Fracture Toughness in Rocks: Issues and Analysis

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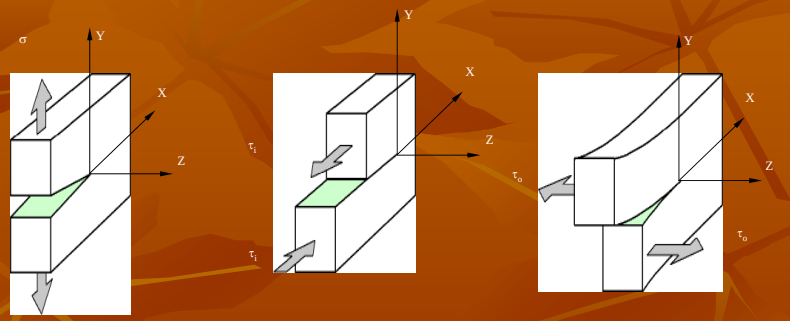
Fracture Toughness

- Resistance of a material to crack propagation
- Considered a material property
- Widely used parameter in fracture mechanics, especially in fracture behaviour of metals
- Established parameter in rock mechanics, but limited experimental data

Fracture Toughness



Mode-I: Opening mode

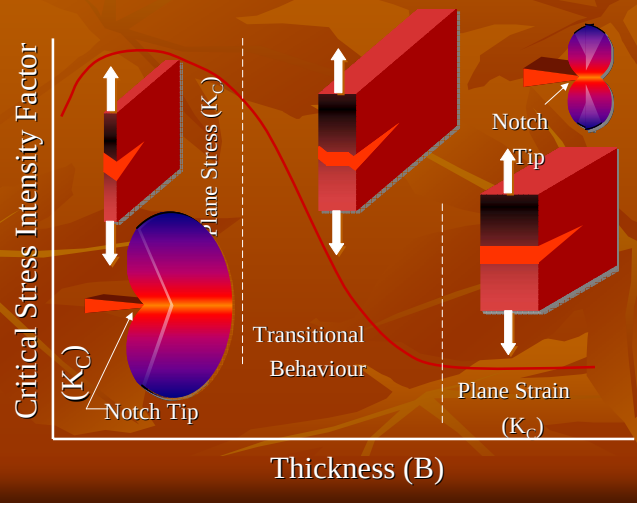
Mode-II: Sliding mode

Mode-III: Tearing mode

Fracture Toughness

FT – Stress Intensity Factor (SIF) – Critical SIF or K_C

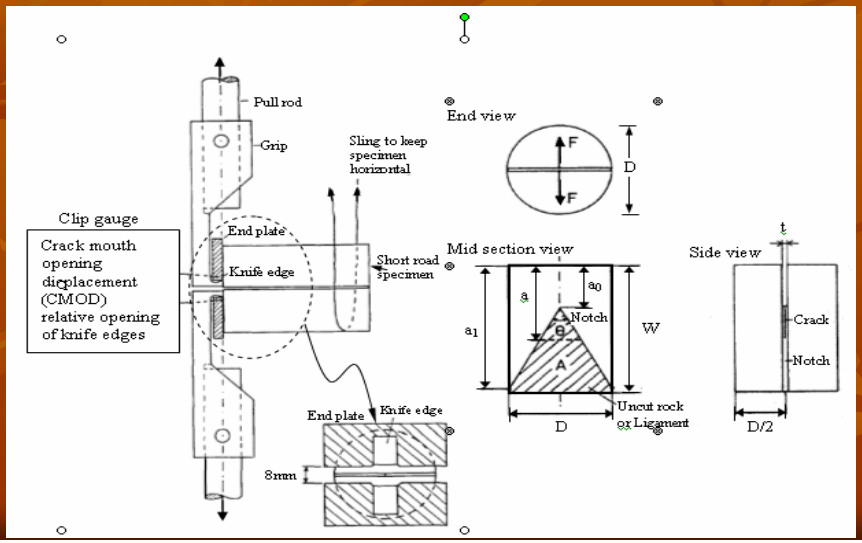
K_C –Thickness of material



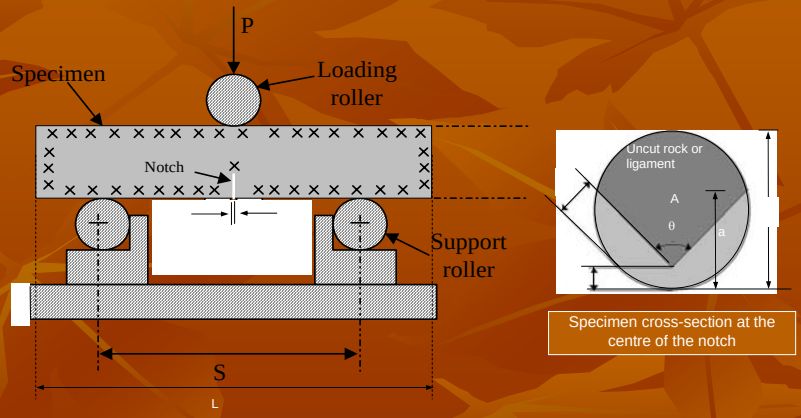
ISRM Recommendations on Measurement of Fracture Toughness

- Aimed at standardizing measurement techniques to reduce discrepancy of results from use of a variety of techniques
- For tensile mode (Mode I), recommended methods are: Short Rod (SR), Chevron Bend (CB), and Cracked Chevron Notched Brazilian Disc method (CCNBD)

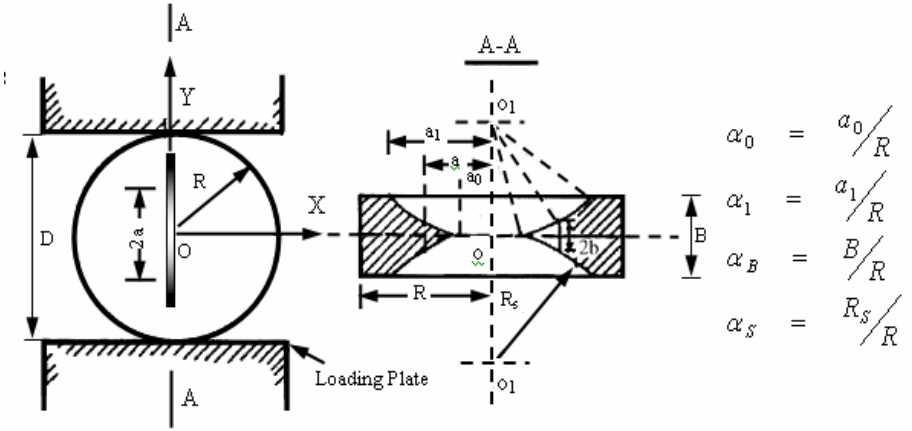
Geometry of specimen, notations and setup used for SR test (after ISRM, 1988)



