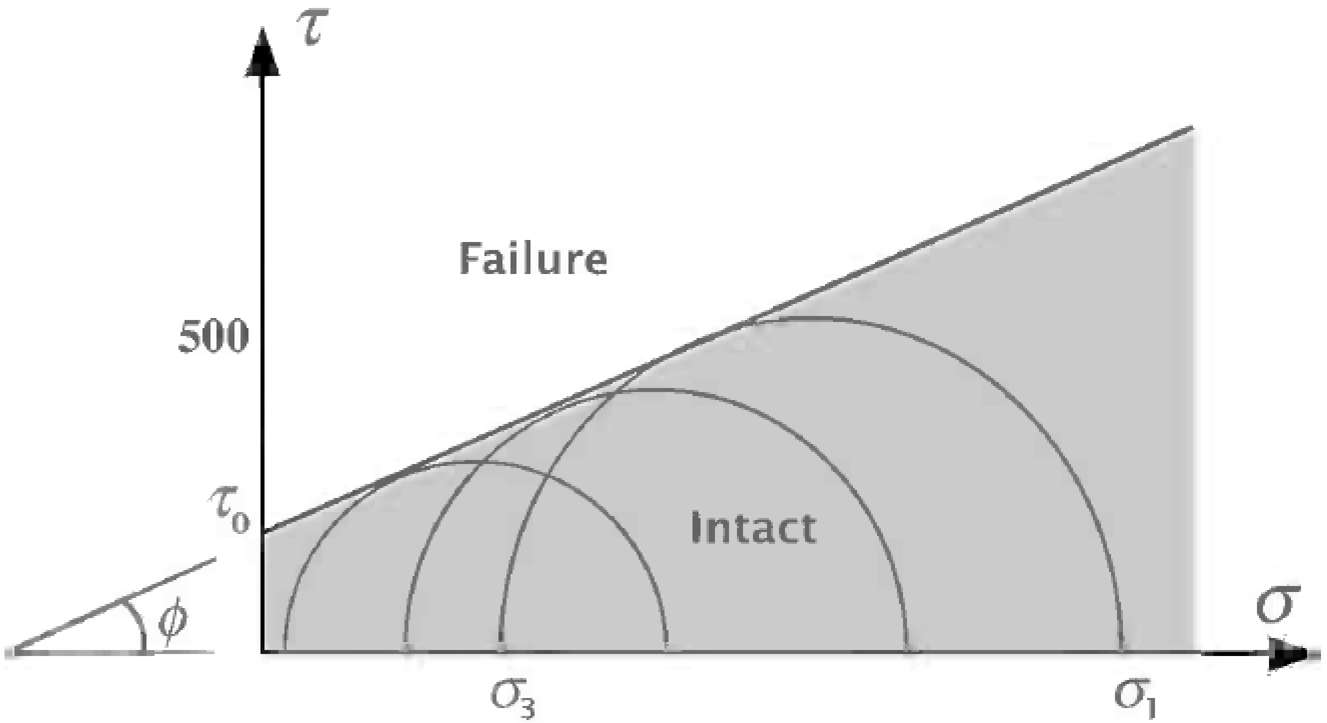
For stress condition

$$\sigma_2 = \sigma_3$$

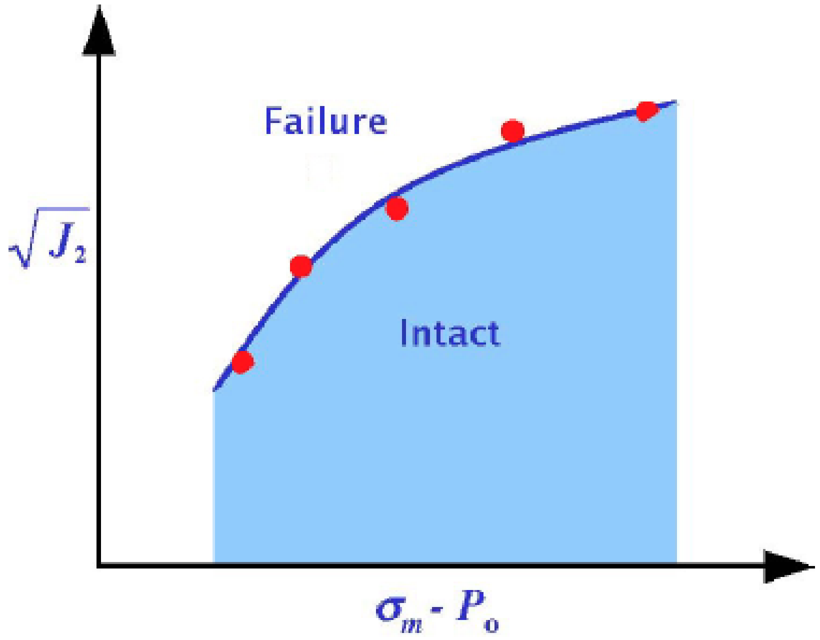
$$q = \left|\sigma_1 - \sigma_3\right|$$

