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A Glimpse into the SUBDUCTION ZONE PLATE INTERFACE

3D structural and mechanical mapping of the Chrystalls Beach mélange, New Zealand

Motivation

Subduction zone plate boundary interfaces are some of the largest shear zones on our planet & are host to the largest earthquakes, plus other slip phenomena[1]. These zones are often highly heterogenous mélanges. The geometries of blocks, proportion of blocks to matrix, and the difference in rheologies between block populations, & between blocks & matrix, influence the mechanical behaviour of these mélange zones[2,3]. Here we report a detailed multi-scale 3D characterisation of the material properties, block geometries, & fracture networks within the Chrystalls Beach mélange, New Zealand.

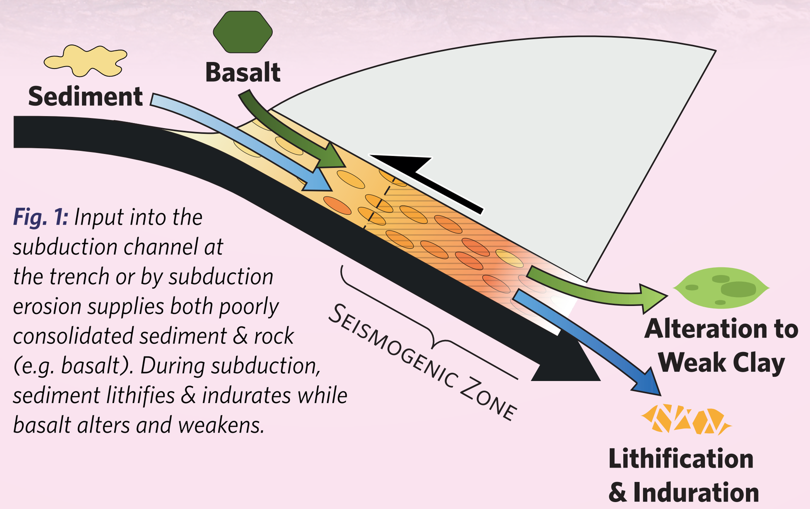
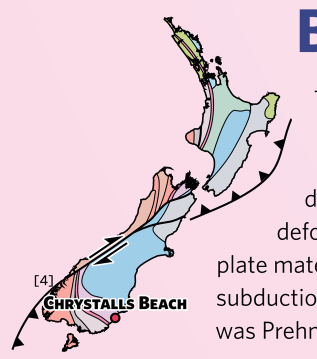


Fig. 1: Input into the subduction channel at the trench or by subduction erosion supplies both poorly consolidated sediment & rock (e.g. basalt). During subduction, sediment lithifies & indurates while basalt alters and weakens.

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[5]. This unit consists of deformed trench-fill sediments mixed with eroded upper-plate material — including exotic blocks of basalt — within the subduction shear zone (Fig. 1). Peak metamorphism of this unit was Prehnite-Pumpellyite facies[5].

Block geometries & vein networks in these outcrops have been well-characterised & reveal mutually overprinting continuous & discontinuous deformation in a fluid-overpressured regime[6].

This mélange represents the plate boundary shear zone in the shallow subduction zone up to the depth of the shallow seismogenic zone[3,5,6].

