Fracture Toughness vs. Tensile Strength for Reservoir Rocks From Saudi Arabia

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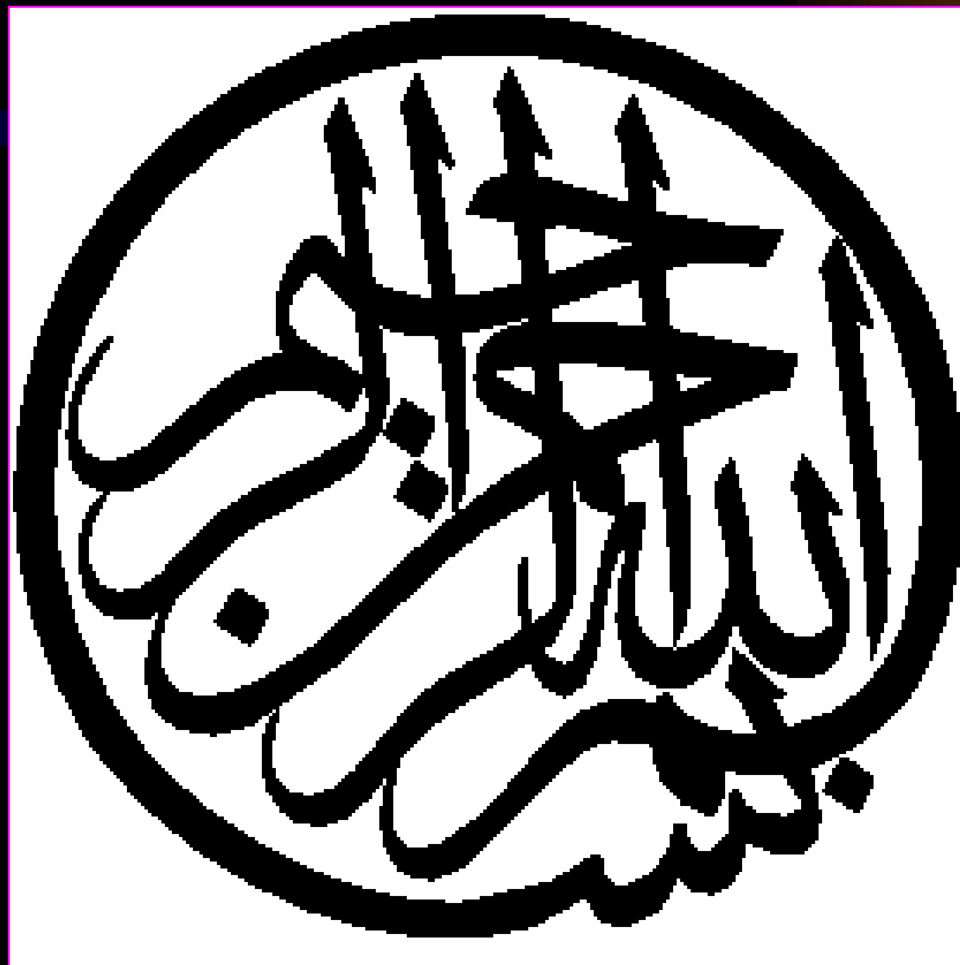
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- Geology
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Definitions

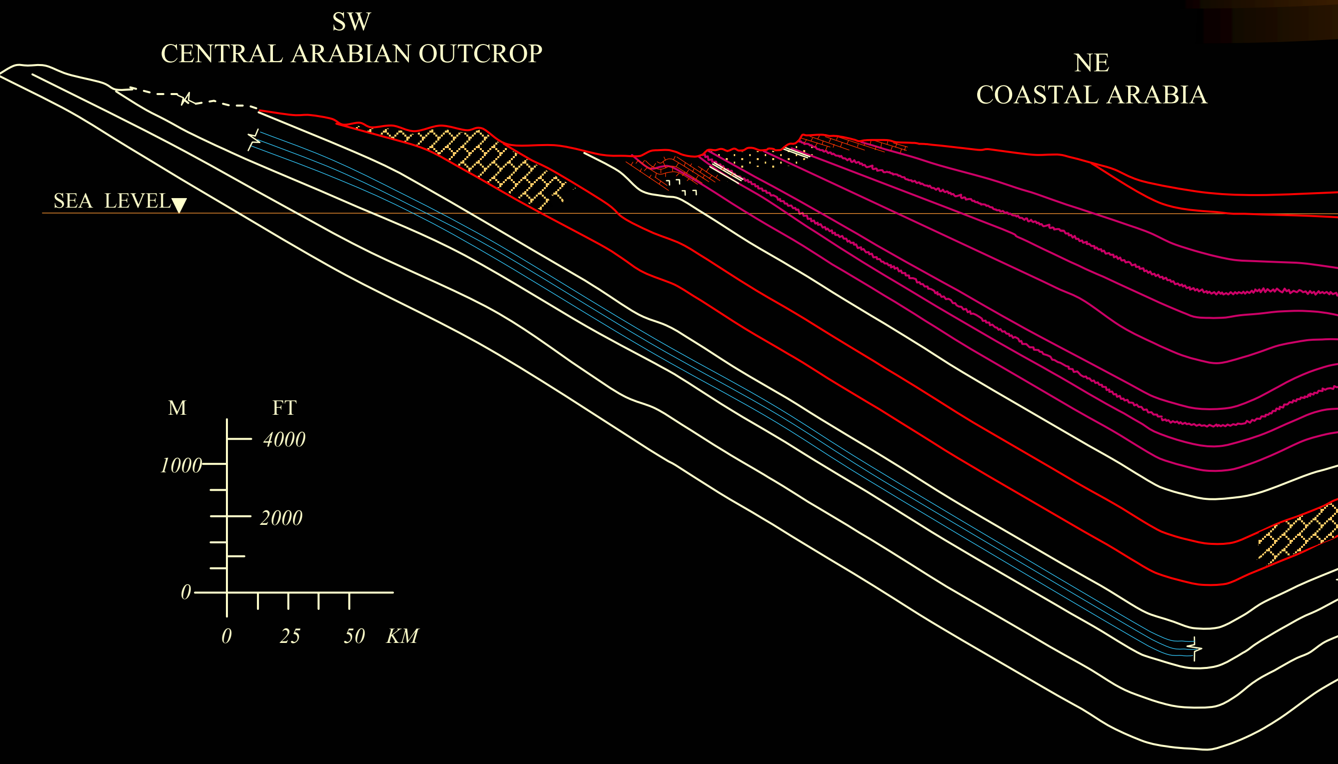
- Fracture toughness
- Tensile strength
- Reservoir rocks
- Hydraulic fracturing

Geology

- Rock samples belong to "*Khuff*" formation, Saudi Arabia.
- *Khuff* formation relates to early Triassic to late Permian age (215 to 270 M.Y.B.P.).
- Structural geology: outcrops in the Central Province up to 100s m altitude, and dips towards the east to a depth of 2000-4000 m in the Eastern Province.
- Thickness of the *Khuff* formation in the *Ghawar* is around 500m.
- Lithology: limestone, claystone, dolomite, anhydrite & sandstone.
- The anhydrite and carbonate sequence is subdivided into four alternating intervals. From top to bottom, the anhydrite-carbonate pairs are called Khuff A, B, C, and D.
- Lithology A as asphanitic-calcarentic limestone, Lithology B as asphanitic limestone, Lithology C as dolomite and limestone, and Lithology D as dolomite and shale.

