Deciphering Heterogeneous Mechanical Stability in an Exhumed Fault Zone through a Structural-Geotechnical Approach: A Case Study from the Great Glen Fault, Scotland

[1]*Namgwon Kim, [1]Zoe K. Shipton, [1]Yannick Kremer, [2]Christopher D. Jack

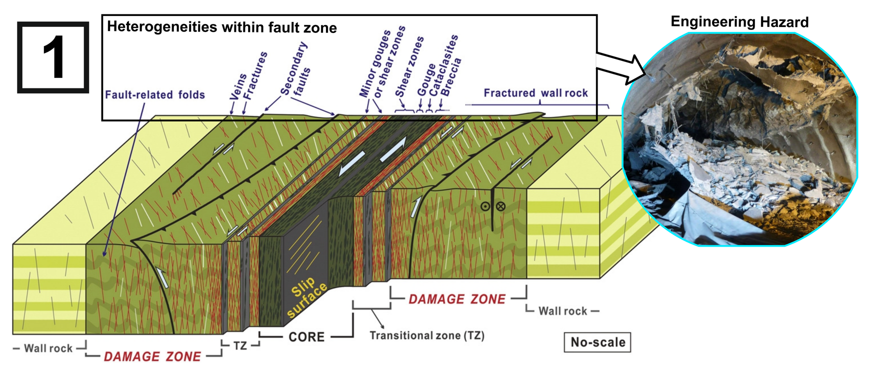
[1]Department of Civil and Environmental Engineering, University of Strathclyde, [2]COWI, 310 St Vincent St, Glasgow

*namgwon.kim@strath.ac.uk

University of Strathclyde Engineering
COWI

Abstract

1. Introduction



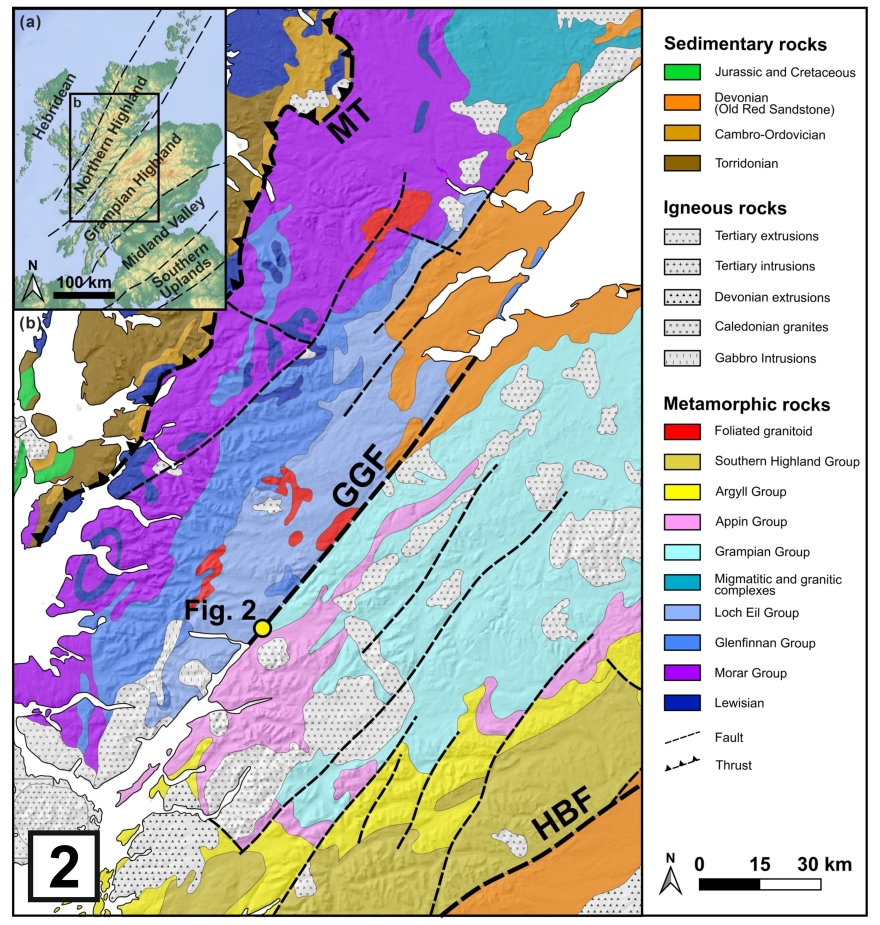
▲ *Figure 1. Schematic block diagram for strike-slip fault zone showing structural heterogeneities causing engineering hazards (modified from Choi et al., 2016).*

- Understanding ground condition is crucial in subsurface engineering projects to plan engineering mitigations.
- Faults are 3D zones with heterogeneous internal architectures, exhibiting mechanical variabilities and causing engineering hazards (Fig. 1).
- Interrelationship between structural and engineering heterogeneities could inform engineering mitigation.