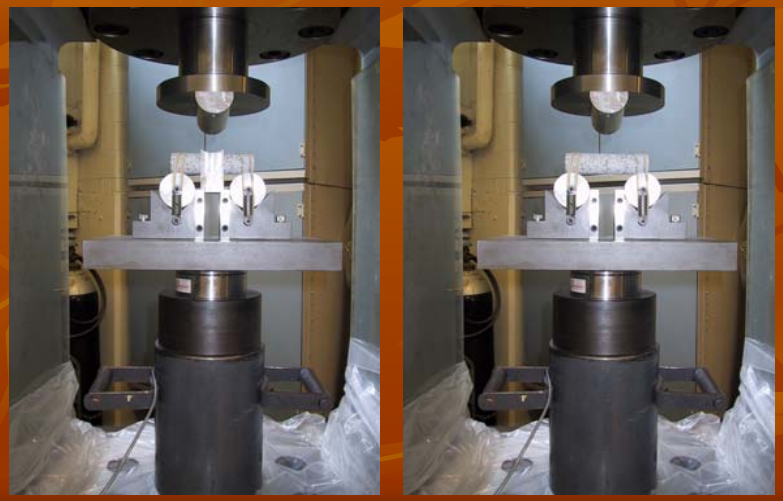
Geometry of specimen and notations used for CB test



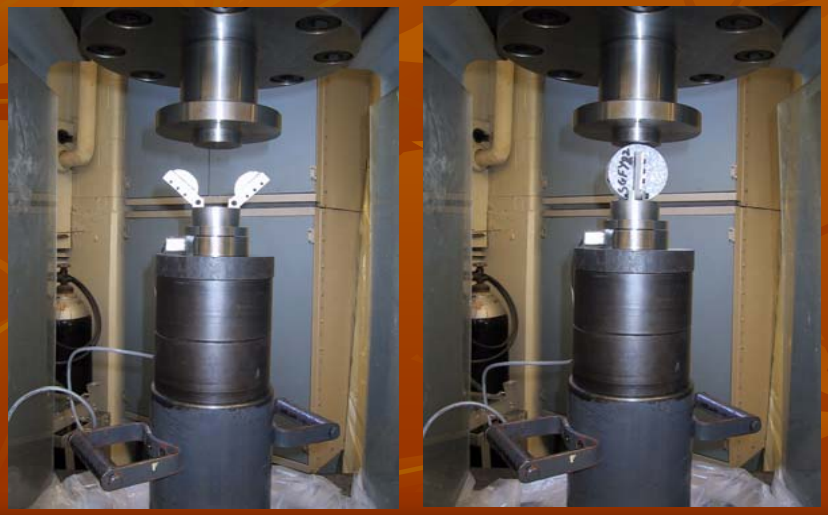
Geometry of specimen and notations used for CCNBD method (ISRM, 1995)



Specimen installation fixture for the CB method



Specimen installation fixture for the CCNBD method



Core and disc specimens for CB and CCNBD tests

Equations used in Calculation of K_{IC}

(ISRM, 1995)

$$K_{IC} = \frac{P_{max}}{B\sqrt{D}}.Y^*_{min}$$

P_{max} = Max. load at failure
B = Thickness of the disc
D = Diameter of the disc
Y^*_{min} = Dimensionless parameter

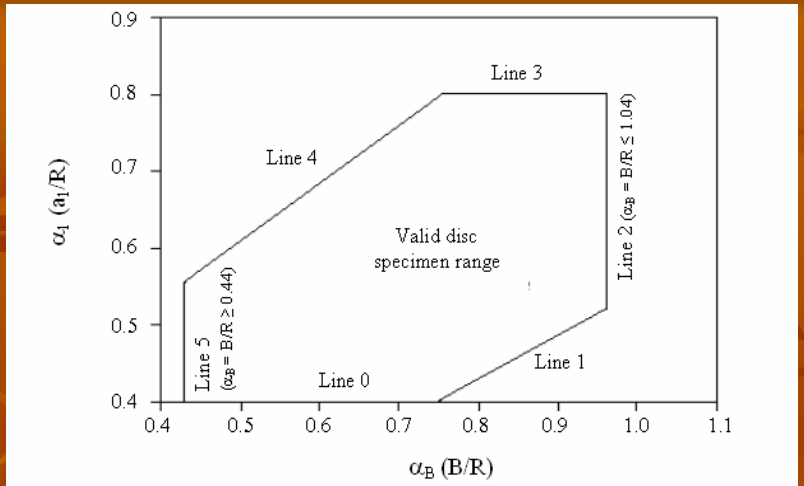
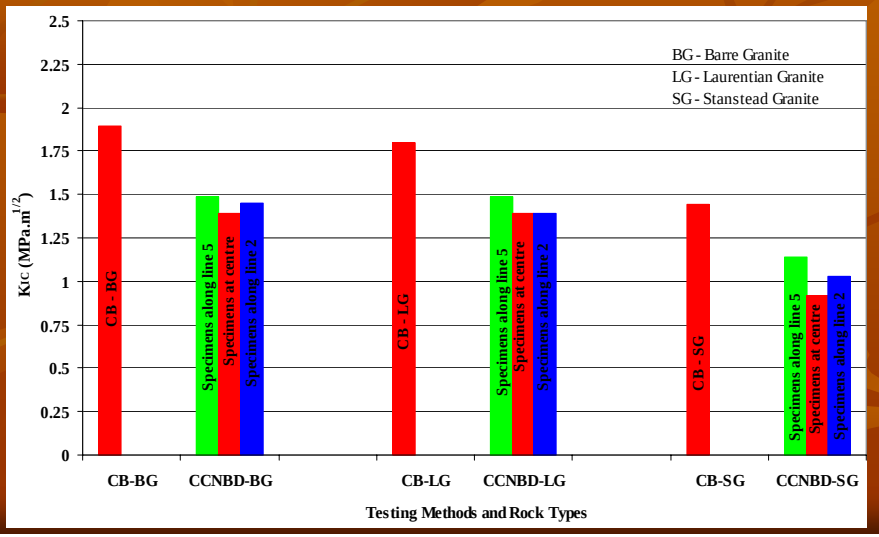
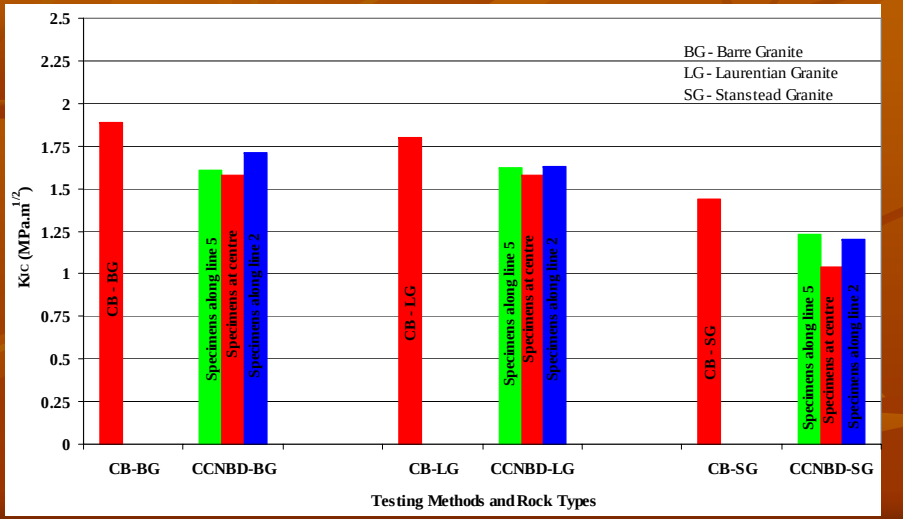


Figure 2: Valid specimen geometrical range for the CCNBD test specimens [after 6].