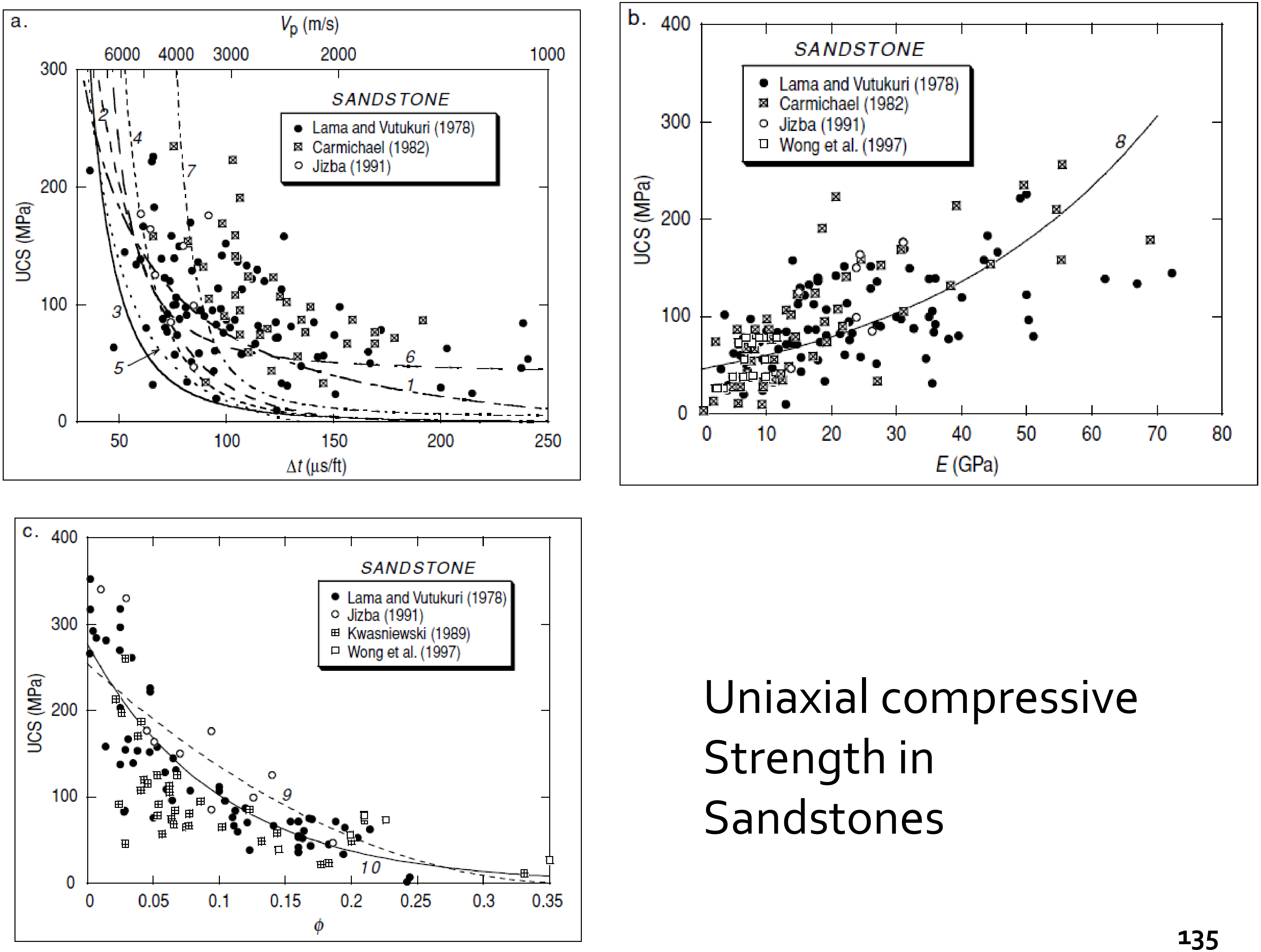
$$r = \sigma_1 - \sigma_3$$

Mohr – Coulomb Failure Criteria



Von Mises Failure criteria





Uniaxial compressive Strength in Sandstones

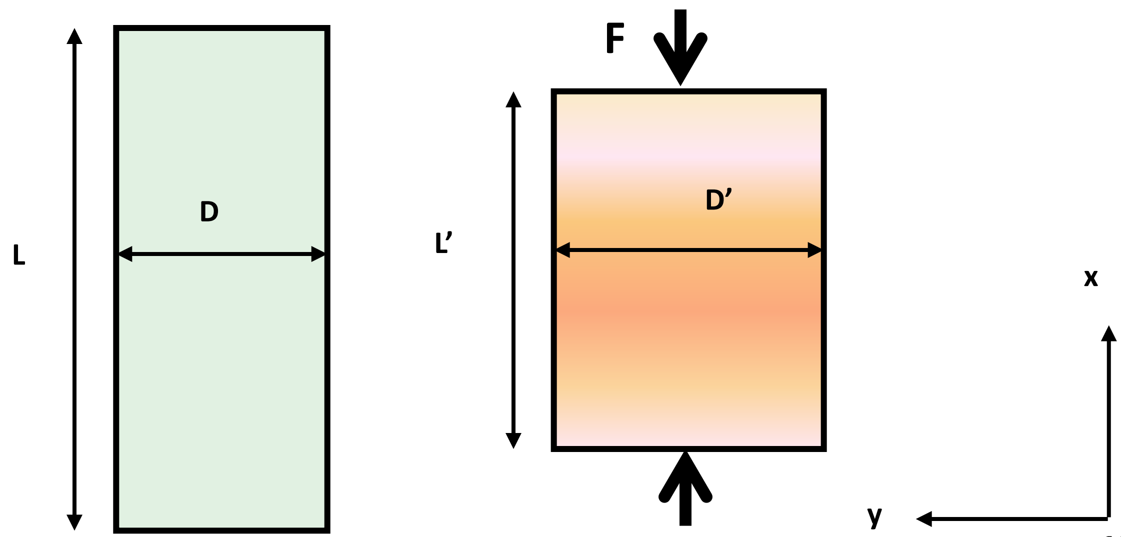
Stress-Strain Relationships

$$\varepsilon_x = \frac{1}{E}\sigma_x$$

E is called Young's modulus or simply the *E-modulus*