→ Key Question: How much the geological deformation history, with sets of overprinting geological processes, can be used to inform engineering understanding of a rock mass.

- This study compares and contrasts geological and engineering approaches on rock mass characterisation to evaluate and forecast mechanical stability.

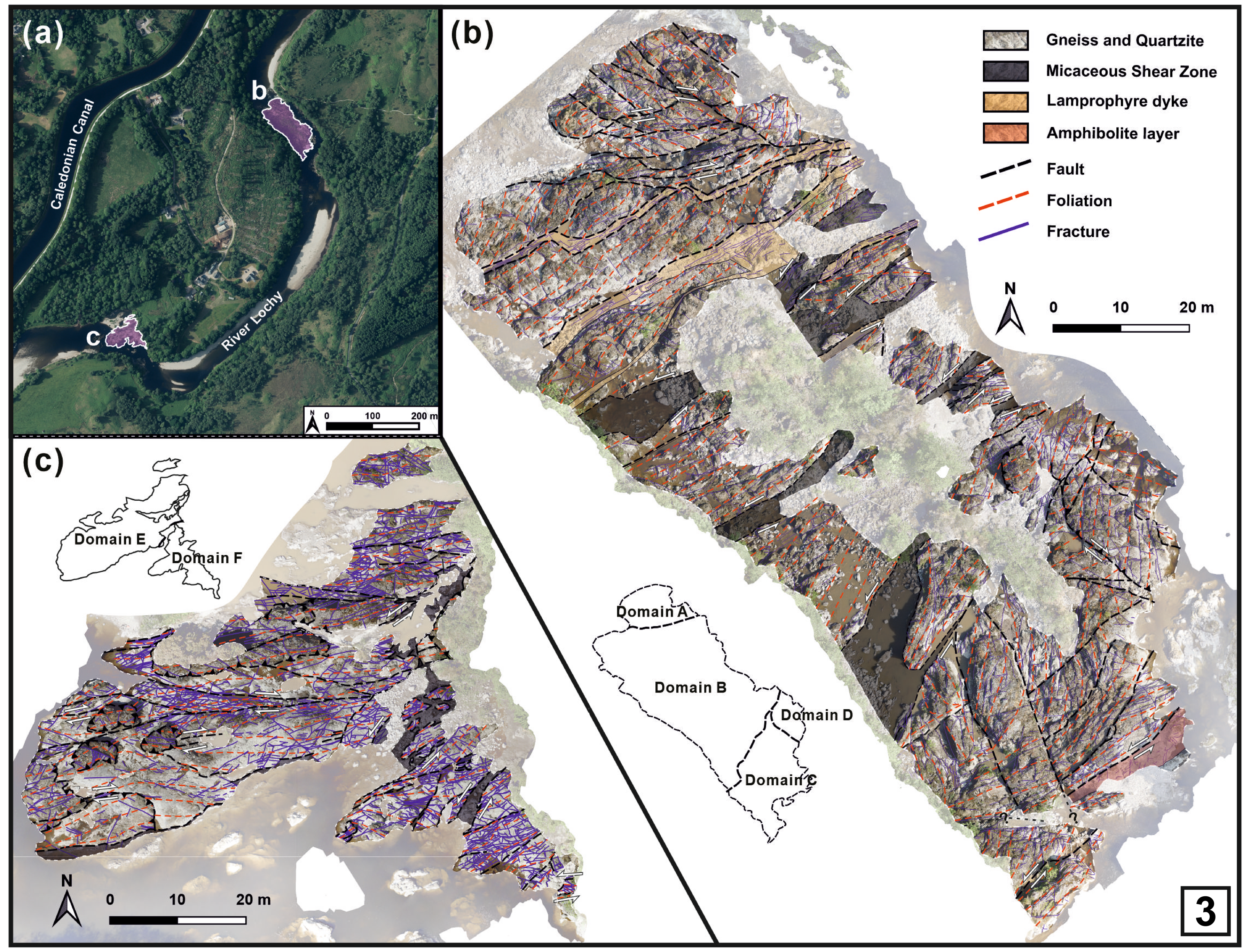
2. Study Area



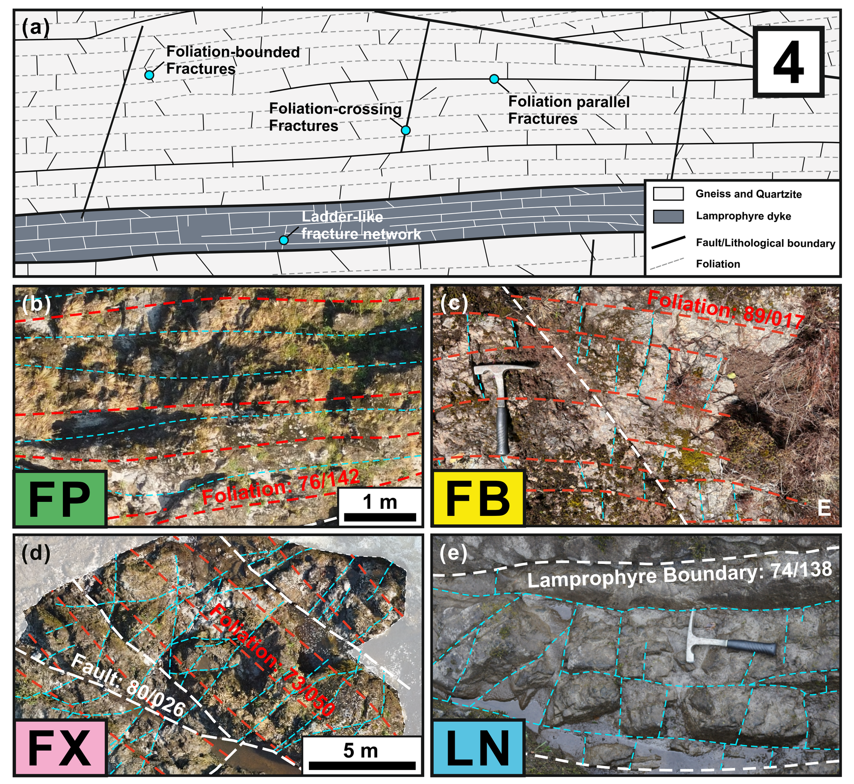
- Since the early Paleozoic, Great Glen Fault (GGF) has accommodated several 100s km of displacement with multiple reactivations and exhumation (Fig. 2).
- GGF is a up to approximately 6 km wide zone composed of various belts of fault rocks and intensely fractured wall rocks.
- Torcastle North (TCN) and South (TCS) outcrops, fault-bounded sliver in the centre of GGF, preserve structural elements (shear zones, foliations, faults, and fractures) formed in the mid-crustal to upper-crustal level (Fig. 3).
- Psammitic to pelitic gneiss with local amphibolites and lamprophyre intrusions.
- Highly heterogeneous structural elements while showing local consistency in geometry and distribution pattern.
- Structural domains are classified by a consistent pattern of structural elements and lithological distribution.

◀ *Figure 2. (a) Tectonostratigraphic terranes in the Northern Britain (modified from Strachan et al., 2002). (b) A regional geological map of Scotland (modified from Searle, 2022) showing location of the Torcastle block (Fig. 2). MT: Moine Thrust, GGF: Great Glen Fault, HBF: Highland Boundary Fault.*

▼ *Figure 3. (a) Location of Torcastle outcrops along the River Lochy. Orthophoto-maps of the Torcastle (b) North and (c) South outcrops showing the detailed distribution of host rock types, foliations, faults, fracture traces, and structural domains.*



3. Fracture Classification



▲ *Figure 4. (a) Schematic illustration of four fracture types on the Torcastle block. Field observations of (b) FP, (c) FB, (d) FX, and (e) LN fractures. Red and cyan dashed lines represent the foliation and fracture traces, respectively.*

- Fractures are categorized into 4 types based on spatial distribution and geometric relationship with local foliations (Fig. 4a).

Different with fracture set !