Map of Saudi Arabia

Schematic Section Showing Cretaceous Surface-subsurface Relationships

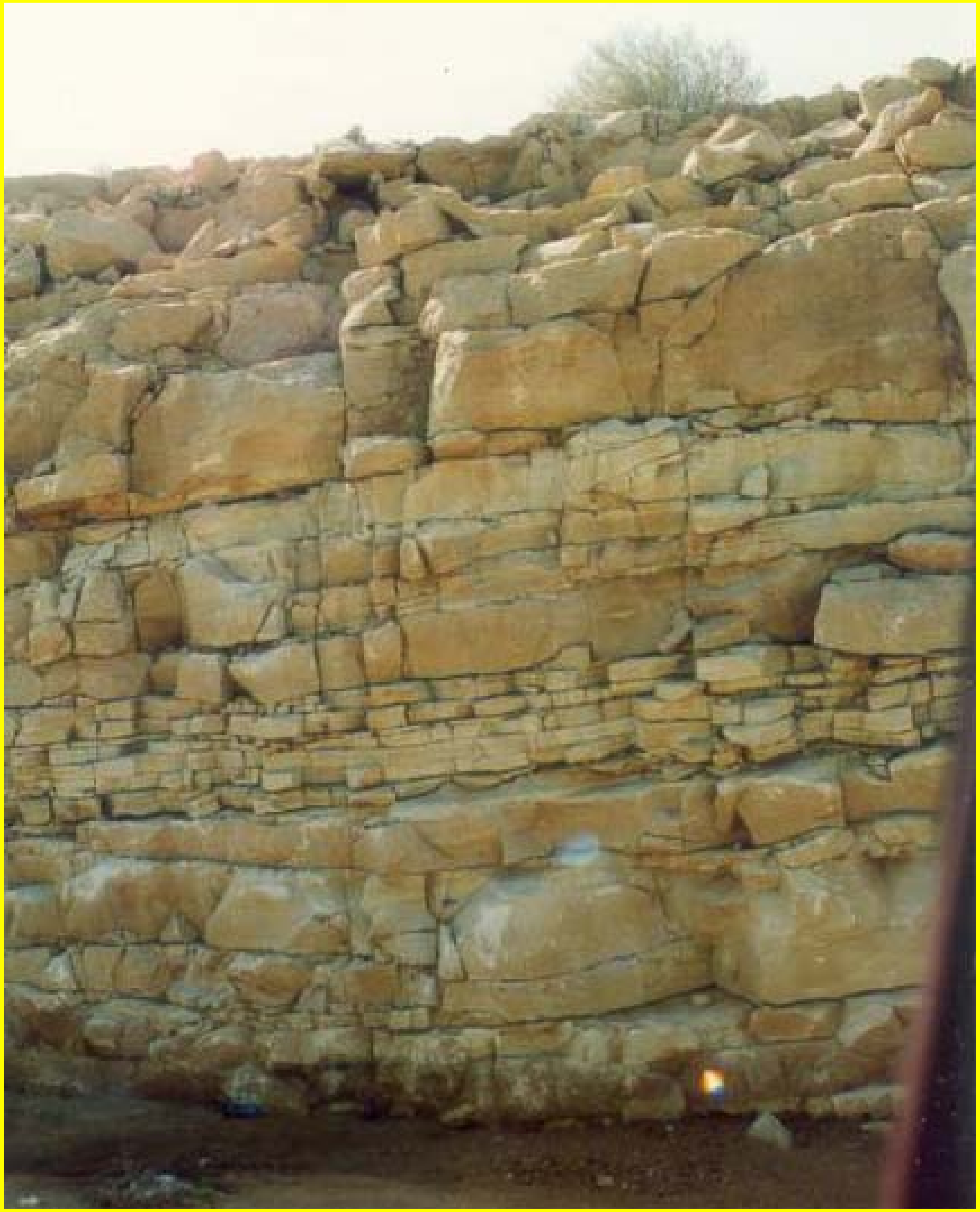


Geolosic Time Scale

Formation	Period (System)	Time (M.Y.B.P.)
	Quaternary	2
	Tertiary	67
Aruma Wasia Buwaib Sulaiy	Cretaceous	140
Hith Arab Marrat	Jurassic	204
Jilh Sudair	Triassic	245
Khuff Unayzah	Permian	283
		440
Qasim	Ordovician	505
Saq	Cambrian	590
Basement	Pre Cambrian	