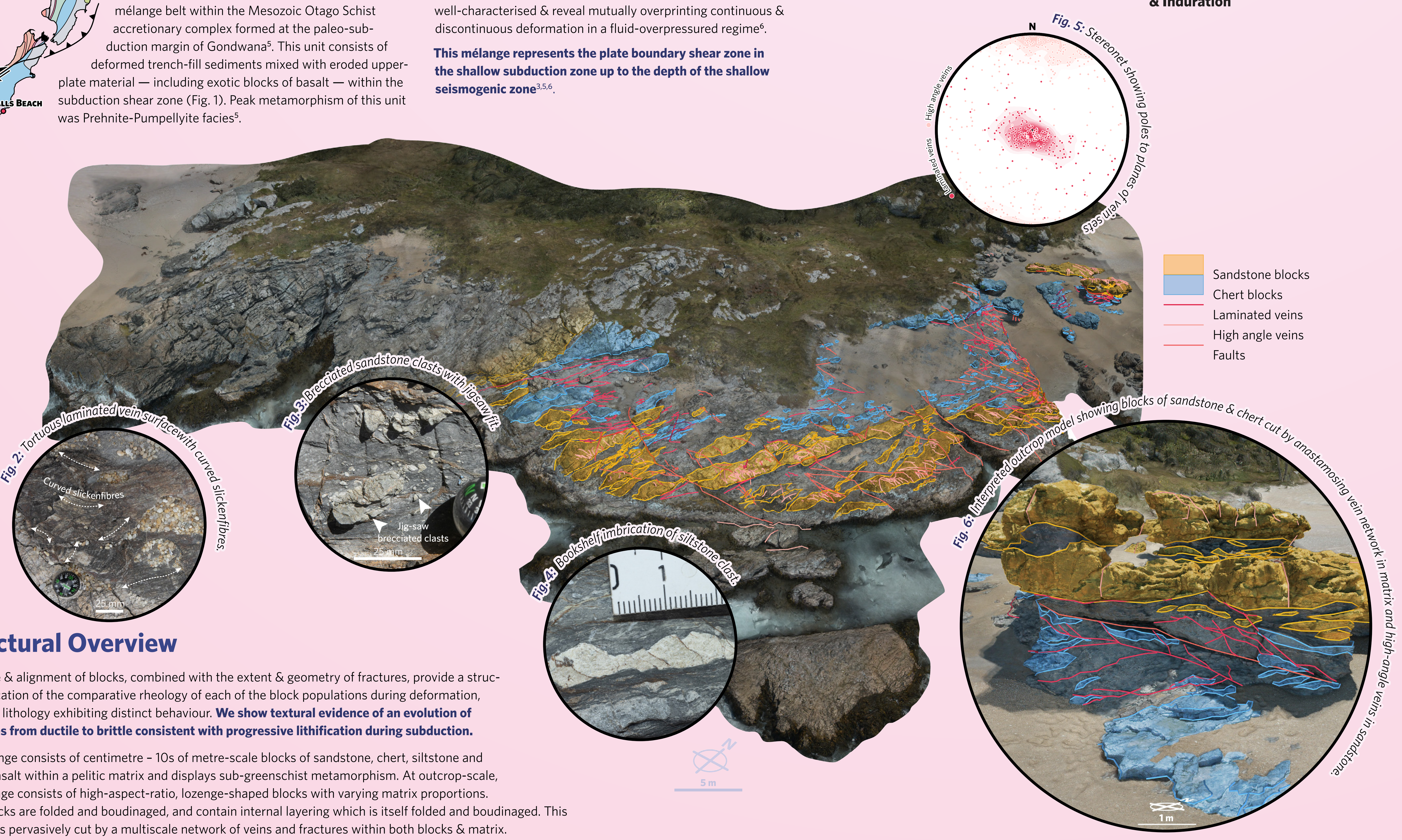


Fig. 5: Stereonet showing poles to planes of vein sets.

Fig. 2: Tortuous laminated vein surface with curved slickenfibres.

Fig. 3: Brecciated sandstone clasts with jigsaw fit.

Fig. 4: Bookshelf imbrication of siltstone clast.

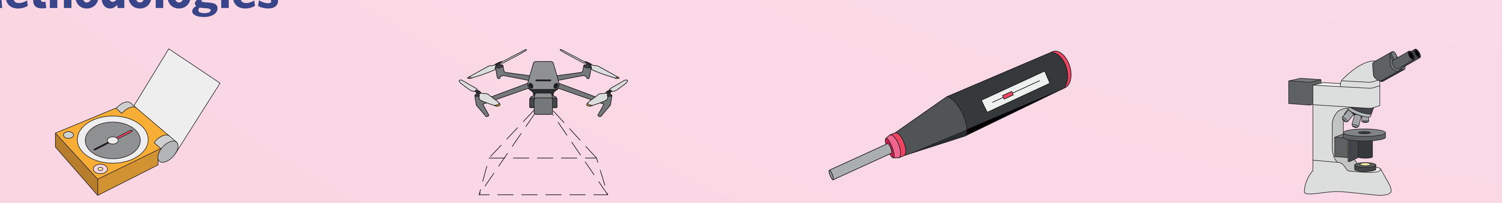
Fig. 6: Interpreted outcrop model showing blocks of sandstone & chert cut by anastomosing vein network in matrix and high-angle veins in sandstone.