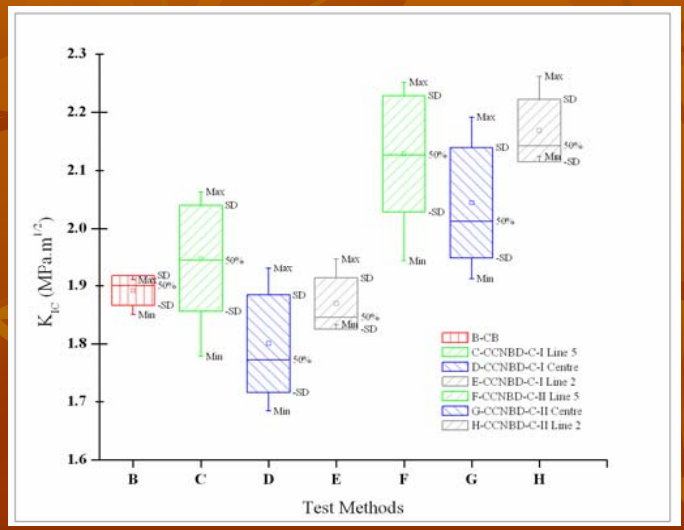
Fracture toughness comparison of the CB and CCNBD (equation 1) methods



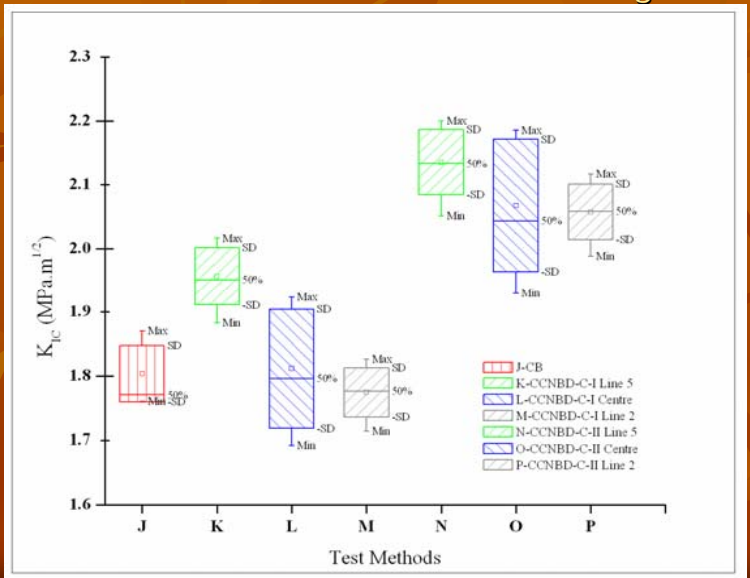
Fracture toughness comparison of CB and CCNBD (equation 1 and revised dimensionless parameter)



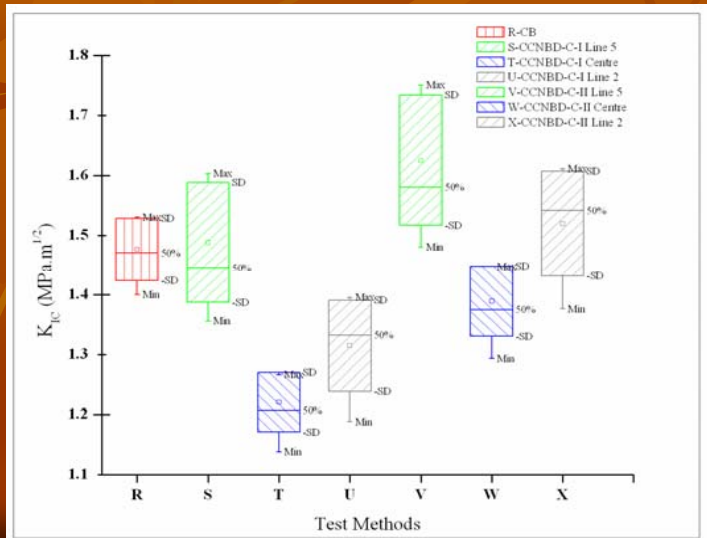
CB and CCNBD values with means, standard deviations and minimum and maximum values for Barre granite



CB and CCNBD values with means, standard deviations and minimum and maximum values for Laurentian granite



CB and CCNBD values with means, standard deviations and minimum and maximum values for Stanstead granite.



Fracture toughness values obtained from CCNBD tests of Selected rock types for case-I and case-II calculations

Rock Type	Case-I fracture toughness values (MPa.m$^{1/2}$)			Case-II fracture toughness values (MPa.m$^{1/2}$)		
	Location of disc specimens on valid geometrical range (figure 2)			Location of disc specimens on valid geometrical range (figure 2)		
	Line 5	Centre	Line 2	Line 5	Centre	Line 2
Barre granite	1.95_8 ±0.092	1.80_6 ±0.084	1.87_6 ±0.044	2.13_8 ±0.100	2.05_6 ±0.095	2.17_6 ±0.053
Laurentian granite	1.96_8 ±0.045	1.81_6 ±0.093	1.77_6 ±0.038	2.14_8 ±0.051	2.07_6 ±0.104	2.06_6 ±0.044
Stanstead granite	1.49_8 ±0.101	1.22_6 ±0.050	1.31_6 ±0.076	1.63_8 ±0.108	1.39_6 ±0.059	1.52_6 ±0.088

Summary of fracture toughness values obtained from CCNBD tests of selected rock types for case-I and case-II calculations

