The Other Ductile – Brittle Transition Zone:

Syn-Deformational Lithification Within the Shallow Subduction Shear Zone and its Implications for Earthquake Nucleation

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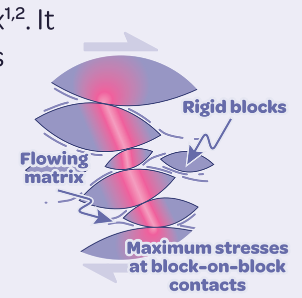
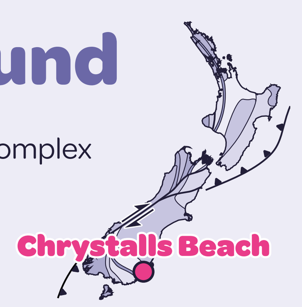
Introduction

Mélange rheology is understood as a two-phase mixture of internally-homogenous, strong & competent blocks within a flowing, weak & compliant matrix[1,2]. It follows that earthquakes within mélanges occur when blocks jam the subduction channel & must break to allow continued shear[1,2].



Recent work shows that **mélange rheologies evolve through time**[3,4,5] & that blocks are internally heterogenous[6]. Our detailed 3D outcrop & microstructural characterisation of the Chrystalls Beach mélange (New Zealand) reveals that coincident lithification & shearing causes fragmentation of blocks without interactions with neighbouring blocks.

Background



The Chrystalls Beach Complex is a terrane-bounding mélange belt within the Mesozoic Otago Schist accretionary complex formed at the paleo-subduction margin of Gondwana[1,7]. This unit consists of blocks of deformed sandstone, chert and rare altered basalt within a pelitic matrix. Peak metamorphism did not exceed ~300°C and ~550 MPa; therefore **deformation occurred before the onset of quartz crystal-plasticity**[1].

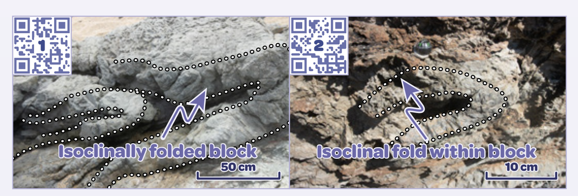
1. Soft-Sediment Deformation

Initial deformation occured during **subduction of unconsolidated interbedded sediment**[7], creating ubiquitous ductile (e.g., folding & boudinage) & fluidisation (e.g., injectites) structures.

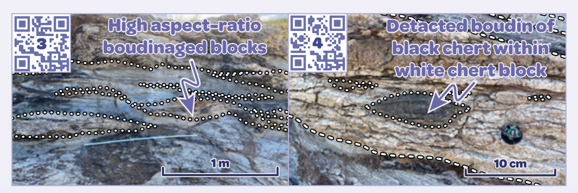
Folding reveals initial shortening at the frontal toe

1 ▶ Some blocks are Isoclinally folded but dominant structural style is long-axis extension.

2 ▶ Block with an internal isolated isoclinal fold hinge indicating folding and stratal disruption[8] occured within the lithologies that would become blocks, possibly predating mélange formation.



Pervasive boudinage indicates early ductile rheology



◀ 3 Chains of blocks with pinch-&-swell structures.

◀ 4 Internal boudin of black chert within block of white chert featuring internal boudinage & anastomosing fracture cleavage.
As this mélange was never subducted to depths of quartz crystal-plasticity, this ductile deformation must have occured prior to lithification.

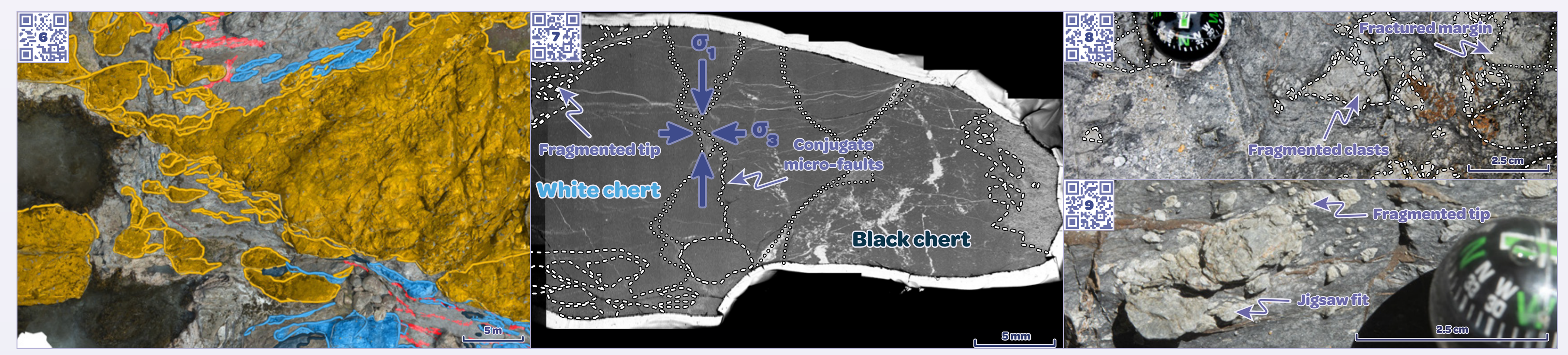
Ubiquitous mudstone injectites indicate fluidised sediment