Structural Overview

The shape & alignment of blocks, combined with the extent & geometry of fractures, provide a structural indication of the comparative rheology of each of the block populations during deformation, with each lithology exhibiting distinct behaviour. **We show textural evidence of an evolution of rheologies from ductile to brittle consistent with progressive lithification during subduction.**

This mélange consists of centimetre – 10s of metre-scale blocks of sandstone, chert, siltstone and altered basalt within a pelitic matrix and displays sub-greenschist metamorphism. At outcrop-scale, the mélange consists of high-aspect-ratio, lozenge-shaped blocks with varying matrix proportions. These blocks are folded and boudinaged, and contain internal layering which is itself folded and boudinaged. This mélange is pervasively cut by a multiscale network of veins and fractures within both blocks & matrix.

Methodologies



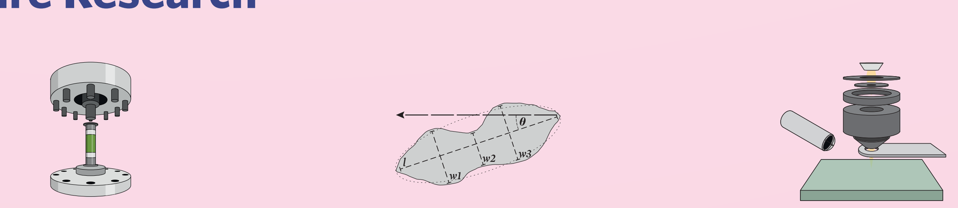
Field structural mapping
Detailed characterisation of block & vein proportions & geometries.

Photogrammetry & 3D analysis
Features picked from a high-resolution tiled photogrammetric outcrop model.

In-situ Strength Tests
Schmidt rebound hammer tests on interiors & margins of all block lithologies & matrix.

Optical & SEM microscopy
High-magnification analysis of fabric, fractures, & veins.

Future Research



Lab-Based Rock Mechanics
Triaxial strength & friction tests to complement & calibrate in-situ measurements & qualitative observations.

Shape Analysis
2D & 3D analysis of block & clast geometries across scales.

Clay Microtexture Analysis
Further SEM microscopy to assess alignment, fabric, & porosity of clay grains using BIB polishing & image analysis.