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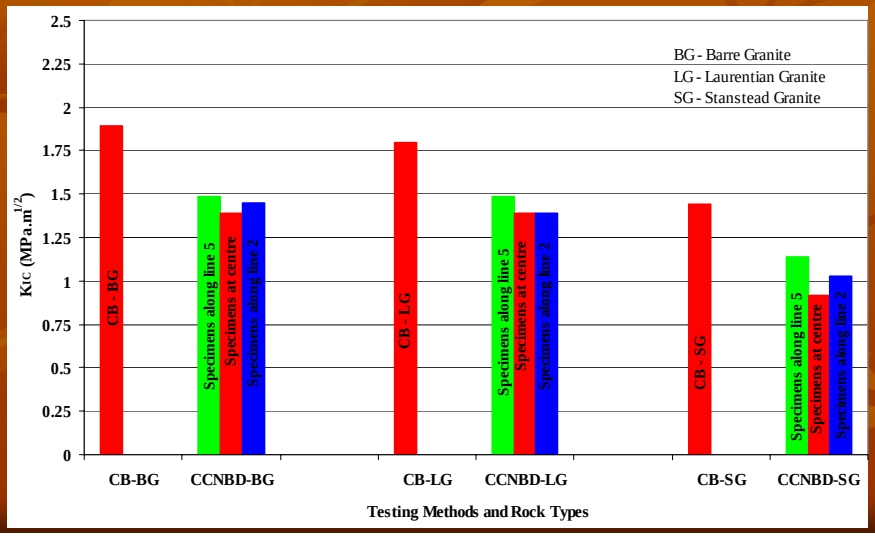
Summary of fracture toughness values obtained from CB tests of selected rock types.

Rock Type	Fracture toughness values ($MPa.m^{1/2}$)
Barre granite	1.89_6 ±0.024
Laurentian granite	1.80_6 ±0.042
Stanstead granite	1.44_5 ±0.053

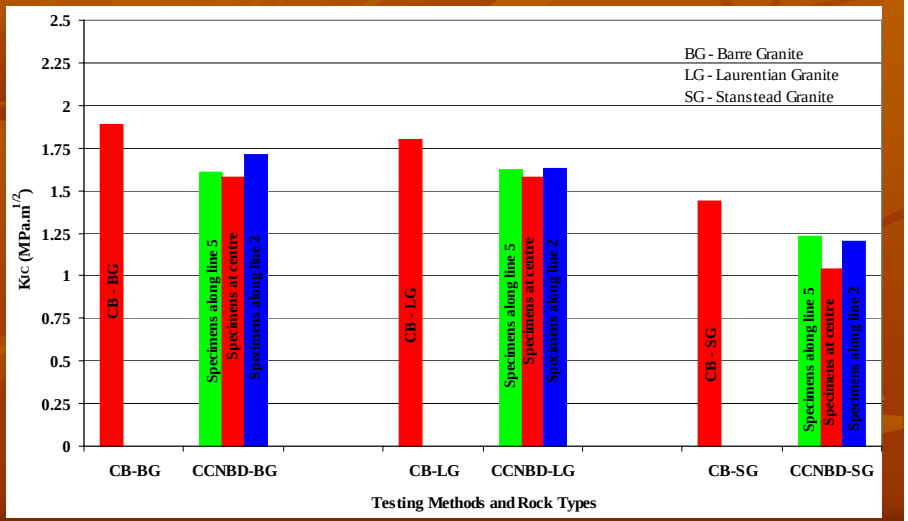
Fracture toughness values obtained from CCNBD tests (using equation 1) of selected rock types for case-I and case-II calculations

Rock Type	Case-I fracture toughness values ($MPa.m^{1/2}$)			Case-II fracture toughness values ($MPa.m^{1/2}$)		
	Location of disc specimens on valid geometrical range (figure 2)			Location of disc specimens on valid geometrical range (figure 2)		
	Line 5	Centre	Line 2	Line 5	Centre	Line 2
Barre granite	1.38_8 ±0.062	1.27_6 ±0.060	1.32_6 ±0.031	1.51_8 ±0.071	1.45_6 ±0.067	1.53_6 ±0.038
Laurentian granite	1.38_8 ±0.032	1.28_6 ±0.066	1.26_6 ±0.027	1.51_8 ±0.036	1.46_6 ±0.073	1.45_6 ±0.031
Stanstead granite	1.05_8 ±0.071	0.86_6 ±0.035	0.93_6 ±0.054	1.15_8 ±0.077	0.98_6 ±0.024	1.08_6 ±0.062

Fracture toughness comparison of the CB and CCNBD (equation 1) methods



Fracture toughness comparison of CB and CCNBD (equation 1 and revised dimensionless parameter)



Equations used in Calculation of K_{IC}

(ISRM, 1995)

$$K_{IC} = \frac{P_{max}}{B.\sqrt{D}}.Y^*_{min}$$

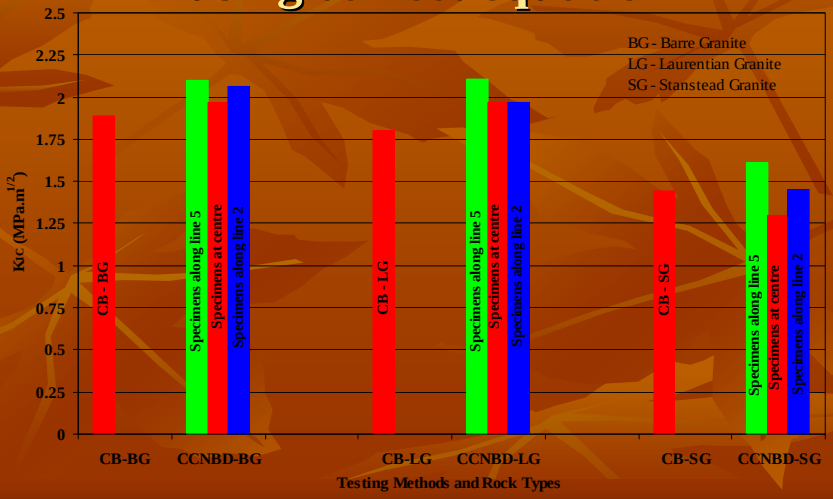
P_{max} = Max. load at failure
B = Thickness of the disc
D = Diameter of the disc
Y^*_{min} = Dimensionless parameter

Correct equation

$$K_{IC} = \frac{P_{max}}{B.\sqrt{R}}.Y^*_{min}$$

R = Radius of the disc

Comparison of Fracture toughness values for CB and CCNBD methods using *correct* equation