Stratigaphic Column of the Khuff Formation in the Ghawar Field

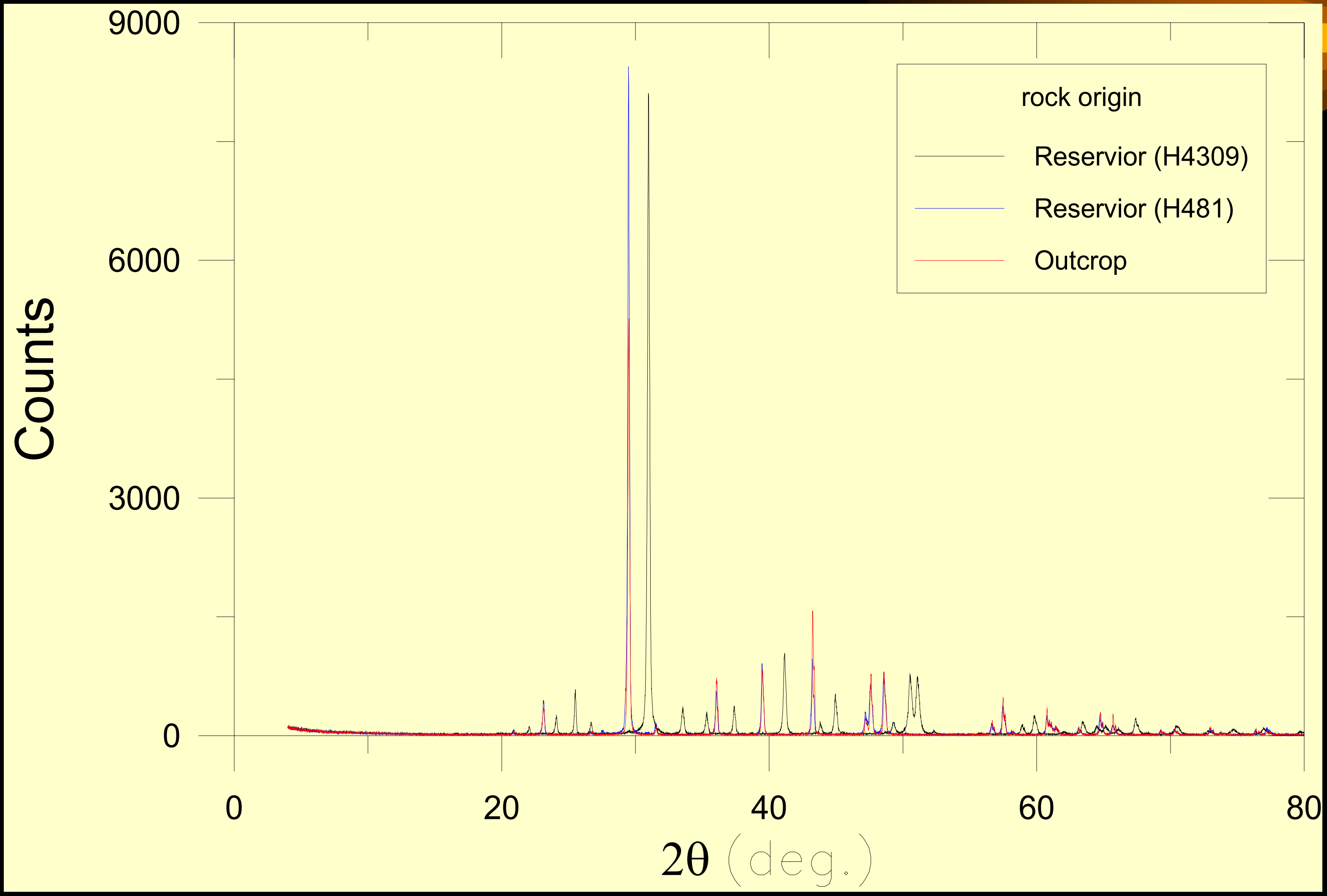
AGE	FORMATION	THICKNESS (m)	LITHOLOGY	DEPOSITIONAL CYCLES	SUB UNITS
TRIASSIC	SUDAIR				
LATE PERMIAN	KHUFF	35		KHUFF-A	KHUFF-A Limestone
		40		KHUFF-B	KHUFF-B Anhydrite
		45			KHUFF-B Carbonate
		115		KHUFF-C	KHUFF-C Evapo-dolomites
		65			KHUFF-C Carbonate
		65		KHUFF-D	KHUFF-D Anhydrite
		100			KHUFF-D Evapo-dolomites
		35			Basal KHUFF Siliciclastics
PERMIAN	UNAYZAH				




Rock Description

- **Reservoir samples:** from the *Ghawar* field, the largest hydrocarbon reservoir in the world producing oil and gas from multi-reservoir zones in the *Khuff* formation.
- Reservoir samples were obtained from different depths, and their lithology was found to vary. Many samples contained impurities such as anhydrite.
- **Outcrop samples:** from the same formation, outcropping in the *Gassim* area, Central Province of Saudi Arabia.

Rock Mineralogy (XRD)



Theoretical Background

1. Tensile strength (σ_t)

For uncracked Brazilian disk :

$$\sigma_t = 2P/\pi BD$$

where:

P = load at failure;

B = thickness of disk; and

D = diameter of disk.

Theoretical Background ...contd.

2. Mode-I fracture toughness (K_I)

For cracked Brazilian disk, Atkinson et al. (1982):

$$K_I = \frac{P\sqrt{a}}{\sqrt{\pi}\,RB} N_I$$

where: K_I = Mode-I stress intensity factor;

R = radius of the Brazilian disk;

B = thickness of the disk;

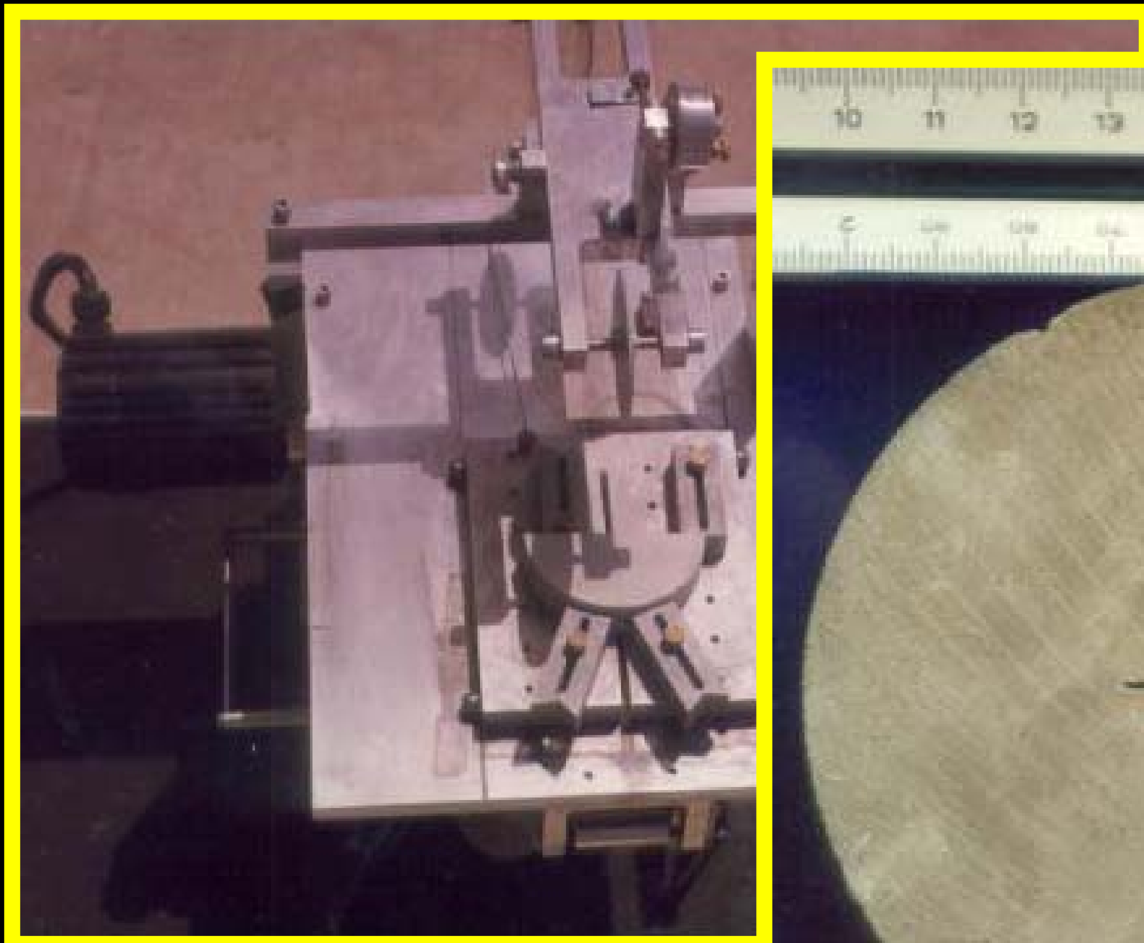
P = compressive load at failure;