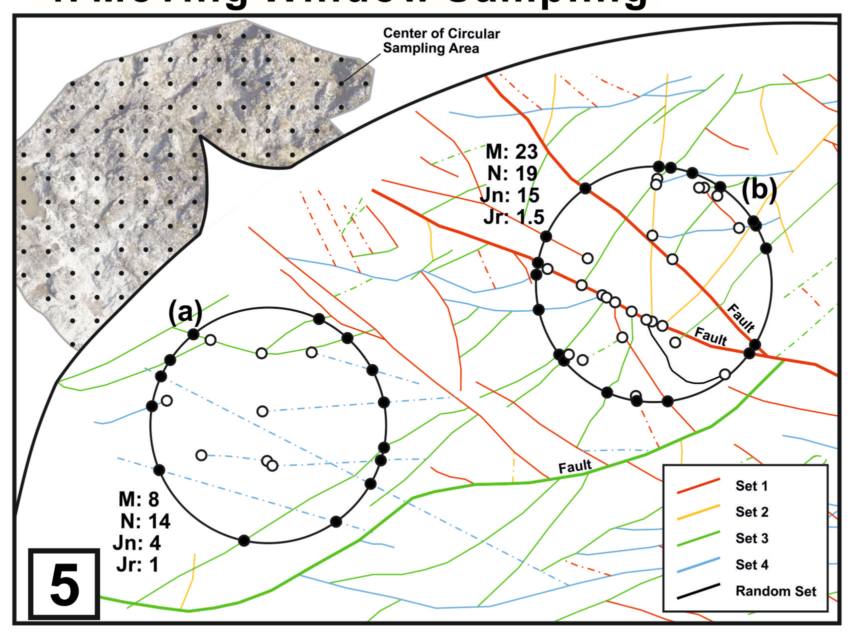
> Foliation-parallel (FP) fractures (Fig. 4b)
- Parallel to local foliations.
- Several decimetres to metres long.

> Foliation-bounded (FB) fractures (Fig. 4c)
- Highly oblique to the local foliations.
- Several centimetres to decimetres long.
- Terminate at the foliation or FP fracture planes.

> Foliation-crossing (FX) fractures (Fig. 4d)
- Cross-cut local foliations.
- Several metres long.
- Bounded by local faults, shear zone, or large FP fractures.

> Ladder-like network (LN) fracture (Fig. 4e)
- Systematic fractures confined in lamprophyre dykes.
- Composed of two fracture sets, oblique & parallel to dyke boundary.

4. Moving Window Sampling



▲ *Figure 5. Graphical example of moving circular sampling method illustrating how Jn, M, N, and Jr were calculated. Solid lines are undulating, and dash-single dotted lines are planar fracture traces, respectively, with different colours for each set.*

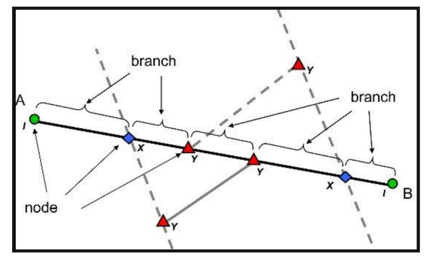
- Using circular sampling window (radius: 1.5 m) on fractures & faults trace map for analysing
- Topological Nodes,
- Fracture Density ($M/2\pi r^2$),
- Sub-parameters of Q-system.

- Fracture sets are classified based on the orientation and geometrical relationship between each set.
- We used a simplified Q-system with fixed Ja (1.0), Jw (1.0), and SRF (5.0) to estimate mechanical stability of TCN and TCS.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