5 ▶ Injectite of mudstone deep within the core of a sandstone block indicates both that the mud was fluidised and that sand was weakly cohesive & able to both fracture and flow.

2. Embrittlement & Fragmentation

As the mélange lithifies, embrittled blocks experience fragmentation by fracturing & brecciation consistent with long-axis–parallel extension – the same stress regime which caused boudinage when the blocks were ductile. Brecciation is strongest at block tips & margins, producing **weak margins & strong cores.**

Blocks fragment at the ductile–brittle transition

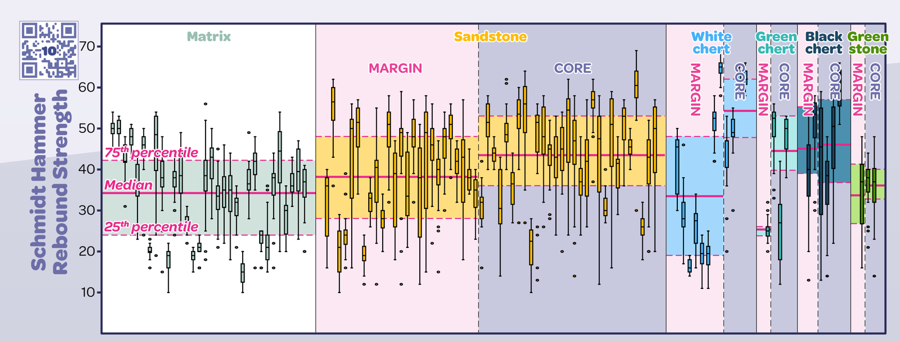


6 ▲ Interpreted photogrammetric model of fragmented sandstone mega-block.

7 ▲ Interpreted SEM-BSE image of a fragmented chert block showing jigsaw fit at the tips & conjugate micro-faults.

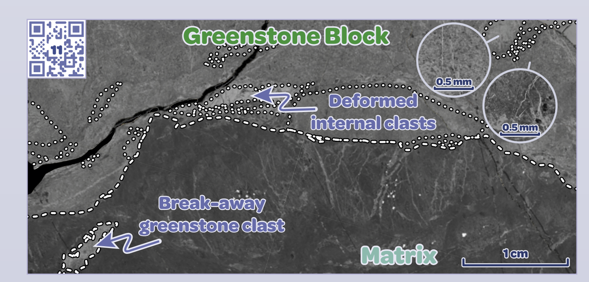
8 ▲ Sandstone mega-block with fragmented margin.
9 ▲ Fragmented clast with jigsaw fit between clasts.

Blocks have weak margins & strong cores



◀ 10 In-situ Schmidt rebound hammer strength results showing that block margins are markedly weaker than block cores and that the strengths of block margins approaches that of the matrix.

Basalt blocks undergo opposite brittle–ductile transition

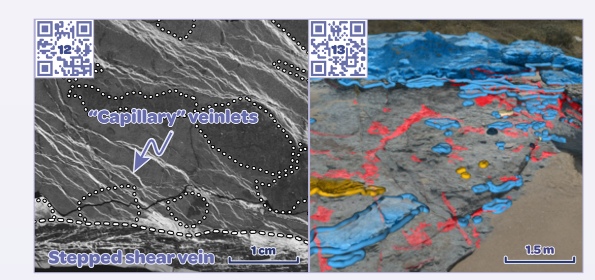


11 ▲ Interpreted SEM-BSE image of altered basalt block showing brecciated texture over-printed by alteration. Fragments of altered basalt show pinch-and-swell & intermingling textures. Insets show relict crystalline texture within internal clast core whereas outside clasts the greenstone is almost entirely altered to clay.