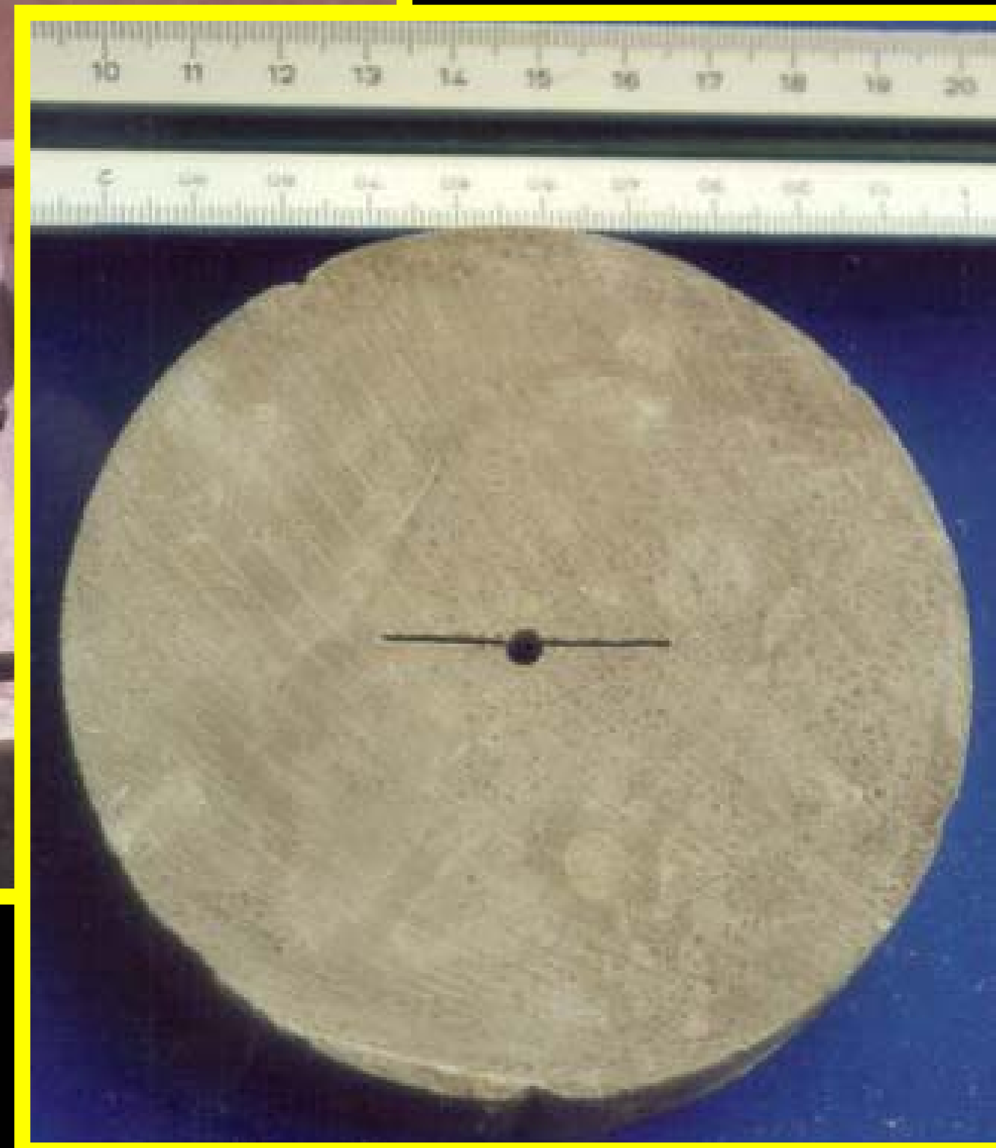
a = half crack length; and

N_I = 1.0 for pure mode-I.

Experimental Program

- Specimen preparation (Brazilian disks)
  - Reservoir & Outcrop
    - D = 100mm (4-inch)
    - B = 25.4mm (1-inch)
  - Uncracked & Cracked
    - a = 29mm (a/R = 0.3)
- Testing conditions
  - Ambient
  - T = 116^{o}C
- Equipment