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x}$$

υ is called Poisson's ratio

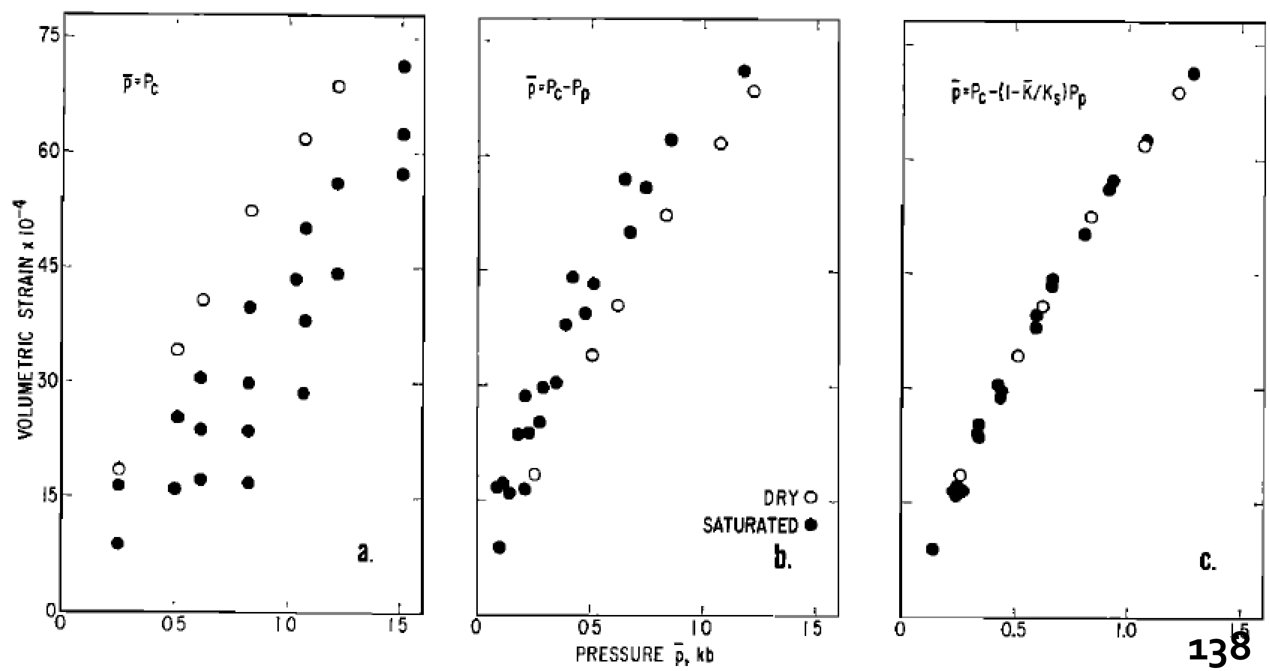


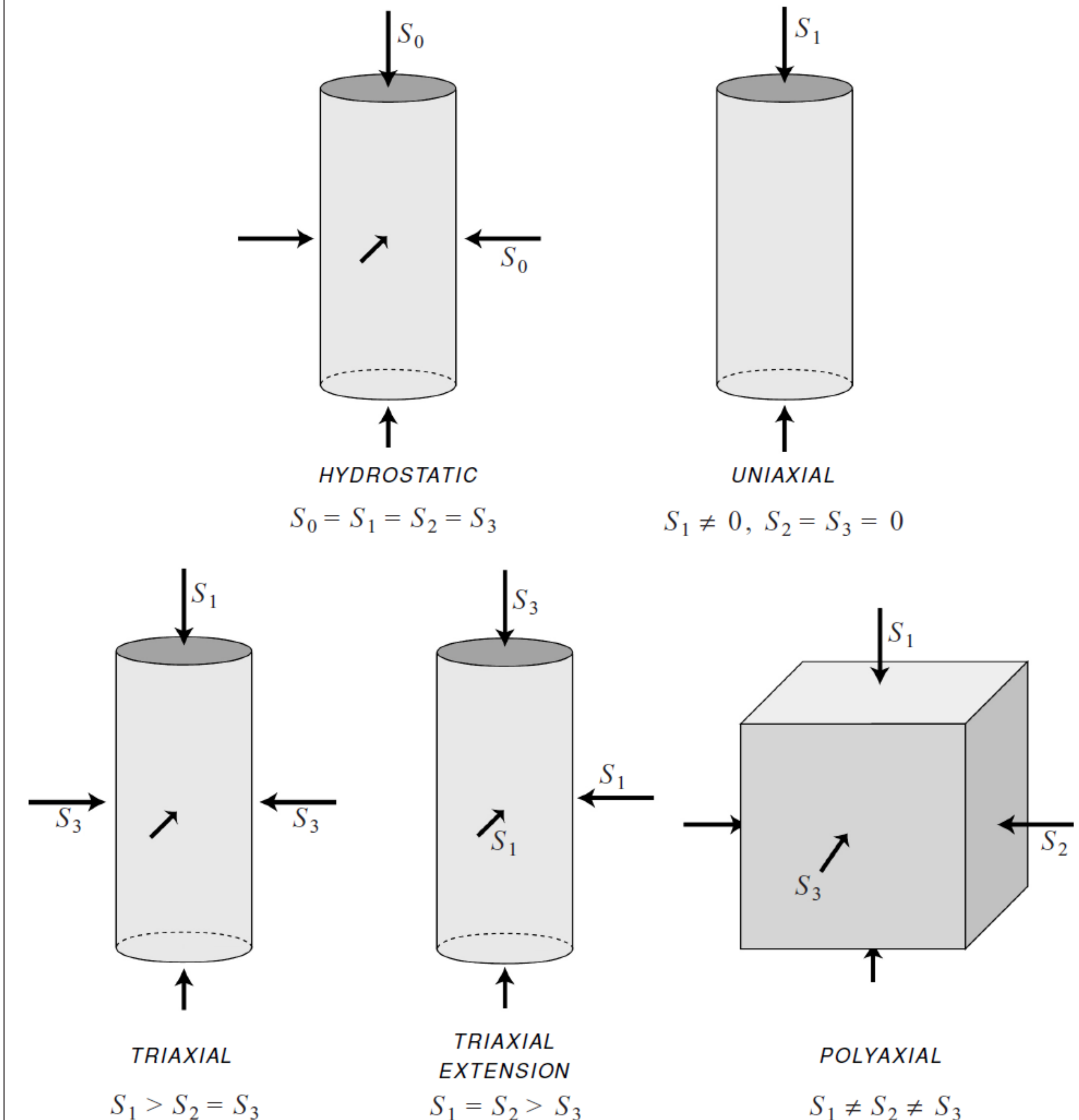
Poisson's Ratio

- Poisson's ratio is typically 0.15 – 0.25
- For weak, porous rocks ν may approach zero or even become negative
- For fluids, the rigidity vanishes; implies ν approaches ½
- For unconsolidated sand, ν is close to ½