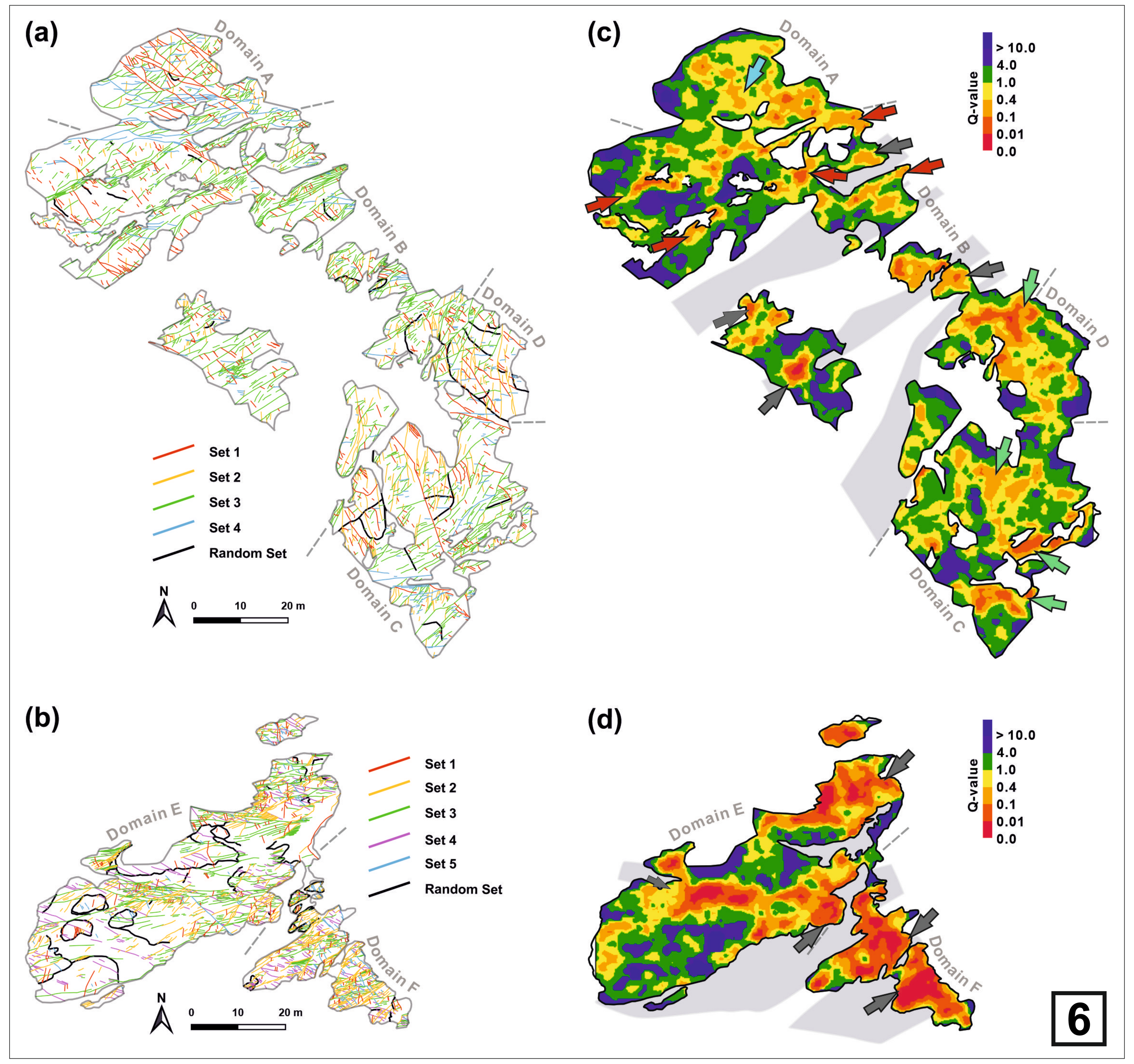
where RQD is the Rock Quality Designation
J_n is the joint set number
J_r is the joint roughness number
J_a is the joint alteration number
J_w is the joint water reduction factor
SRF is the stress reduction factor