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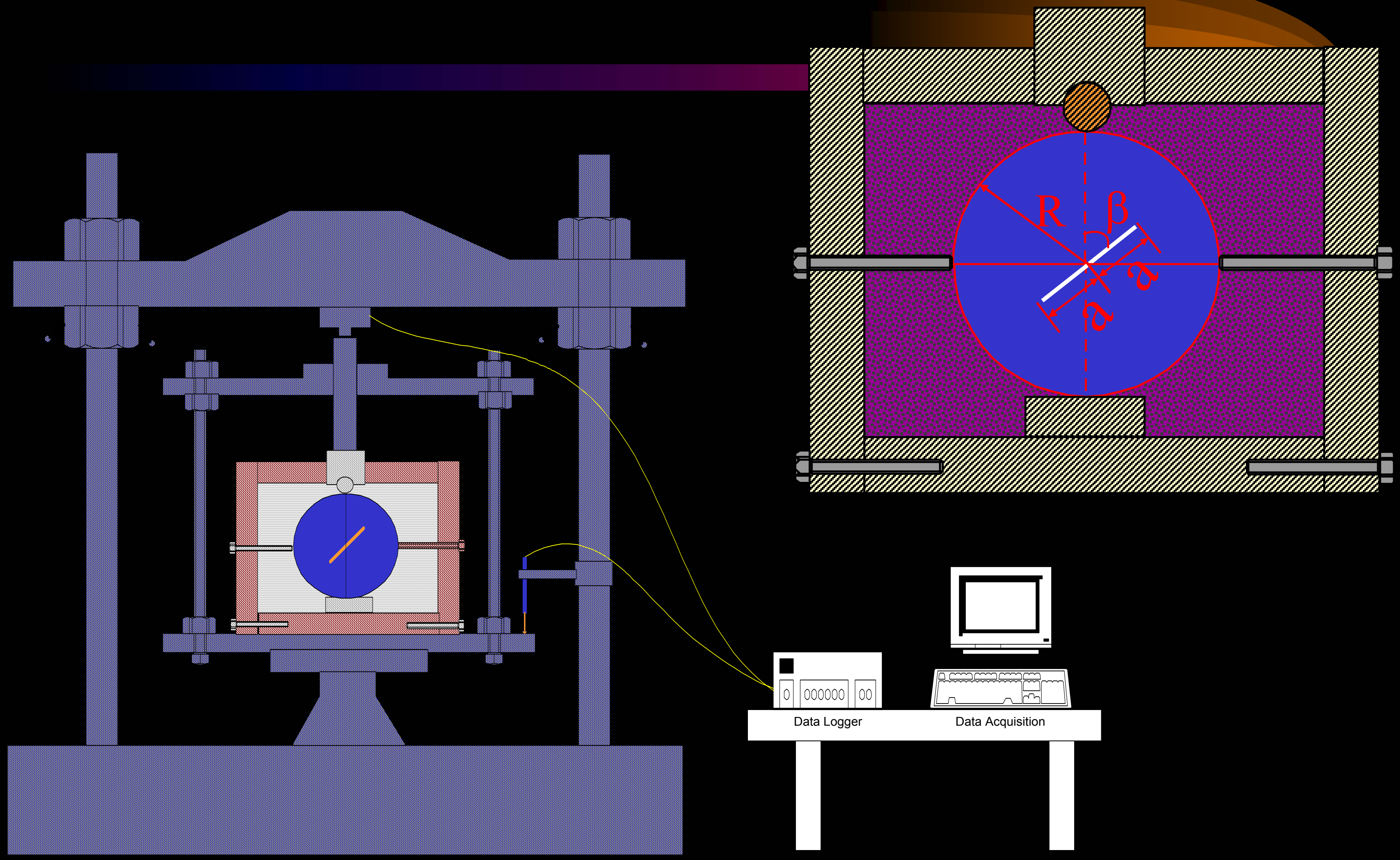
Schematic of the Testing Equipment

Experimental Setup for Testing at T = 116°C



Results & Discussions

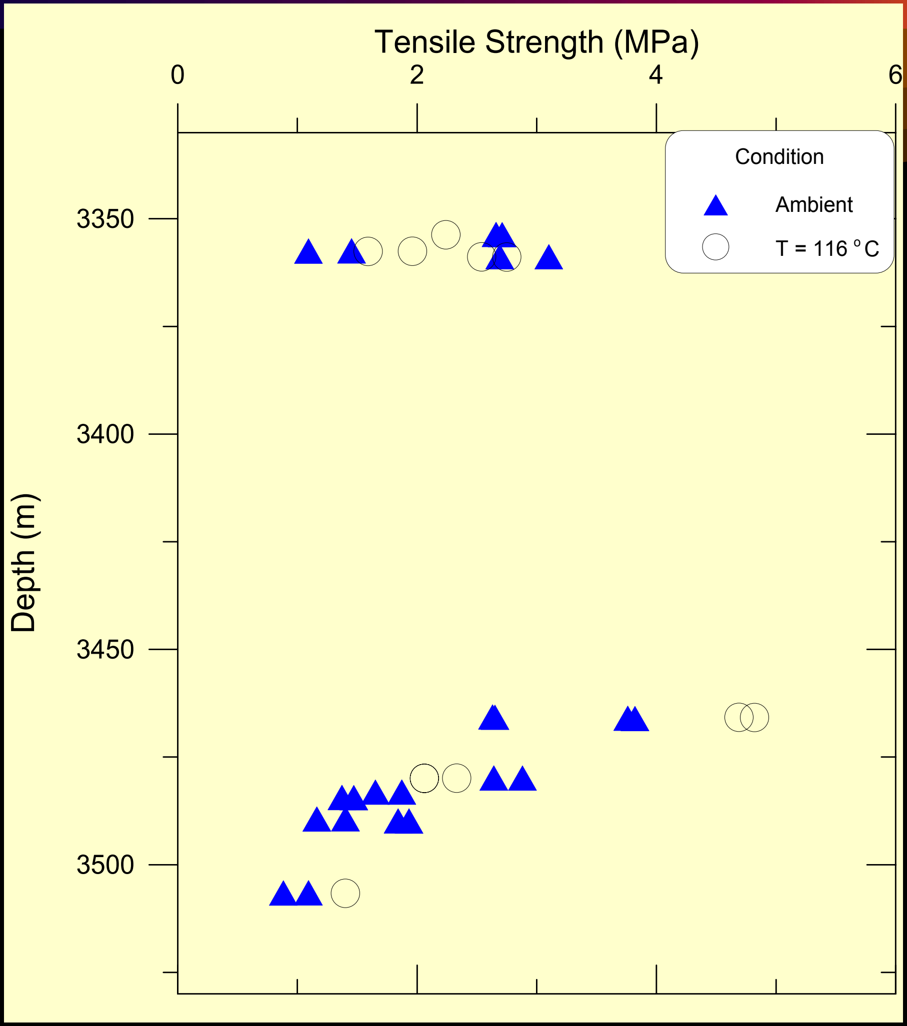
1. Tensile strength (σ_t) from uncracked Brazilian disk:

1.1 At ambient conditions:

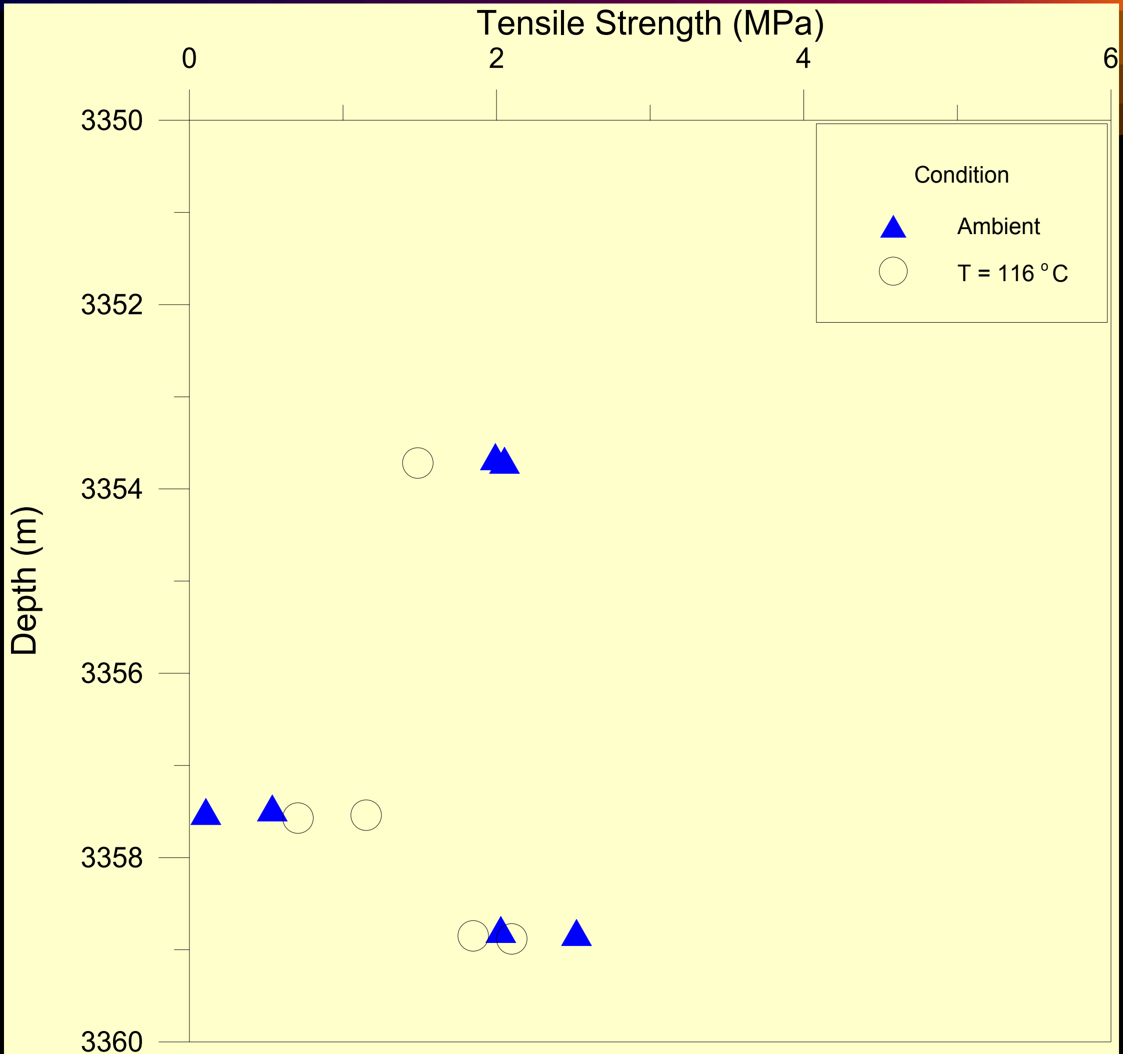
Outcrop: σ_t = 2.38 to 2.50 MPa

Reservoir: σ_t = 0.88 to 3.82 MPa

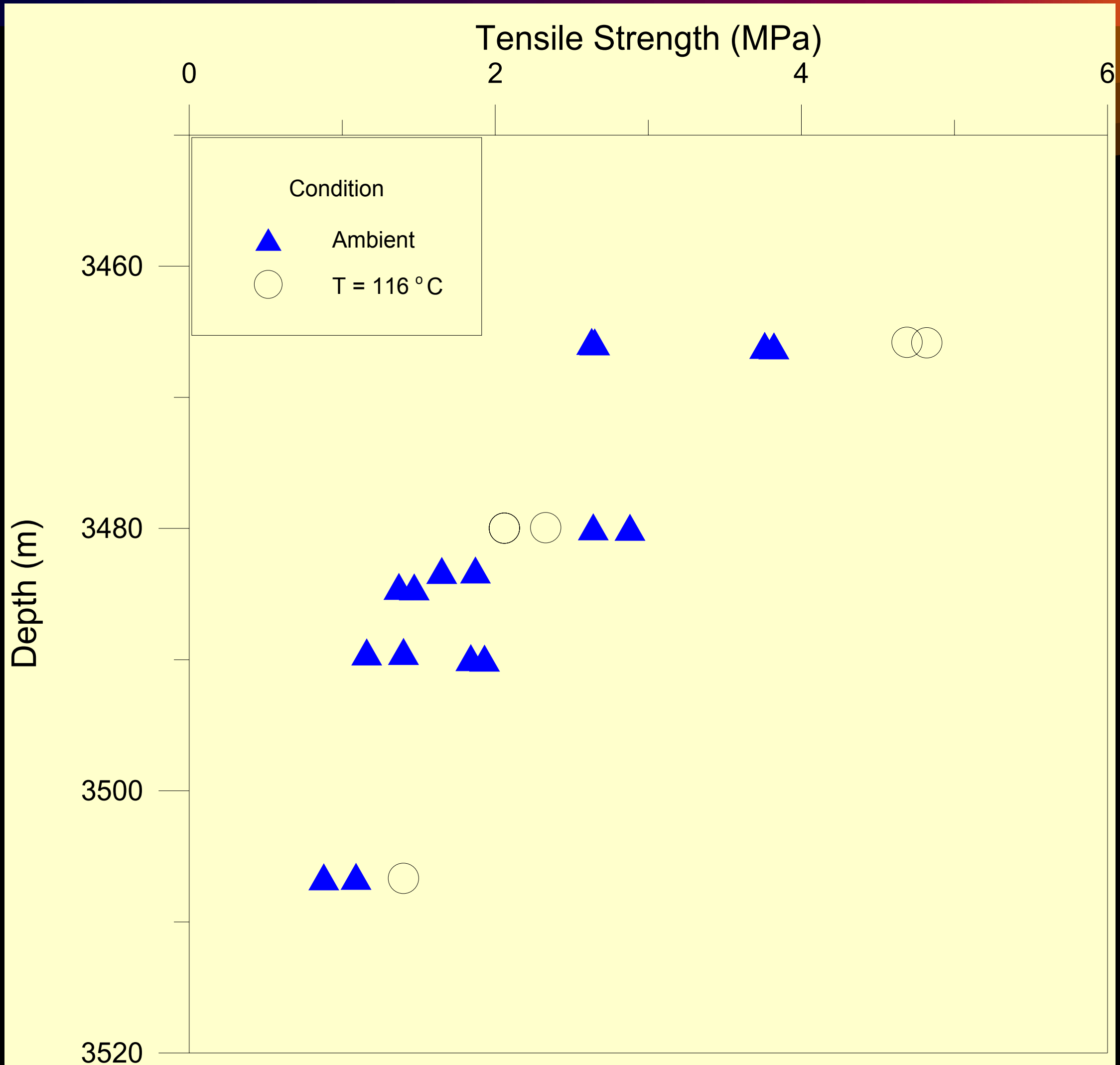
Variation of Tensile Strength With Depth



Variation of Tensile Strength With Depth



Variation of Tensile Strength With Depth



Results & Discussions … Contd.