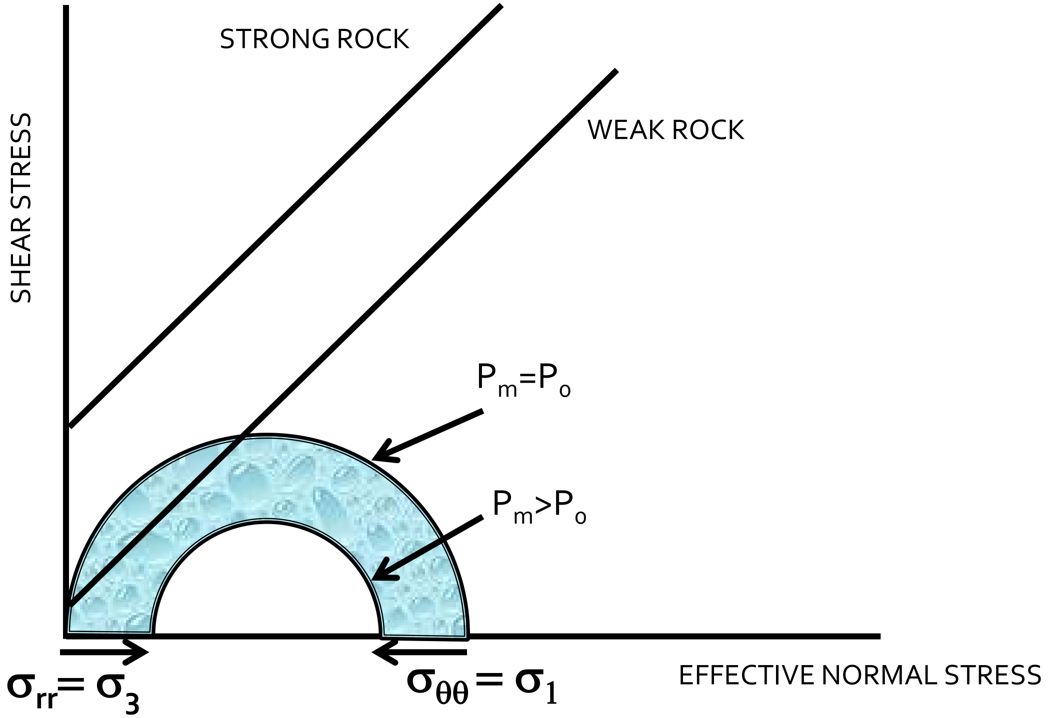
Poroelasticity

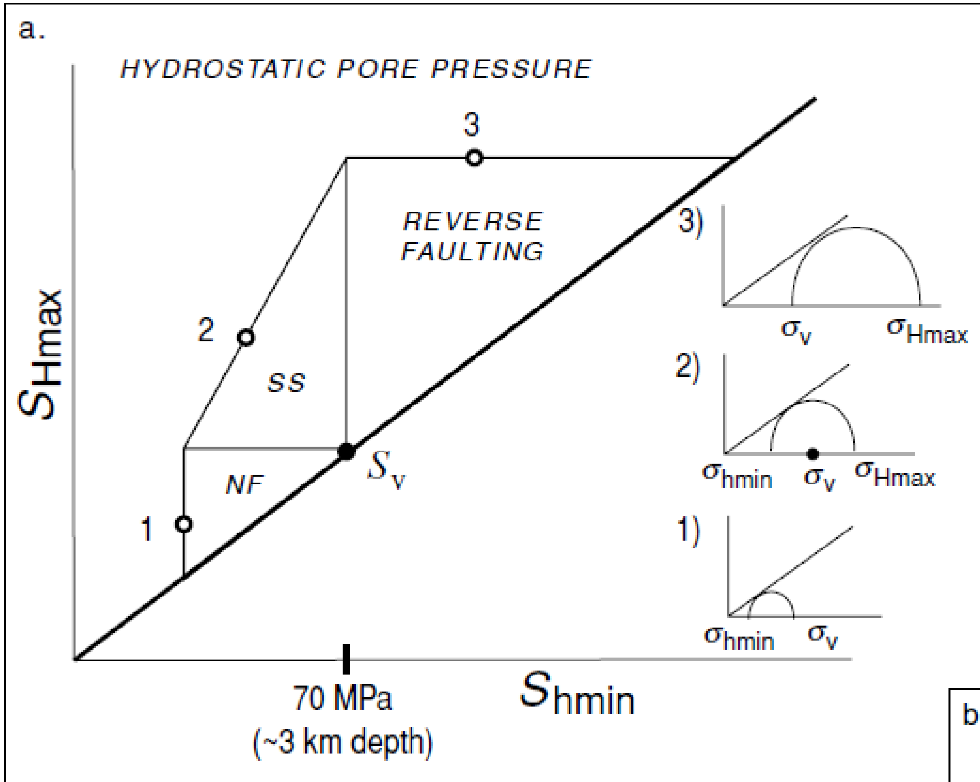
- Effective Stress
- Biot Coefficient
- Gassmann’s Equation