EVOLUTION OF RHEOLOGIES

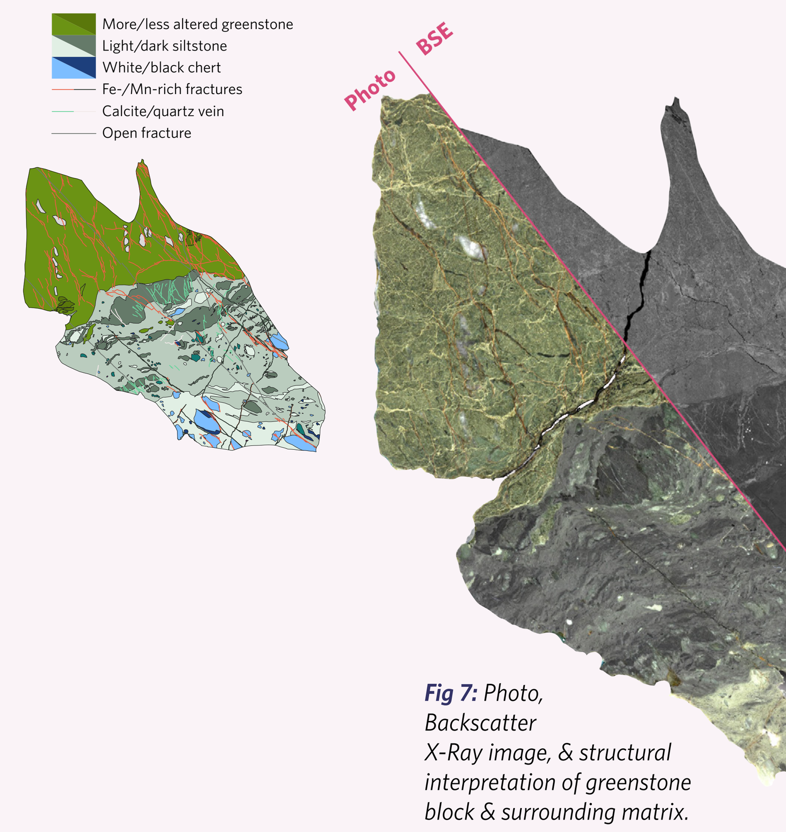


Fig 7: Photo, Backscatter X-Ray image, & structural interpretation of greenstone block & surrounding matrix.

Blocks & matrix display textural evidence of an evolution of rheologies, mostly from ductile to brittle, during subduction due to diagenesis, alteration, & shallow metamorphism.

Sandstones are poorly sorted with angular, poorly-aligned grains. Metre – 10s of metre-scale sandstone blocks have high aspect ratios, pinch-and-swell structures, and blunt tips; they display internal relict bedding which is extensively boudinaged, folded, and dismembered. Matrix injections are abundant at block margins and pelitic injectites are common in block interiors. Smaller blocks mostly resemble their larger counterparts; however, some blocks have low aspect ratios and are angular with jig-saw fit between brecciated clasts. Sandstone is commonly cut by veins and fractures. **Sandstones therefore exhibit textural evidence of early macroscopically-ductile deformation accommodated by cataclastic flow overprinted by brittle deformation responsible for brecciation and fracturing.**

Metre – 10s of metre-scale chert blocks have high aspect ratios and sharp tips, and feature internal relict bedding which is boudinaged, folded, and dismembered. Chert blocks feature folded veins and pressure-solution seams. The dominant fractures within these blocks follow relict bedding. Some <10 cm-scale chert clasts are angular and have low aspect ratios; these represent brecciated fragments. This suggests that the early history of mixed concurrent brittle and plastic behaviours overprinted by brecciation.

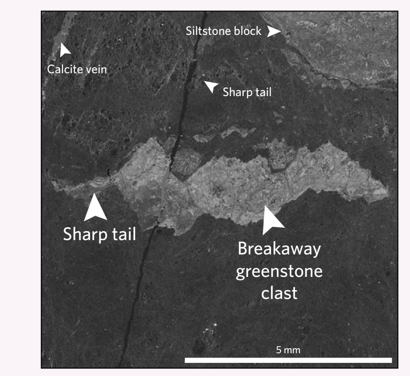


Fig 9: Lozenge-shaped breakaway clast of greenstone with irregular margins & sharp tips.

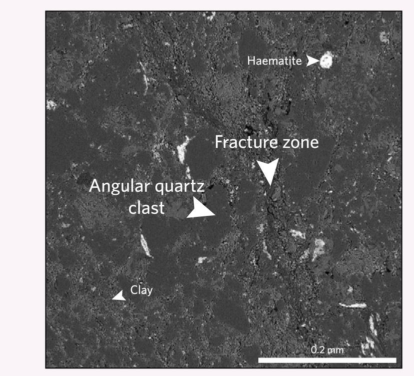


Fig 10: Angular & fractured clasts indicative of cataclastic flow.