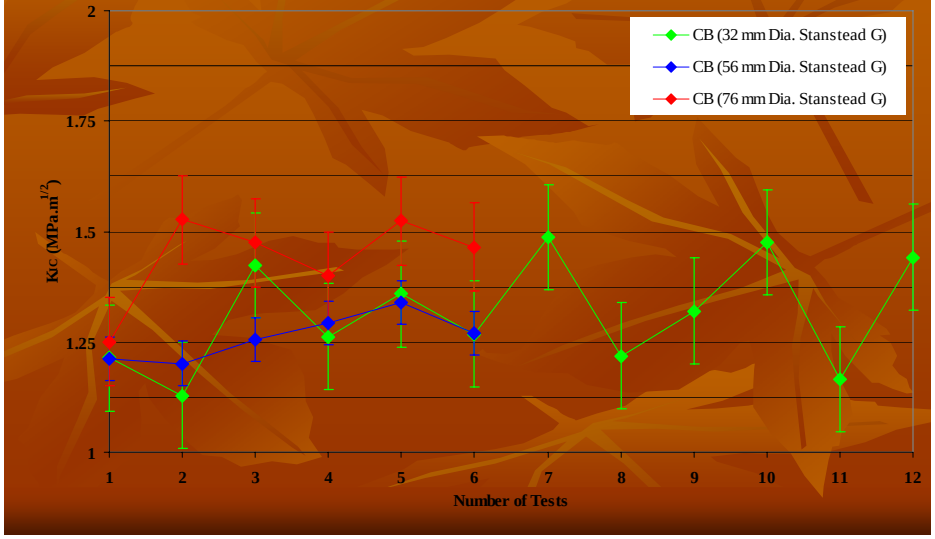


Summary of the strength properties

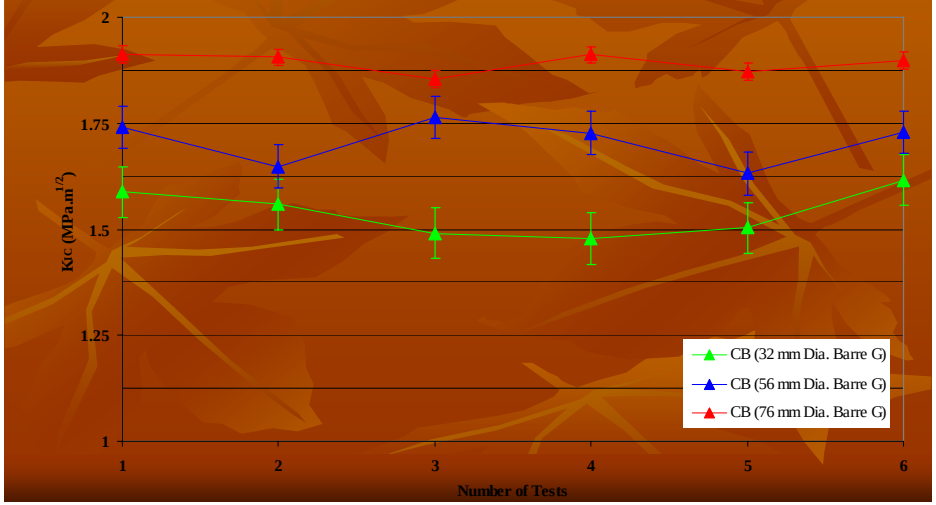
Rock Type	UCS 'σ_c' (MPa)	Static Young's Modulus 'E' (GPa)	Static Poison's Ratio 'ν'	Tensile Strength 'σ_{tB}' (MPa)	Point Load Strength $I_{S(50)}$ (MPa)
Barre Granite	212_3	82_3	0.16_3	12.70_6	7.69_8
Laurentian Granite	259_2	92_3	0.21_3	12.79_6	9.08_8
Stanstead Granite	173_3	66_3	0.16_3	7.88_6	6.43_8

Fracture Toughness and Sample Diameter

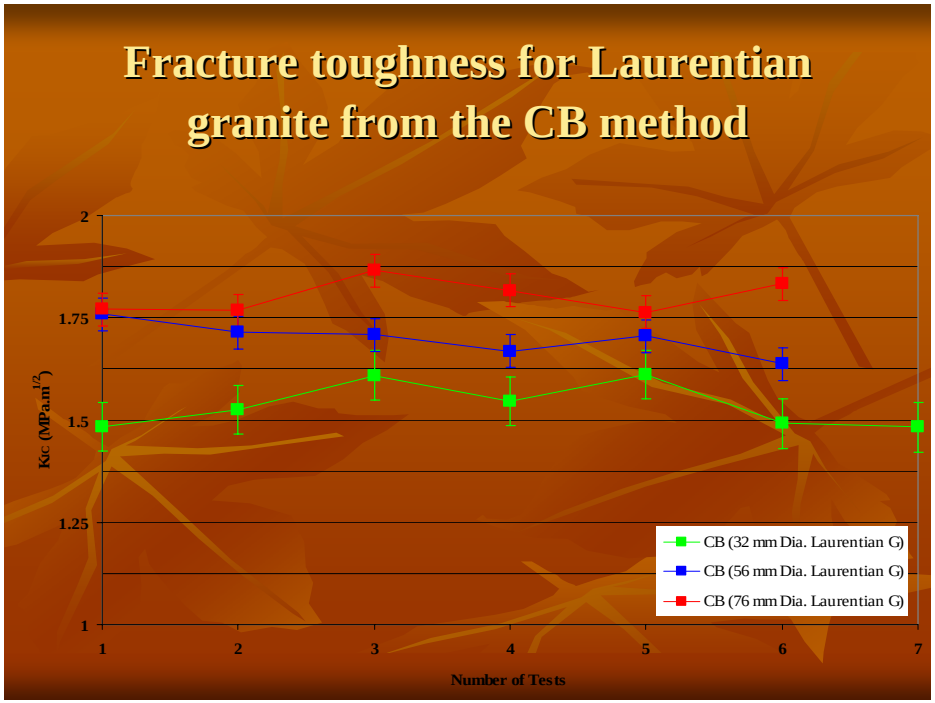
Fracture toughness values for Stanstead granite with CB method as a function of sample diameter



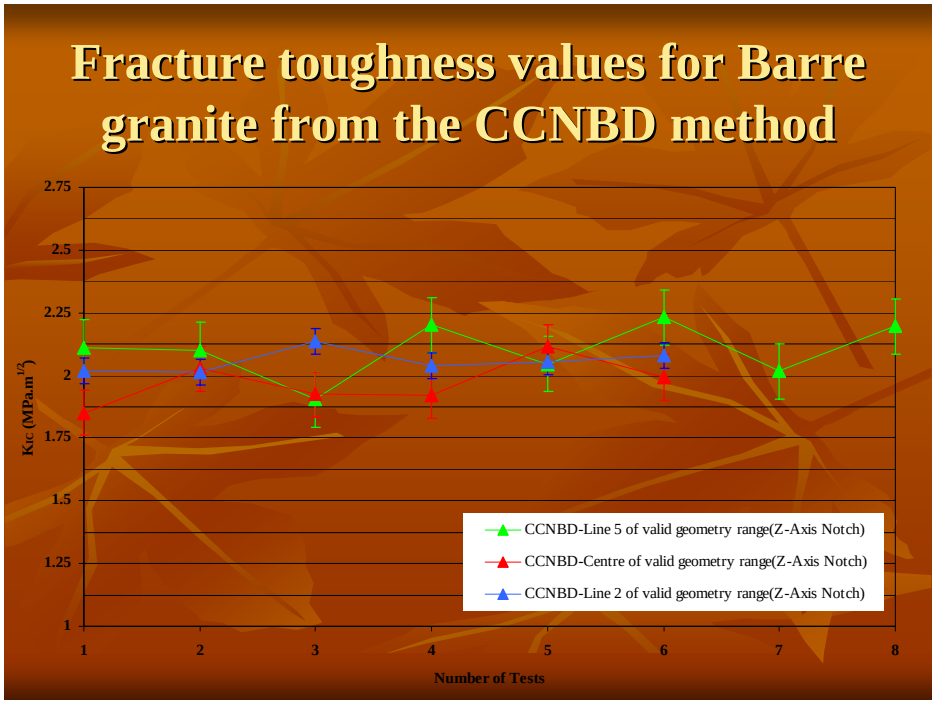
Fracture toughness values plot of the Barre granite from the CB method