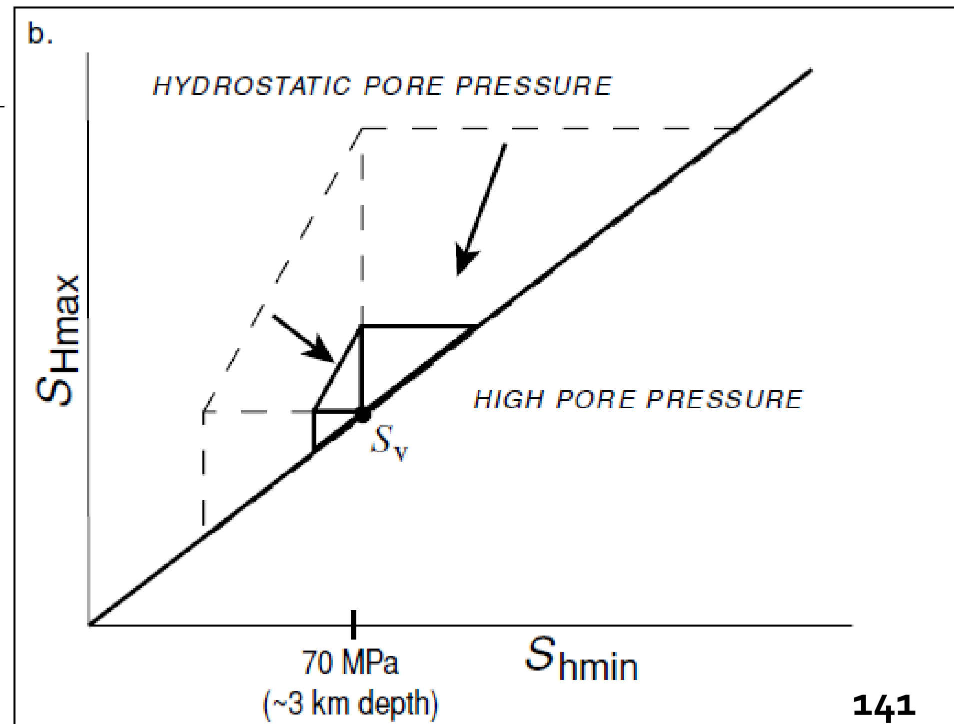



S_0
S_0
HYDROSTATIC
$S_0 = S_1 = S_2 = S_3$
S_1
UNIAXIAL
$S_1 \neq 0,\ S_2 = S_3 = 0$
S_1
S_3
S_3
TRIAXIAL
$S_1 > S_2 = S_3$
S_3
S_1
S_1
TRIAXIAL EXTENSION
$S_1 = S_2 > S_3$
S_1
S_2
S_3
POLYAXIAL
$S_1 \neq S_2 \neq S_3$