Greenstone blocks originate from a basalt protolith that has been pervasively altered to clay. They are brecciated and contain clasts which retain pseudomorphs of their crystalline texture surrounded by sheared and more altered material. These blocks are cut by dismembered quartz veins and a dense network of anastomosing fractures. Adjacent to the blocks, breakaway clasts are lozenge-shaped, have irregular margins and sharp tips, and are more extensively altered than their parent block. **This indicates an early brittle history responsible for brecciation and veining overprinted by distributed deformation;** the geometric similarity between the breakaway greenstone clasts and the siltstone clasts suggests that the greenstone had weakened to a rheology akin to the weakest blocks in the mélange by the time of their inclusion.

The mélange matrix exhibits an extensive lozenge-shaped fabric with abundant clasts of siltstone. These clasts are moderate – high aspect ratio, and display strong alignment; clast margins are frequently irregular and exhibit mingling textures with the matrix, indicating rheological similarity. Aligned clay particles form sheared domains between lozenges. Matrix exhibits early history of pervasive distributed deformation overprinted by veins and fractures.

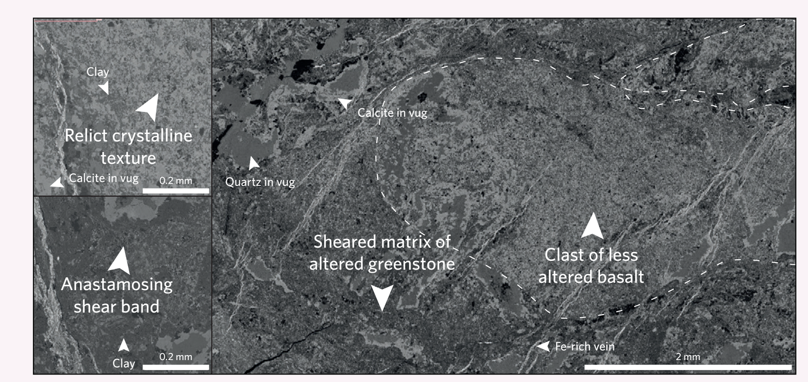


Fig 8: Brecciated clast within greenstone showing relict crystalinity surrounded by altered & sheared clay-rich material.

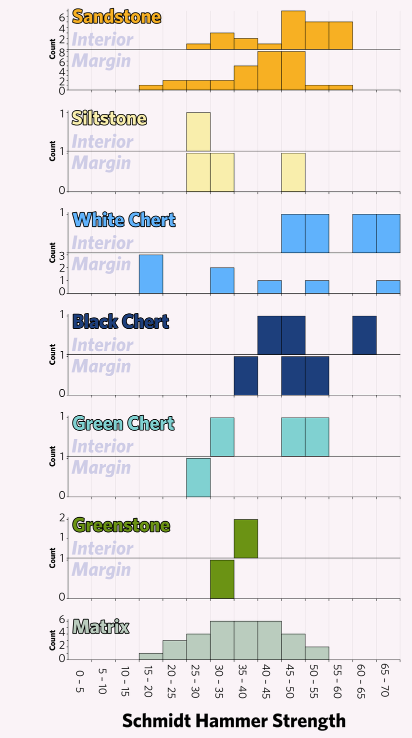


Fig 11: Results from Schmidt rebound hammer in-situ strength tests.

In-situ strength tests reveal significant overlap in the present strength of the matrix and all block types. Strengths at the margins of blocks are systematically lower than in block interiors. Chert is the strongest block lithology in the mélange while siltstone is the weakest; these observations accord with interepretations from textural evidence.