Fracture toughness for Laurentian granite from the CB method



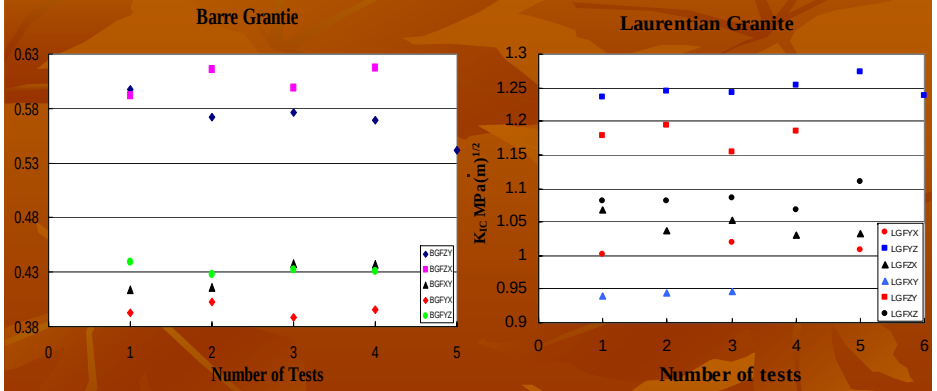
Fracture toughness values for Barre granite from the CCNBD method



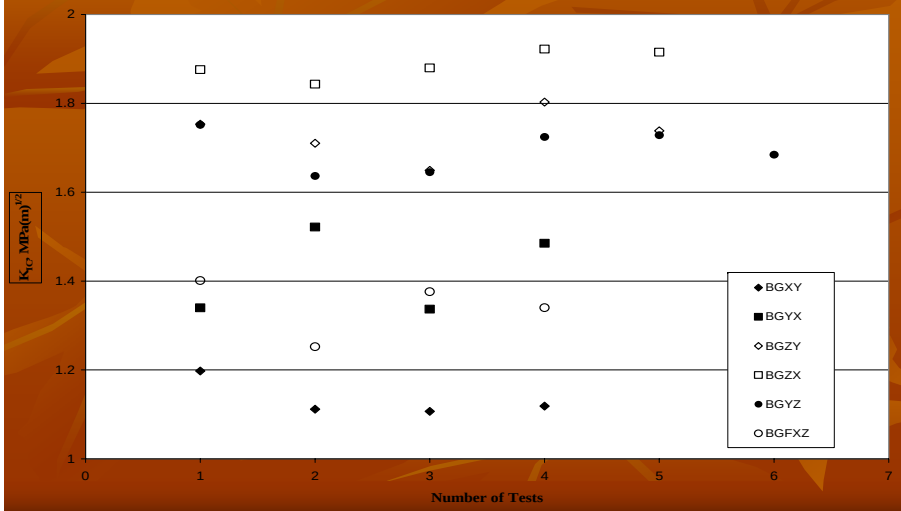
How unique is Fracture Toughness for a typical rock?

Fracture toughness K_{IC} measured along 6 orthogonal planes to determine isotropy of fracture toughness in selected rocks

Variation of K_{IC} along Different Planes for Tested Granites



Fracture Toughness Anisotropy in Barre granite



Systematic and large variations in the measured value of fracture toughness in apparently homogeneous granite, along different directions.

Reasons for this marked anisotropy?

Characteristics of Crack in Fracture Toughness Test

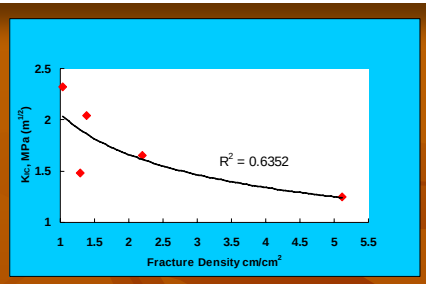
- *Macro-crack* extended from notch tip
- Role of pre-existing *micro*-structure not considered
- Assumption certainly wrong because stress concentrations must develop at tip of microstructure

Micro-structure and Fracture Toughness

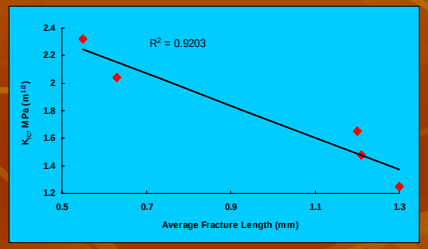
Micro-structure:

(grain size, micro-crack dimension, and micro-crack density)

Example of FT dependence on Micro-fracture characteristics



Variation of Fracture Toughness with Average Fracture Density for the five Granites

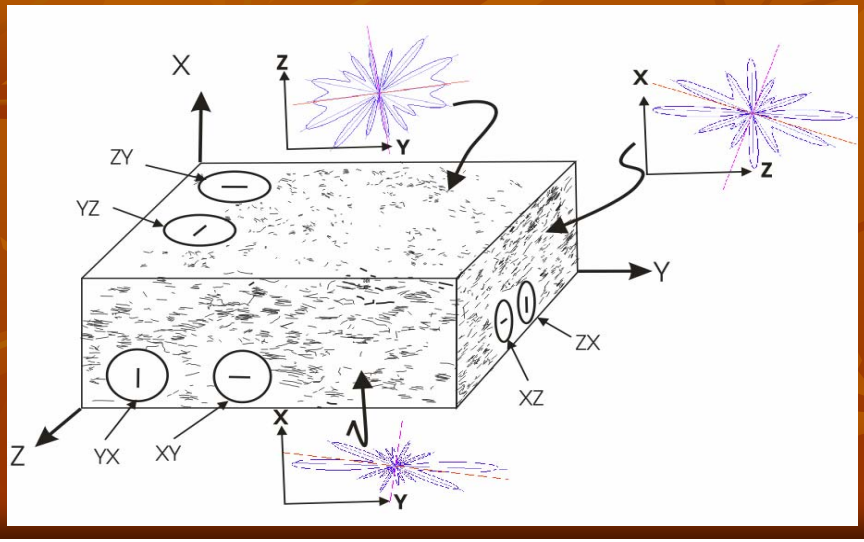


Variation of Fracture Toughness with Average Fracture Length for the five Granites