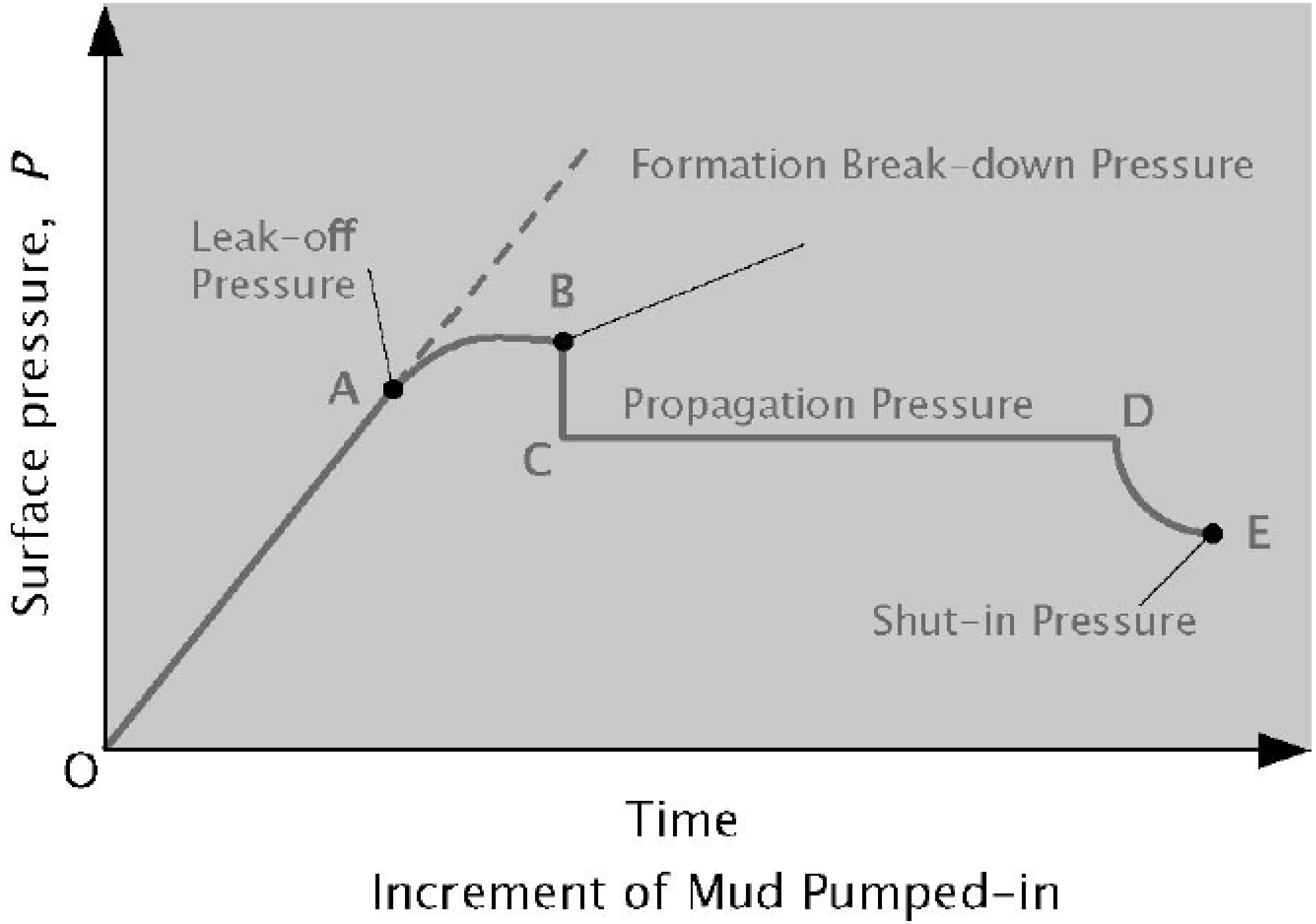
Effective Stress and Rock strength



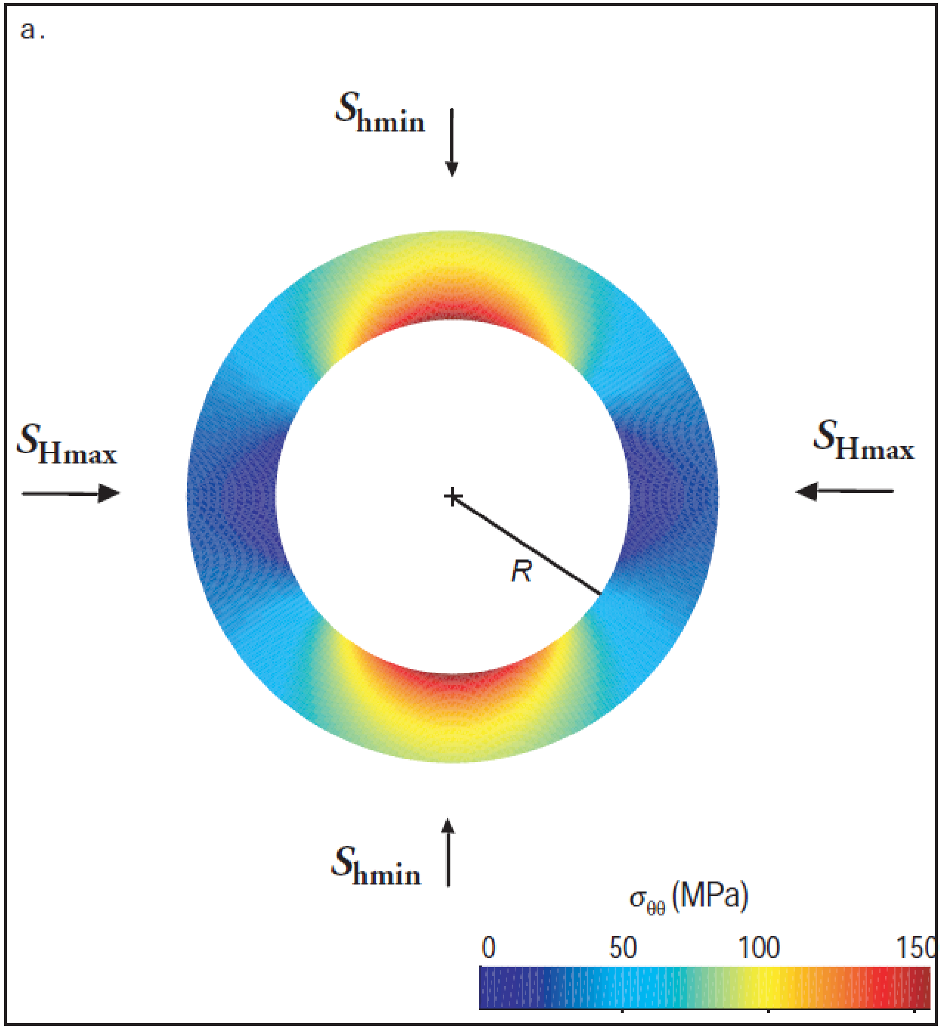

a.
HYDROSTATIC PORE PRESSURE
3
REVERSE FAULTING
2
SS
NF
1
S_v
S_{Hmax}
3)
σ_v σ_{Hmax}
2)
σ_{hmin} σ_v σ_{Hmax}
1)
σ_{hmin} σ_v
70 MPa
(~3 km depth)
S_{hmin}

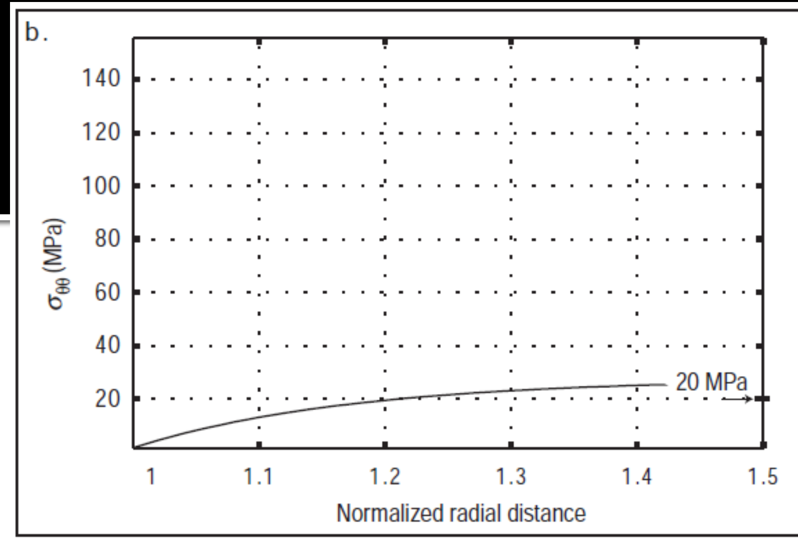

b.
HYDROSTATIC PORE PRESSURE
S_{Hmax}
HIGH PORE PRESSURE
S_v
70 MPa
(~3 km depth)
S_{hmin}

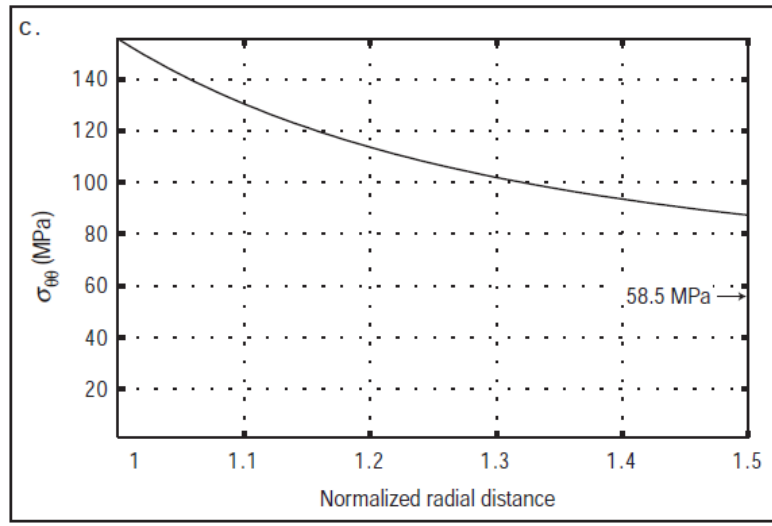
LOT



Formation Break-down Pressure
Leak-off Pressure
B
A
Propagation Pressure
D
C
E
Shut-in Pressure
Surface pressure, P
O
Time
Increment of Mud Pumped-in