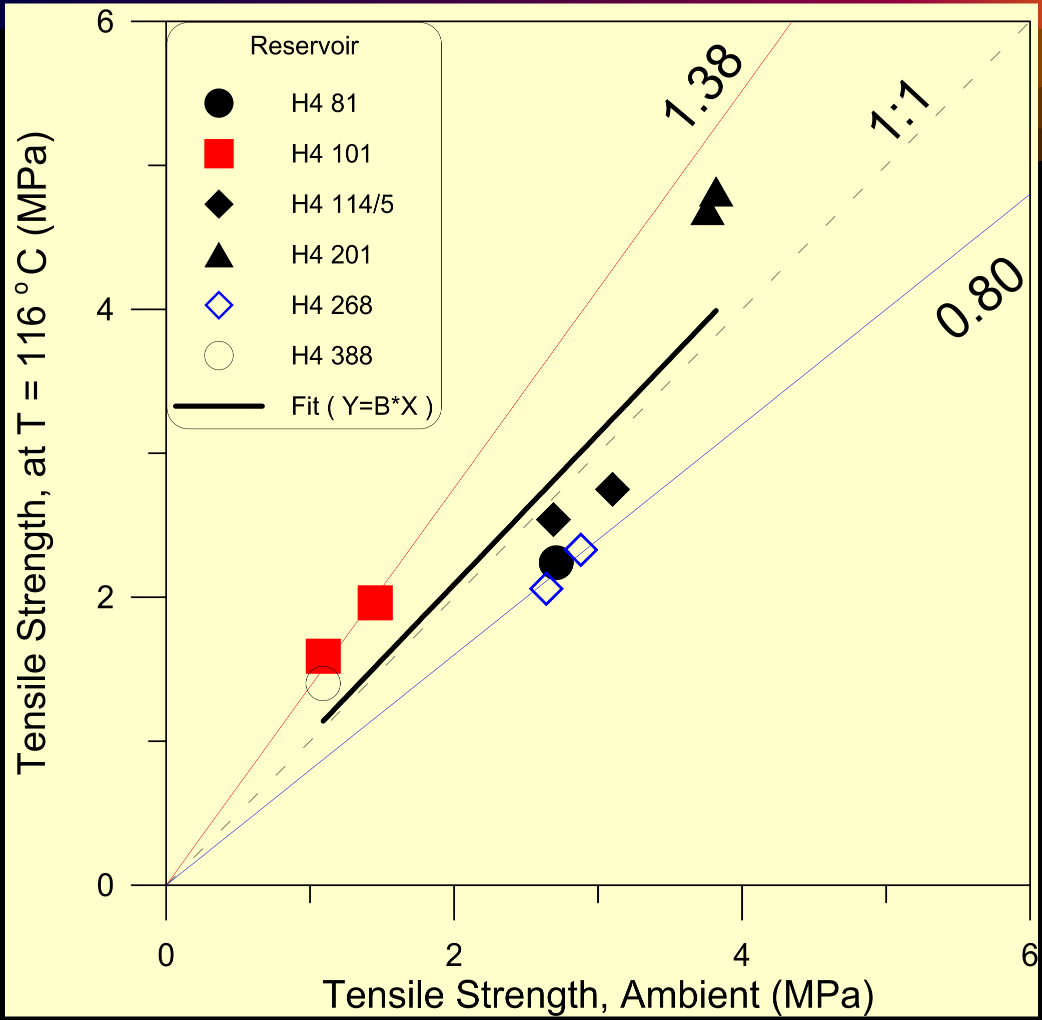
1.2 At T = 116 ^oC :

Reservoir:

Ratio of $(\sigma_t)_{116°C}$ to $(\sigma_t)_{ambient}$ = 0.8 to 1.38

$(\sigma_t)_{116°C} = 1.045 * (\sigma_t)_{ambient}$, with $R^2 = 0.961$

Comparing Tensile Strength at Ambient and Reservoir Temperatures



Results & Discussions … Contd.

2. Mode-I fracture toughness (K_I) from cracked Brazilian disk:

2.1 At ambient conditions:

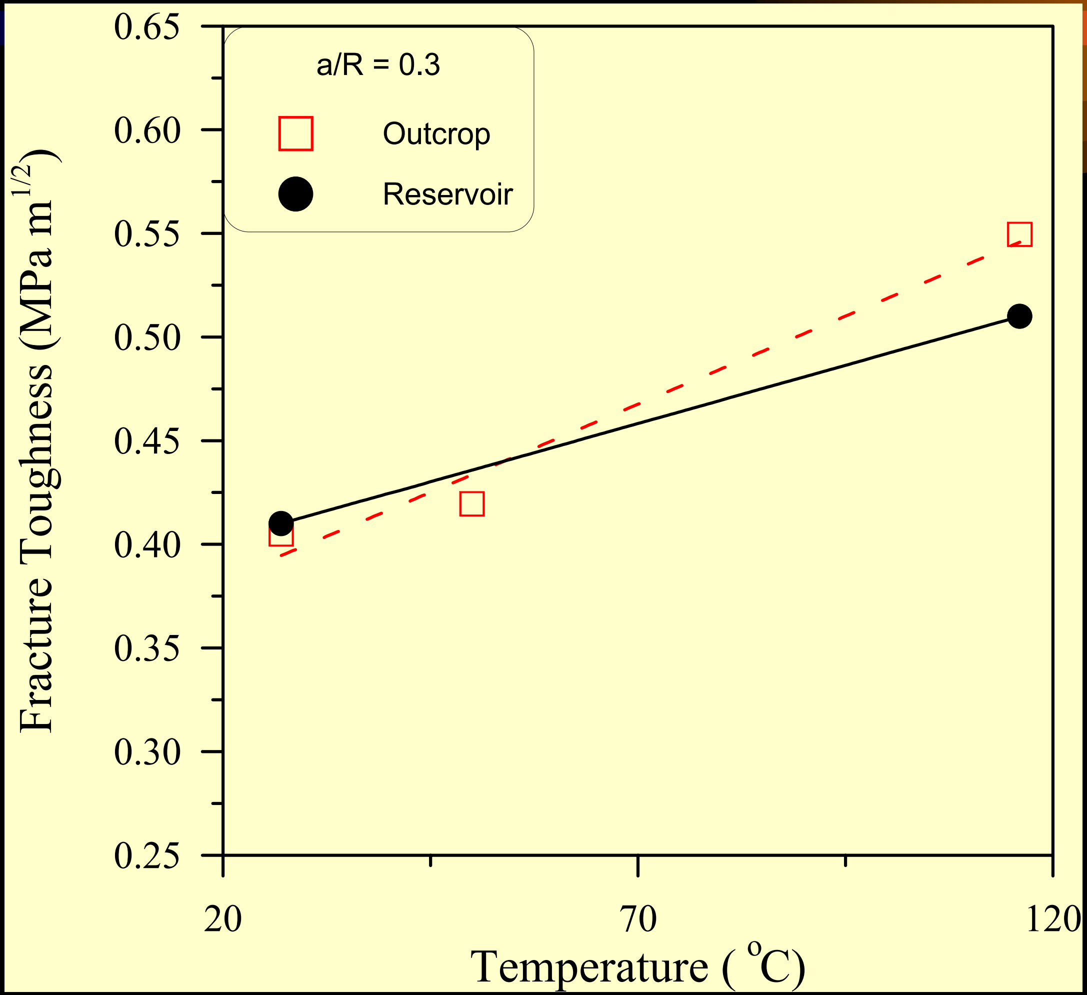
Outcrop: $K_I = 0.39$ to 0.47 MPa $m^{1/2}$