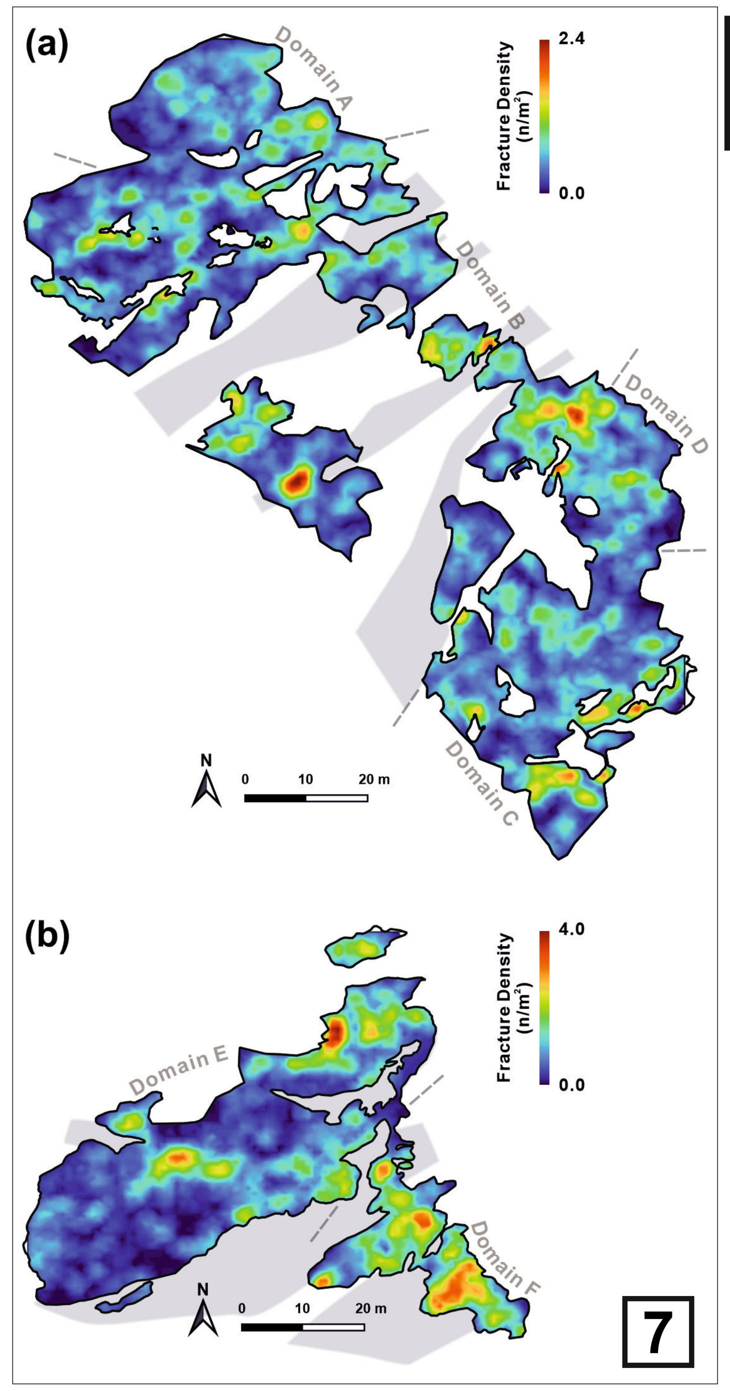
Definition of Q-value



Topological nodes (Sanderson and Nixon, 2015).

5. Parameter Maps & Correlation Coefficients (R^2)





- Low Q-value (< 1.0) zones are related to (1) major shear or fault strands and embedded blocks, (2) intruded igneous dykes, (3) abutting areas of faults with different orientations, and (4) highly rotated blocks showing re-oriented local foliations (Domain A in TCN; Fig. 6).
- Low Q-value and high X & Y node density (mechanically unstable) mainly accompanied by high fracture density area except Domain A (Figs. 7 and 8).
- Domain A shows relatively high Correlation coefficient (R^2) value from X & Y node density & Jn and low R^2 value from fracture density on low Q-values (Table 1).
- Mechanical weakness on Domain A is related to abundant intersection of FP and FX fractures.
- Highly rotated foliations in Domain A could have resulted in a higher angle to tectonic compression leading development of abundant FX fractures (c.f. Tien et al., 2006).