3. Strain Localisation

Continued lithification leads to further localisation of shear, exemplified by stepped shear veins[9]. As these veins are not themselves deformed, further distributed deformation did **not** follow formation of these veins.

Shear zones & veins represent localisation of strain away from distributed shear in the matrix

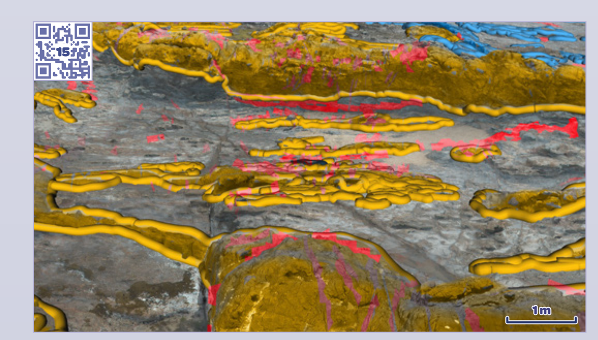


◀ 12 Interpreted SEM-BSE image showing the relationship between a stepped shear vein and the anastomosing "capillary" veinlets.
◀ 13 Interpreted photogrammetric model showing anastomosing network of stepped shear veins. These form a network with straight veins in blocks at a high angle to block long axes.

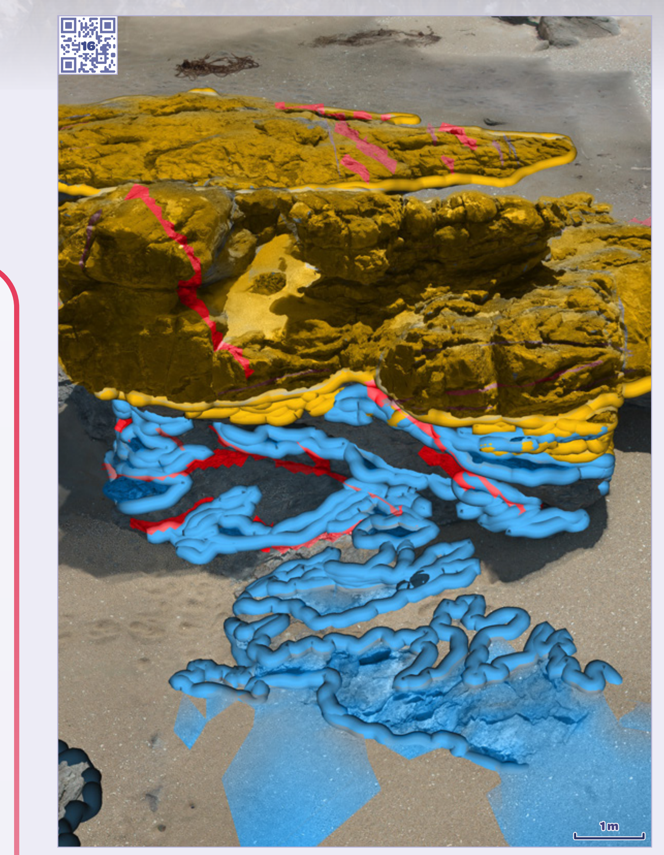
Fluid over-pressure pulses produce complex vein networks

14 ▶ Dense mesh of straight veins within a sandstone block in stockwork pattern consistent with low effective stresses due to fluid over-pressure, possibly due to seismogenic fluid-pressure pulses. In 3D, these veins are more commonly at a high angle to the block long-axes.

Block-on-block contacts are not sites of increased fractures



◀ 15 Interpreted photogrammetric model showing no association between block-on-block contacts and increased fracture density. This challenges the notion that primarily blocks break in force-chains due to block-on-block jamming. Instead, the densest vein networks occur in proximity to thick stepped veins.



Conclusions

As blocks can extensively fracture without block-on-block contact, **mélanges with low block-to-matrix ratios may also nucleate earthquakes.**

Mélange blocks have weaker margins and stronger cores. As such, the **rheological contrast at lithological contacts may be less than otherwise expected** although they are still often exploited by shear zones.

Rigid blocks in a ductile matrix – the scenario in which jammed blocks break in force-chains – is only one of **a spectrum of rheological relationships** mélanges may transition through as they subduct.

References

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