Reservoir: $K_I = 0.29$ to 1.18 MPa $m^{1/2}$

2.2 At T = 116 °C:

K_I increased by 25%

Comparing Mode-I Fracture Toughness at Ambient and Reservoir Temperatures



Results & Discussions … Contd.

3. Fracture toughness vs. Tensile strength

- For reservoir specimens:

  $K_I = 0.3057 * \sigma_t$, with $R^2 = 0.946$

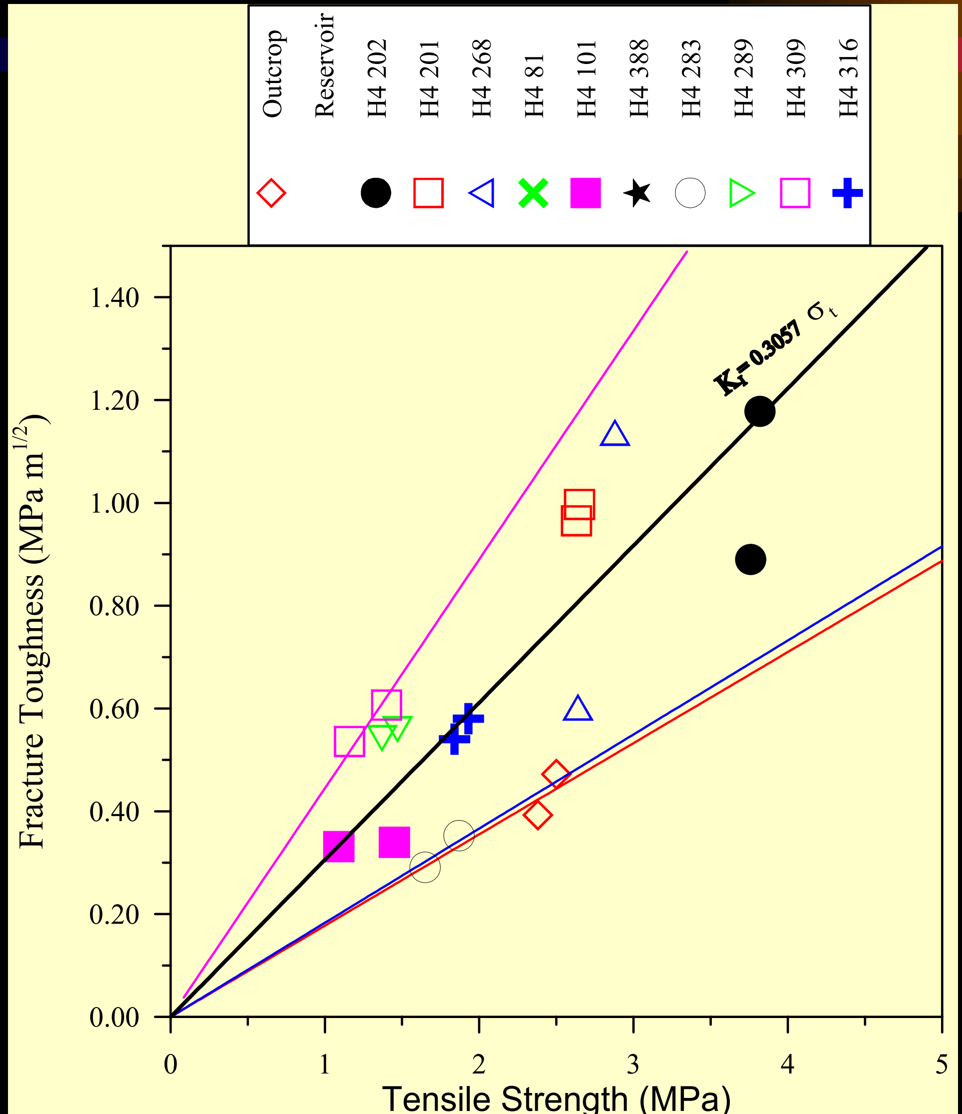
  Ratio of $K_I/\sigma_t = 0.4449$ to $0.1831\ m^{1/2}$

- For outcrop specimens

  Ratio of $K_I/\sigma_t = 0.1775\ m^{1/2}$

- Theoretical value of K_I/σ_t is 0.3070
- Ratios obtained from the data reported by Lim et al. (1994) for various rocks = 0.0752 to 0.2142
- K_I/σ_t Ratio has a unit of ($m^{1/2}$)

Correlation Between Mode-I Fracture Toughness and Tensile Strength



Conclusions

- Tensile strength (σ_t) and the fracture toughness (K_I) for rock samples from the same formation varied considerably.
- Variation is ascribed to the existence of different members within the same formation.
- σ_t varied from 0.88 to 3.82MPa, more than four times.
- K_I varied from 0.29 to 1.18 MPa $m^{1/2}$, about four times.
- Temperature does not significantly affect the values of K_I and σ_t. K_I and σ_t are slightly higher at higher temperatures.
- K_I is linearly proportional to σ_t, with an average proportionality constant of $0.3057 m^{1/2}$.
- K_I can be correlated to the σ_t.
- Above conclusions are valid for both the outcrop and reservoir samples of the investigated rock.

Thank You.