CHANNELISATION OF FLUID PATHWAYS

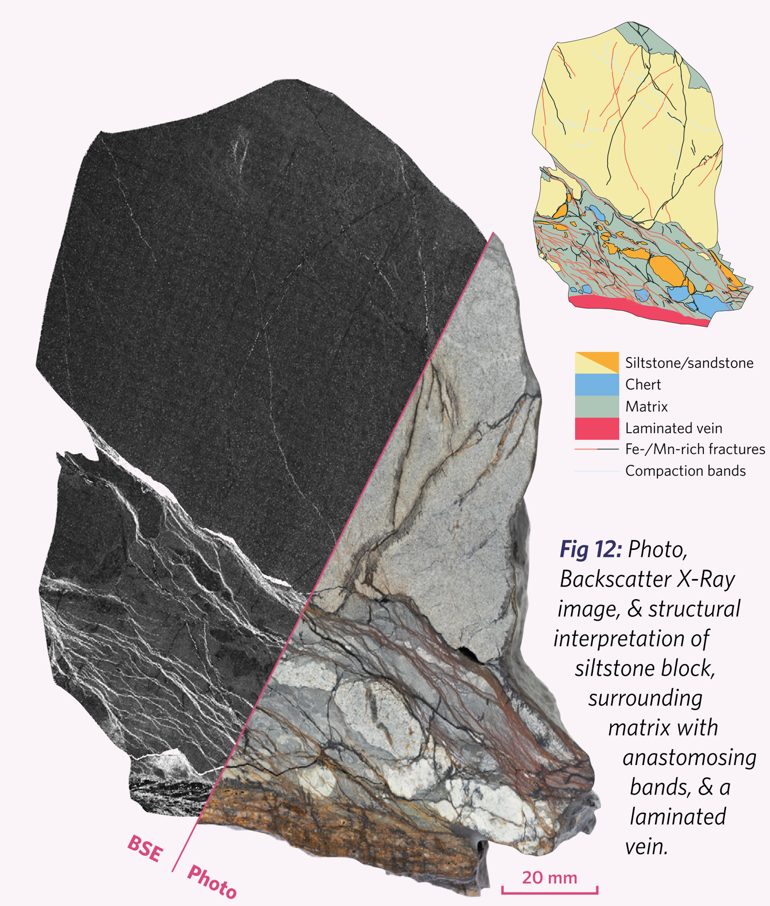


Fig 12: Photo, Backscatter X-Ray image, & structural interpretation of siltstone block, surrounding matrix with anastomosing bands, & a laminated vein.

Anastamosing veins & fractures reveal a multi-scale, self-similar network of channelised fluid flow.

This mélange is cut by several-cm thick laminated veins of quartz and calcite with the iron alteration. These vein form an anastomosing network approximately parallel to the mélange fabric. They predominantly cut the matrix and localise at block margins. These veins feature several generations of curved slickenfibres indicating multiple slip directions.

An additional set of quartz veins and fractures, predominately confined to sandstone blocks, cut at a high angle to the long axis of blocks and chaotic orientations with respect to the other axes. These veins have a highly heterogenous distribution within blocks not conforming to relict bedding. These veins and fractures are straight, do not anastomose, and mostly terminate at or before block margins but can extend into matrix and between blocks.

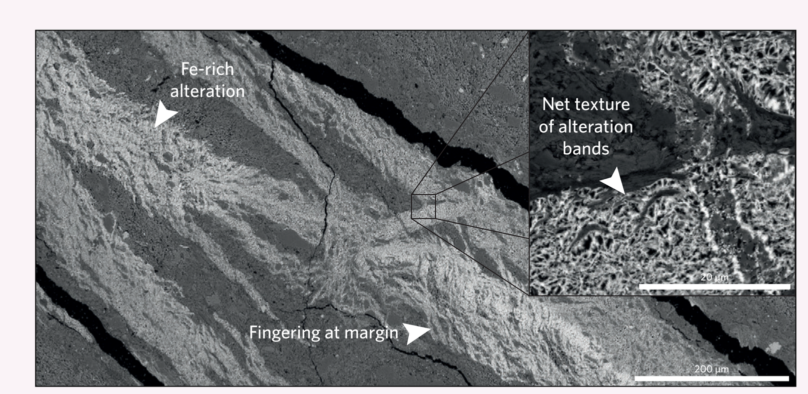


Fig. 13: Iron alteration bands without central fractures.

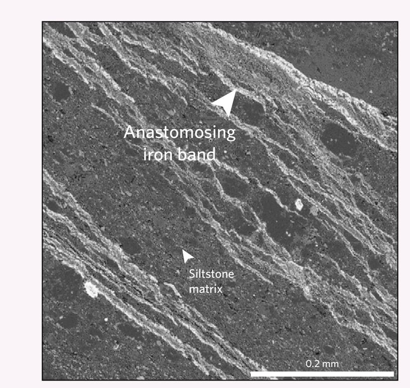


Fig. 14: Anastomosing network of iron alteration bands cutting siltstone.