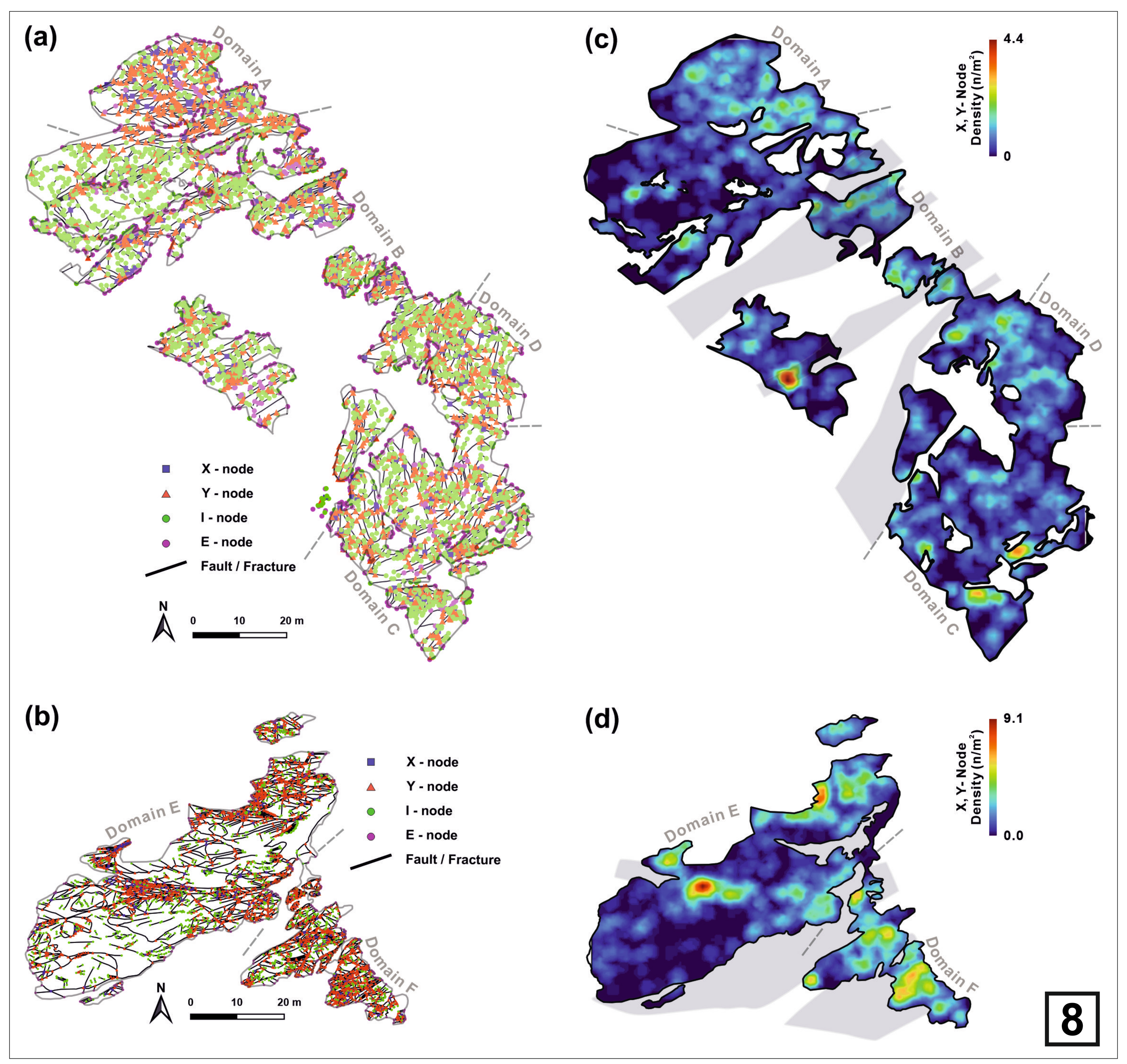
▼ *Table 1. Correlation coefficient (R^2) values between Q-value below 1.00 and various parameters in sampling windows of TCN, TCS, and each structural domain.*

R2 with Q-values below 1.00	Whole TCN	Domain A	Domain B	Domain C	Domain D	Whole TCS	Domain E	Domain F
Fracture density	0.79	0.71	0.80	0.79	0.76	0.96	0.94	0.98
RQD	0.54	0.63	0.52	0.56	0.59	0.50	0.51	0.51
Jn	0.14	0.23	0.16	0.15	0.13	0.19	0.17	0.20
Jr	0.02	0.00	0.02	0.02	0.16	0.00	0.01	0.01
X and Y node density	0.39	0.52	0.43	0.39	0.36	0.83	0.80	0.86

◀ *Figure 6 (left). Trace maps of faults and fractures in (a) TCN and (b) TCS with different colours for each set. Q-value map of (c) TCN and (d) TCS emphasizing rock mass qualities lower than 'good' (10 < Q < 40). The coloured arrows indicate the location of the structural features showing low Q-value zones. The inferred traces of major micaceous shear zones are marked as grey areas.*