S_{Hmax} = 90 Mpa

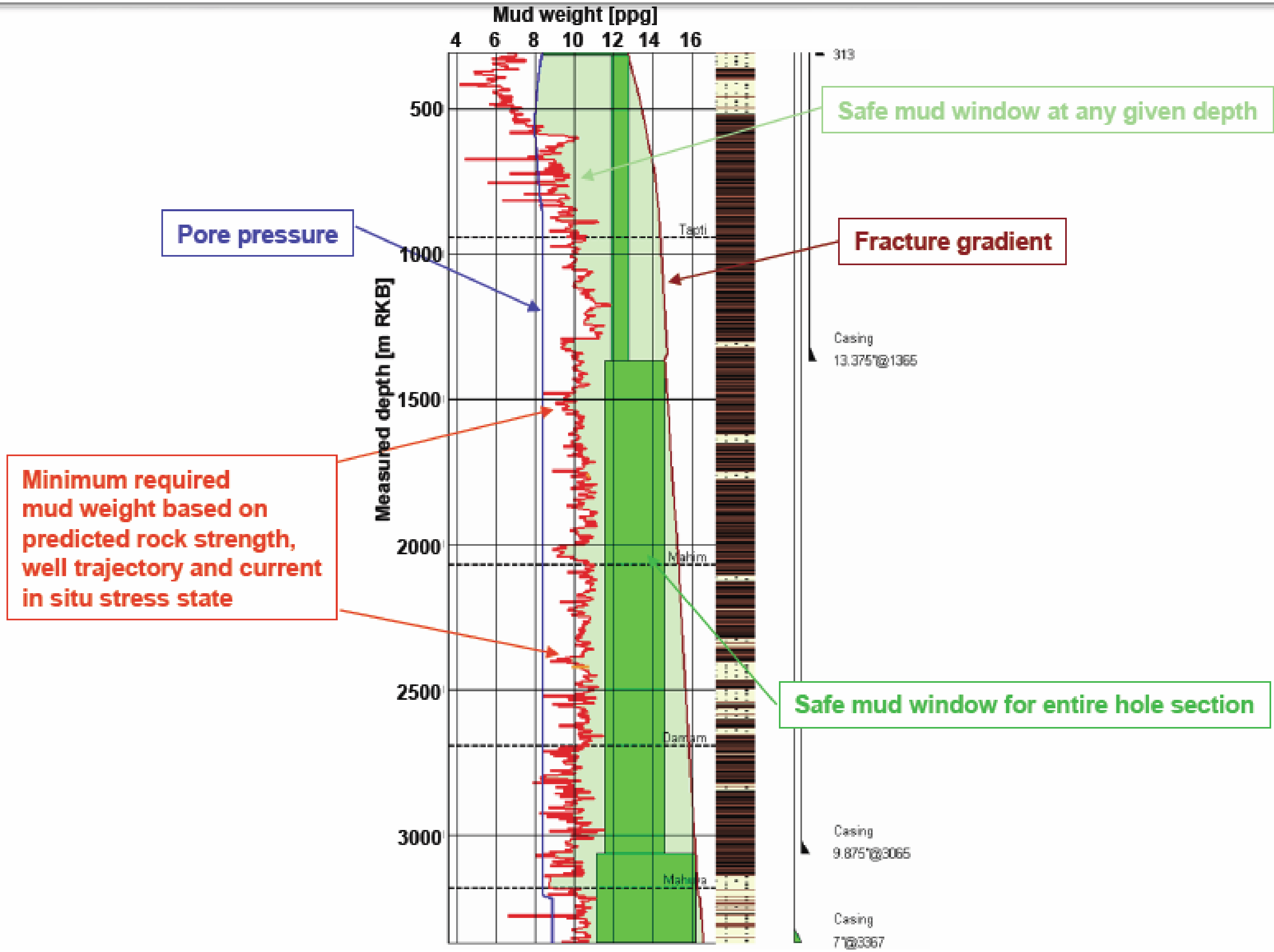
S_{Hmax} orientation is N90E (East West)

S_V = 88.2 Mpa (depth 3213 m)