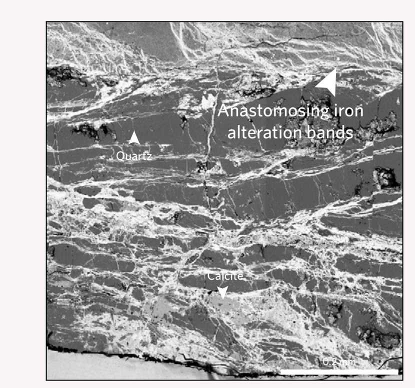


Fig. 15: Laminated quartz & calcite with iron alteration & anastomosing bands extending into matrix.

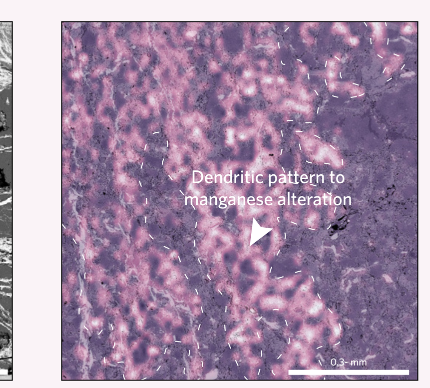
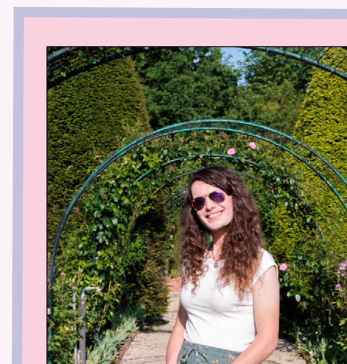


Fig. 16: Dendritic fingering structure of manganese alteration at margin of alteration band.

Additionally, a network of <1mm thick anastomosing bands marked by iron & manganese alteration pervasively cuts all lithologies. These bands often contain no visible fracture that would have localised these fluids. Iron & manganese alteration is microscopically diffuse and generally displays dendritic fingering at the margins of the bands. These bands typically originate from laminated veins and in places both cut and follow the pre-existing lozenge fabric.

In combination with the laminated veins, these thin bands form a self-similar network of channelised fluid pathways reflecting the localisation and diffusion of disequilibrium fluids through the subduction shear zone. Heterogeneity at margins of fluid channels promotes further channelisation at a lower fractal order. This anastomosing network cross-cuts the lozenge-shaped mélange fabric, indicating that this channelised fluid system originated at depth within the subduction zone. Our next textural studies will investigate the origin of these veins.



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Sharing is encouraged

References

1. Ide, S., Beroza, G.C., Shelly, D.R. and Uchide, T. 2007. A scaling law for slow earthquakes. Nature, 447, 76–79.
2. Vannucchi, P., Clarke, A., de Montserrat, A., Ougier-Simonin, A., Aldega, L. and Morgan, J.P. 2022. A strength inversion origin for non-volcanic tremor. Nature Communications, 13, 2311.
3. Fagereng, A. and Sibson, R.H. 2010. Melange rheology and seismic style. Geology, 38, 751–754.
4. Price, R., Mortimer, N., Smith, I. and Maas, R. 2015. Whole-rock geochemical reference data for Torlesse and Waipapa terranes, North Island, New Zealand. New Zealand Journal of Geology and Geophysics, 58, 213–228, https://doi.org/10.1080/00288306.2015.1026832.
5. Fagereng, Å. and Cooper, A.F. 2010. Petrology of metabasalts from the Chrystalls Beach accretionary mélange - implications for tectonic setting and terrane origin. New Zealand Journal of Geology and Geophysics, 53, 57–70.
6. Fagereng, Å. 2011. Geology of the seismogenic subduction thrust interface. Geological Society, London, Special Publications, 359, 55–76,