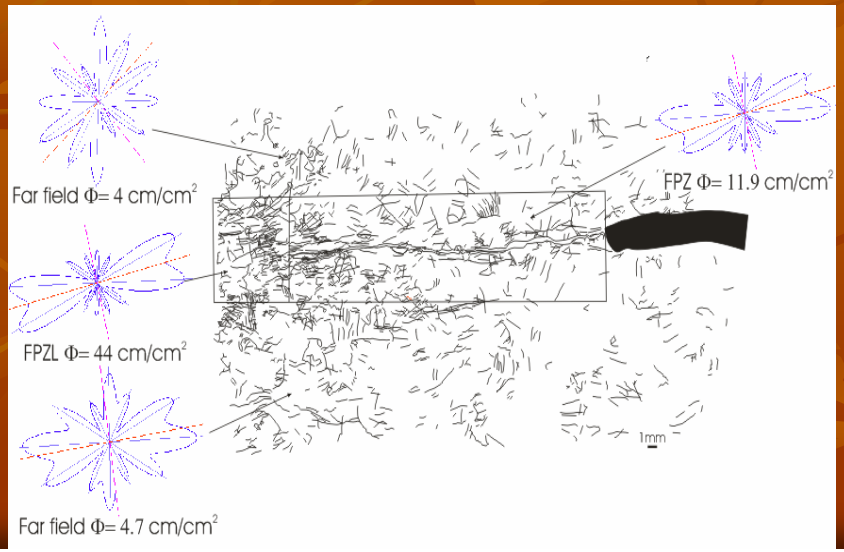
Need for Systematic Investigation of the Correlation between FT and Micro-structure

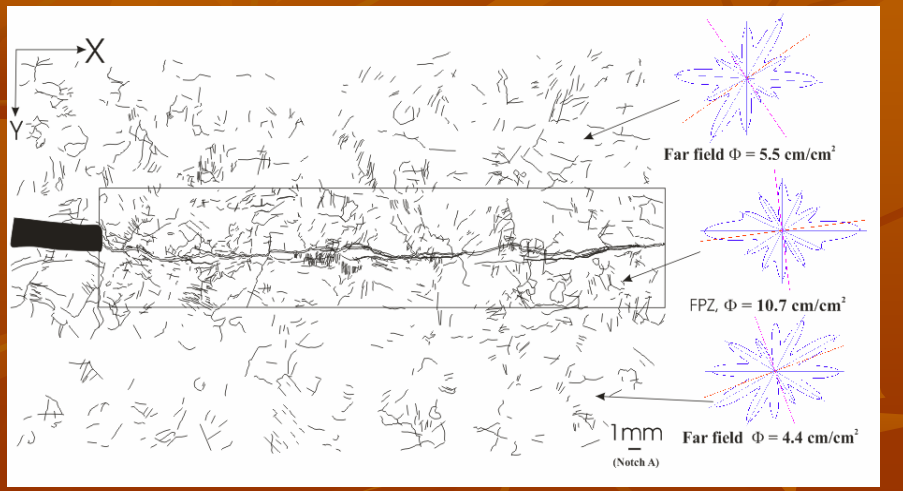
Mapping of micro-fracture in 3D, and Testing fro FT along specific Planes

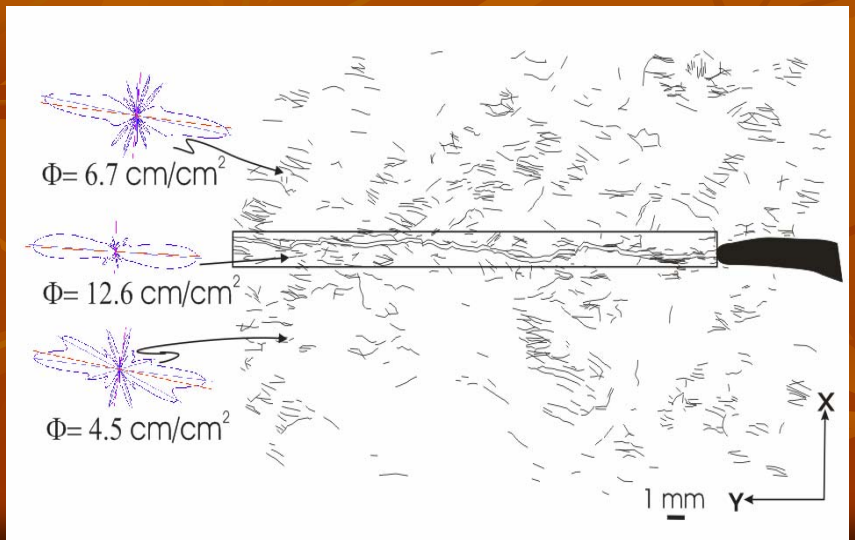
Orientation and Density of Micro-cracks in Barre granite



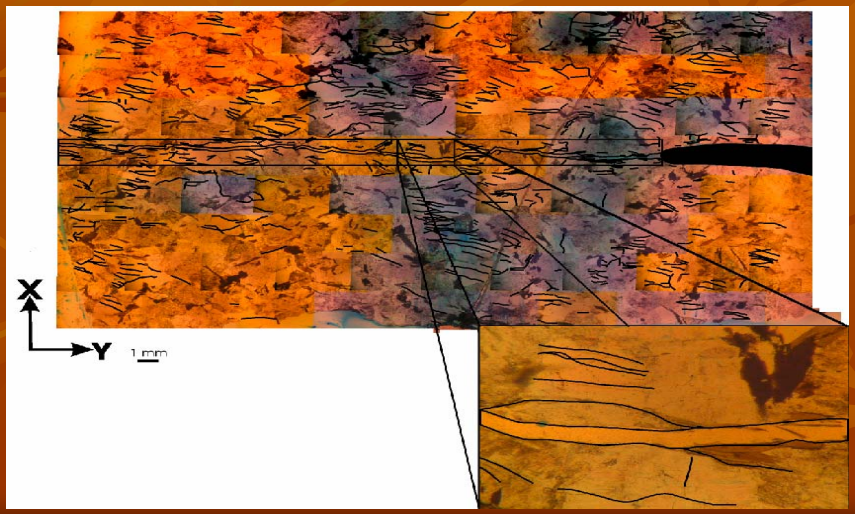
Micro-structure characteristics surrounding Primary crack from Fracture Toughness test