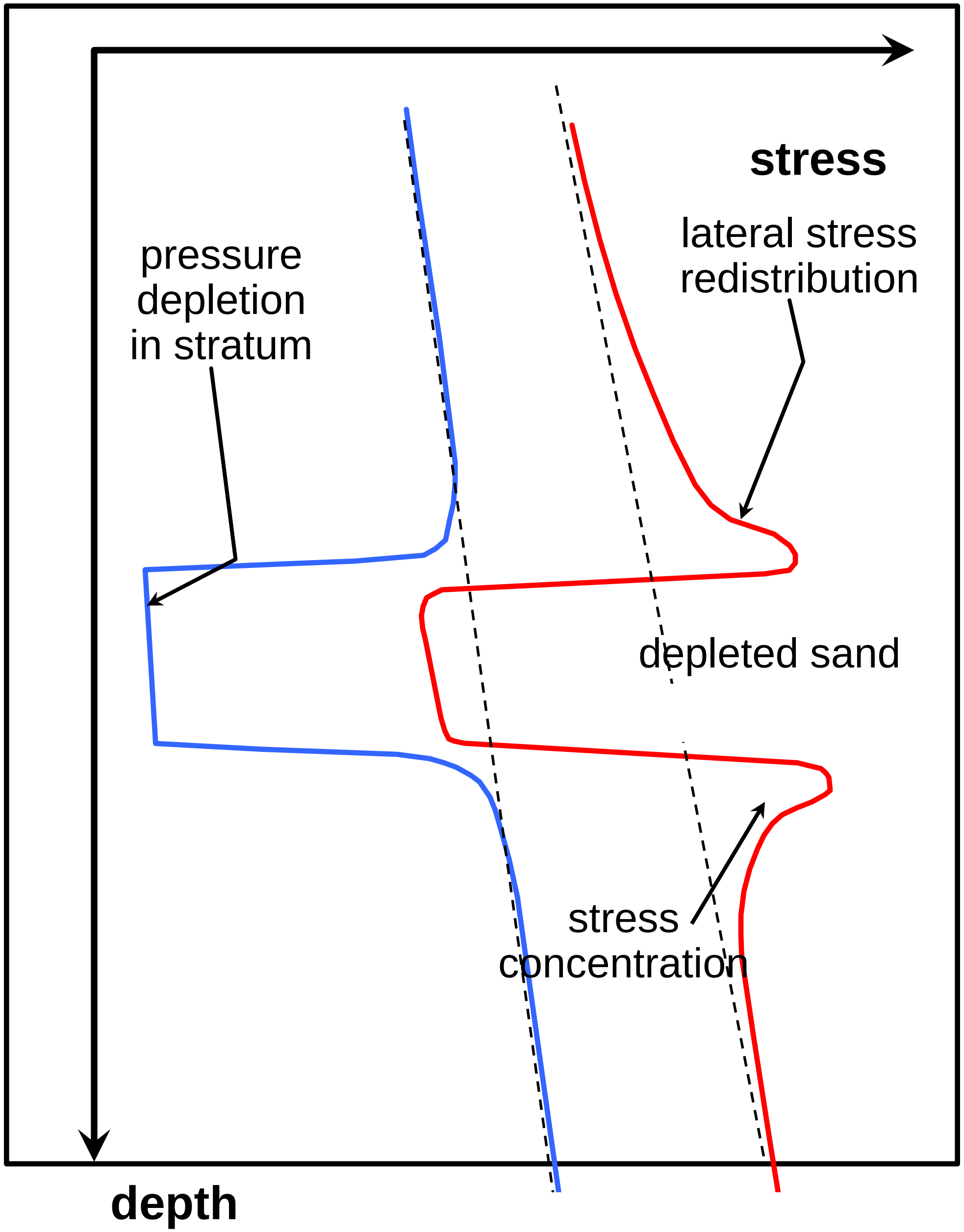
S_{hmin} = 51.5 MPa

$P_p = P_{mud}$ = 31.5 MPa

Vertical Well Plan



Effect of Depletion



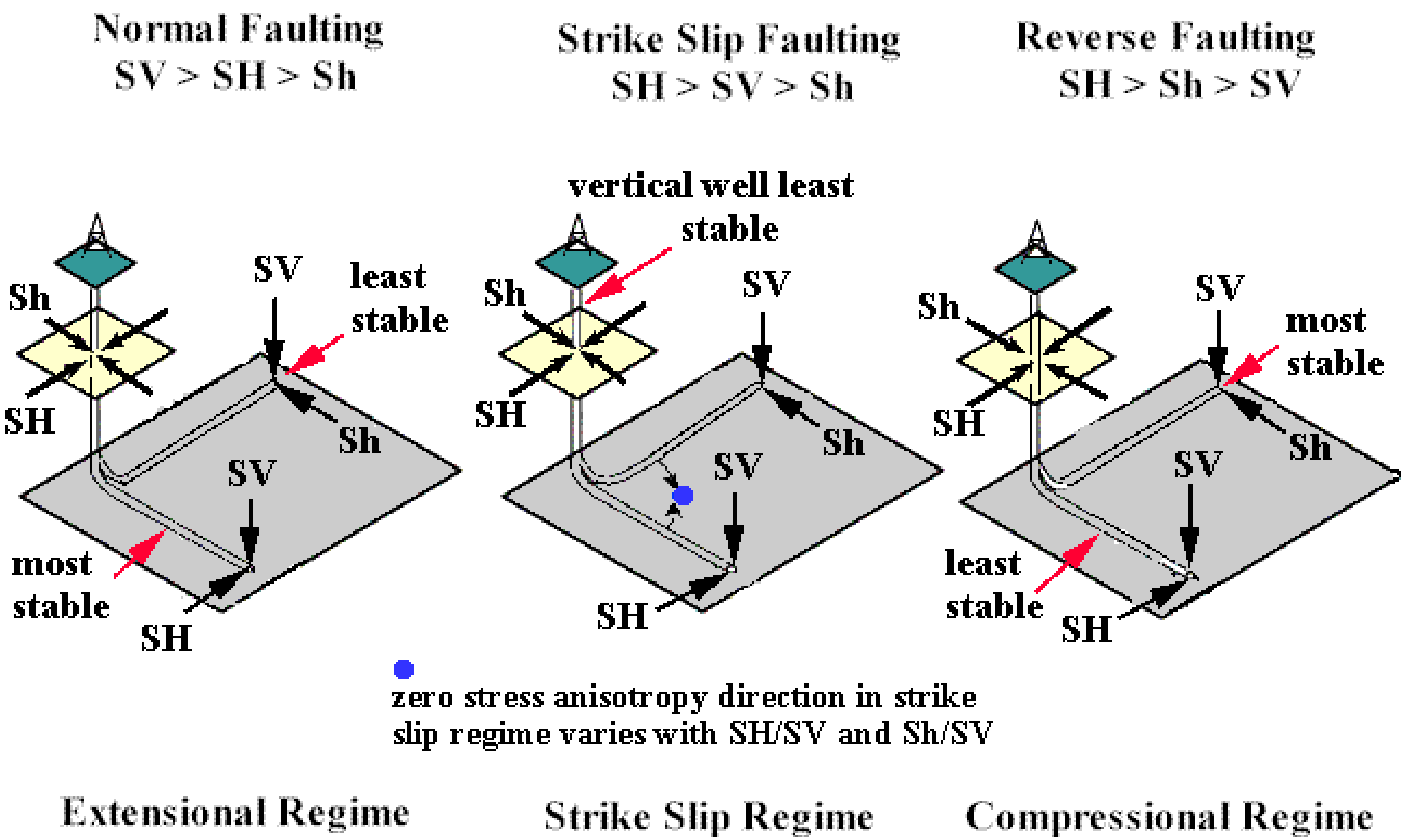
- Drop in pore pressure in depleted zone.
- The reservoir shrinks because of drop in pore pressure.
- Increase in horizontal stresses above and below the zone.
- Effect of vertical stresses are negligible.

Effect of depletion

Consequences:

- Slower drilling rate because rock is tougher
- Lost circulation and blow out risks go up substantially.
- More casing strings and LCM squeezes.
- Most serious in HTHP wells, Multiple zones.

Well Orientation in Tectonic settings



Thankyou