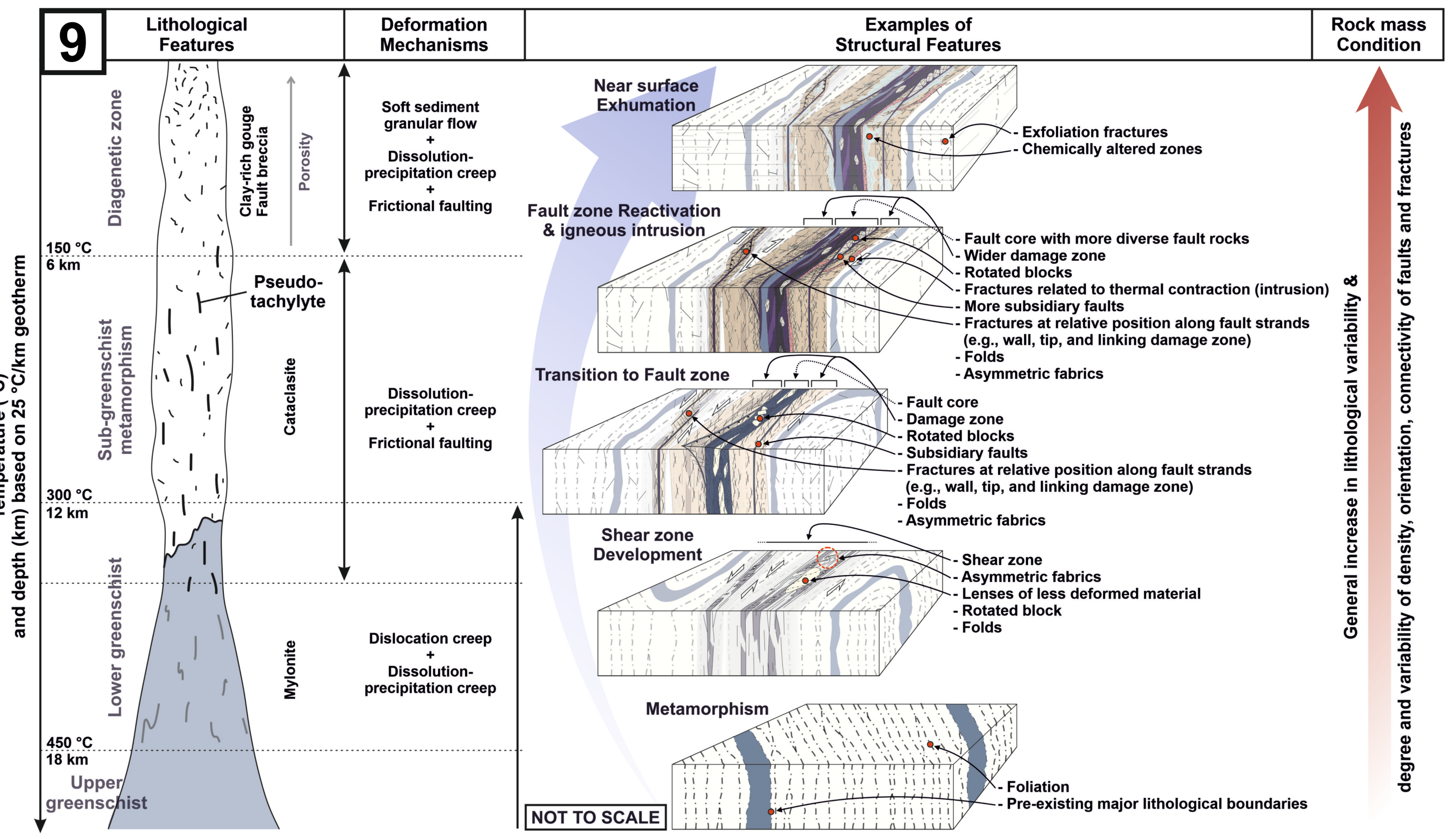
◀ *Figure 7 (right). Fracture density map of (a) TCN and (b) TCS with warmer colours for higher fracture densities and vice versa (sampling window radius: 1.5 m).*

▲ *Figure 8 (lower left). Distribution of topological nodes in (a) TCN and (b) TCS shown in different colours produced by NetworkGT software. The density map of X and Y nodes in (c) TCN and (d) TCS reflecting fracture connectivity (sampling window radius: 1.5 m).*



6. Conclusion

- Heterogeneous internal architecture and mechanical stability in outcrops of exhumed crustal-scale strike-slip fault zone.
- Fracture geometry and distribution are highly variable, but clearly related to the pre-existing local foliation trend and dyke distribution.
- Spatial distribution of mechanically unstable zones reflects the close interplay between geological deformation processes and resultant mechanical stability during the fault zone evolution (Fig. 9).
- Comprehensive understanding of the fault zone internal architecture (accumulated through the evolution history), is crucial to anticipate the spatial pattern of the mechanical variability.



▲ *Figure 9. Conceptual model for evolution of a crustal-scale fault zone exhumed from the mid-crustal to near surface environment. Lithological cross section on left hand side modified from Sibson (1983) and Scholz (1988). Block diagrams show examples of the structural features developed at each evolution stage, related to the lithological and structural variabilities contributing to general increasing trend in mechanical complexity of the rock mass. Note that the timing of igneous intrusion and chemical alteration are arbitrary.*