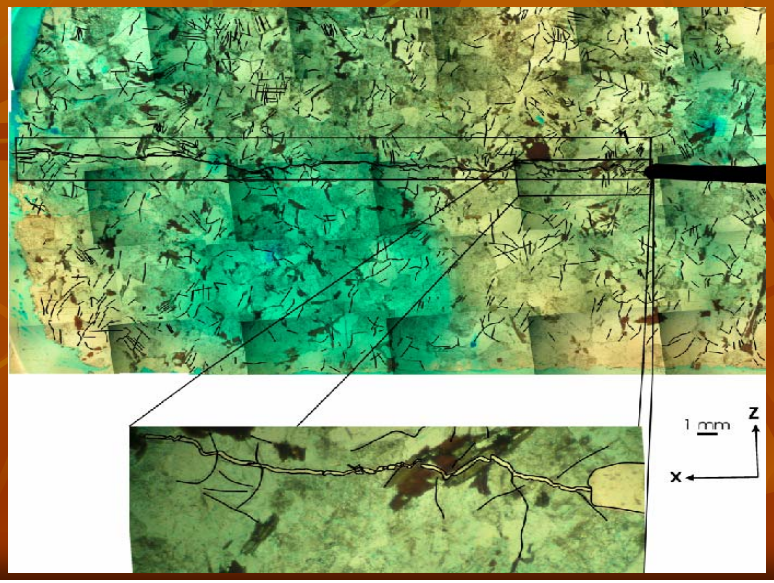
Primary crack and Micro-structure



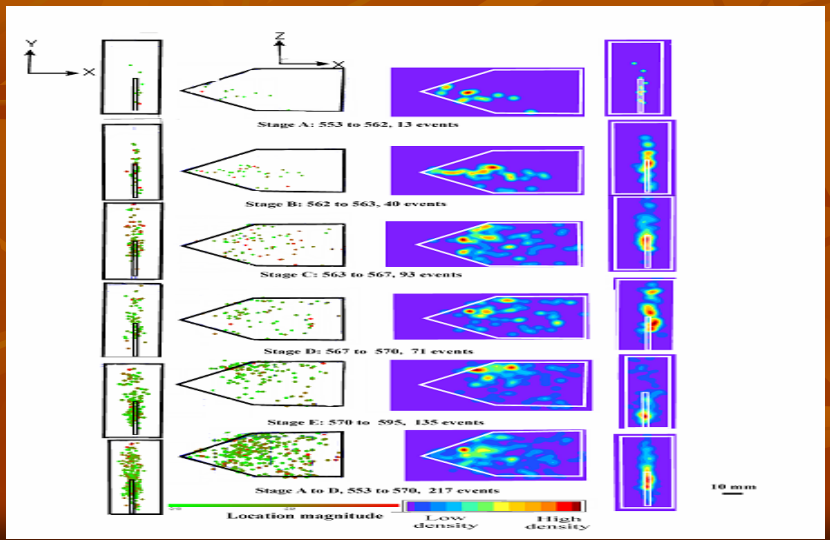
Interaction of Primary Crack and Micro-fracture

Fracture Process Zone in vicinity of Primary crack and Micro-structure

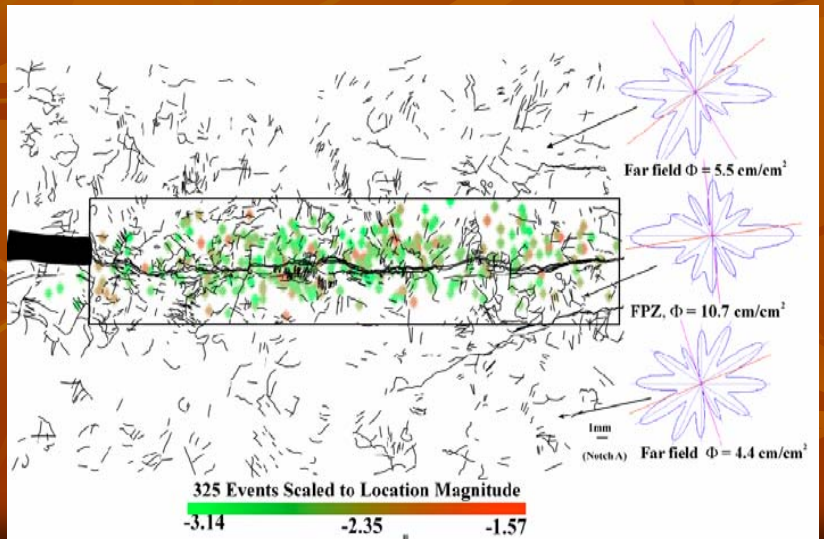
Primary crack and Micro-structure



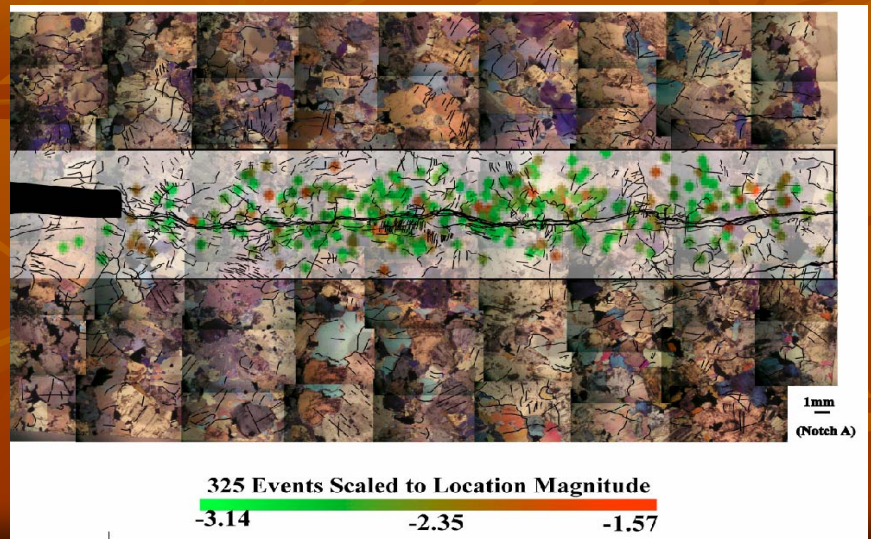
Tracking of Primary Crack with Acoustic Emission



Magnitude of Acoustic Emission and Primary Crack Progression



Micro-structure density around Primary crack and Fracture Process Zone (FPZ)



Conclusions

- Discrepancy between CB and CCNBD methods due to use of incorrect equation
- Incorporation of further ‘refinements’ in calculation methods found ineffective in eliminating discrepancy
- Recommended sample diameter to be 54 mm for fine/medium grained rock and 75 mm for coarse grained rock
- Fracture toughness shown to be highly variable in anisotropic rocks
- Anisotropy in fracture toughness critically related to microstructure and its orientation

Future Research

- Fracture toughness under ***static*** vs. ***dynamic*** loads, i.e. ***strain-rate effects***
- Role of micro-structure under high strain-rate loading
- Fracture process zone (FPZ) and micro-structure under dynamic loads
- Correlation of fracture toughness with strain rate, dynamic strength, micro-structure, temperature, and acoustic emission, parts of on-going research