

# Halite Microstructures Reveal Deformation Mechanisms Occurring in Salt Detachments Underlying Resource-Rich Fold-Thrust Belts\*

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## Abstract

Fold-thrust belts, particularly in deepwater, play host to large amounts of the world's petroleum resources in their associated fold and thrust structures. The mechanics and geometry of these structures are controlled by underlying detachments; however, these are relatively unstudied. Detachments are often overpressured shale or salt, which are difficult to image with seismic tools; often demonstrating little or no features. The deformation of salt is understood at large (km–10m) scales. However, very little is known of the microstructural deformation mechanisms in salt detachments that control the large-scale deformation. We have used four samples from two salt detachments underlying petroleum producing basins in Australia and Pakistan to determine the microstructural mechanisms of deformation. Employing two techniques— $\gamma$ -irradiation and acid etching—together revealed previously unobservable microstructures that demonstrate the micro-scale deformation. The  $\gamma$ -irradiation procedure induces the formation of colour centres within the halite matrix turning the salt mass blue, in thin section. Uncoloured areas are the result of crystal lattice deformation in the form of dislocations, grain, and sub-grain boundaries already present, thus, are unchanged during irradiation. The etching process polishes the notoriously difficult halite and highlights high and low angle disparities in crystallographic orientation unobtainable with conventional polishing techniques. Microstructures observed using these techniques indicate the type of deformation experienced and processes occurring. Preliminary results show vastly different deformation histories for the two detachments. Samples from Pakistan indicate multiphase deformation and recovery: dislocation creep and dynamic recrystallisation followed by solution-precipitation creep and grain boundary migration. Australian samples show simpler features with limited sub-grain dislocations yet greater grain scale microcracking indicating entirely recovered grains after significant deformation. Starkly different geological settings,

histories, and lithological heterogeneities contribute to the disparity structural geometries in the overriding fold-thrust belts, which are reflected in the observed microstructures. Linking the deformation at the micro-scale to the seismic or regional scale in these examples allows for a better understanding the factors controlling the mechanics and geometry of these major petroleum trapping structures.

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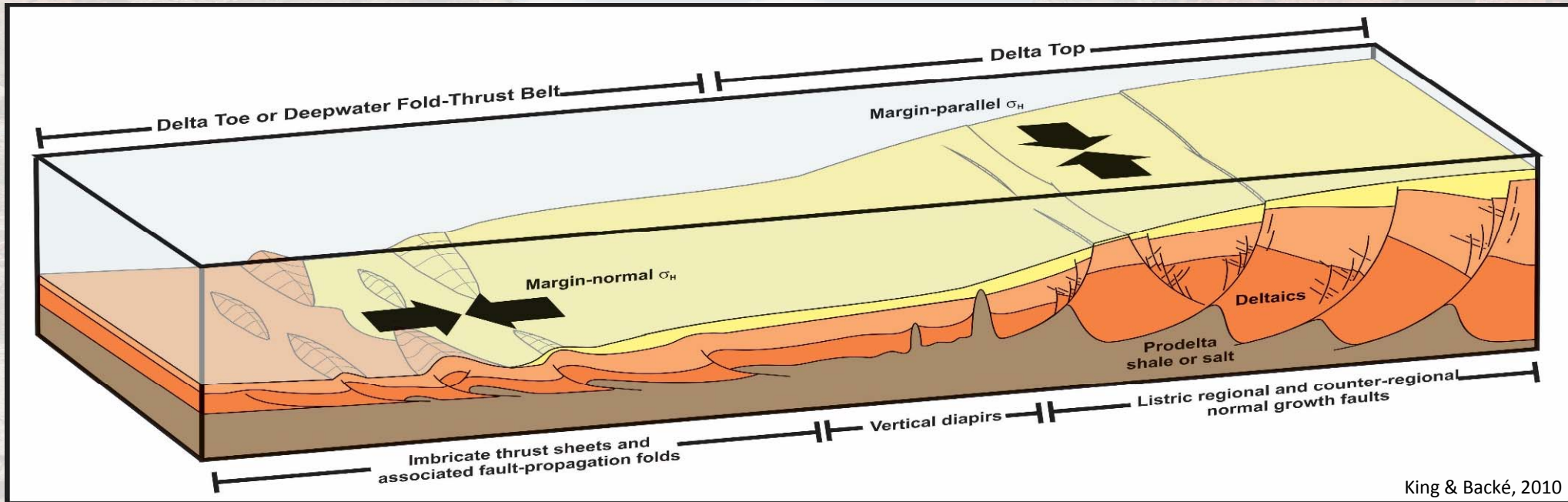
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# Background

- Prominent settings for hydrocarbon exploration
- Deformation controlled by detachment
- Detachment composition: salt or shale

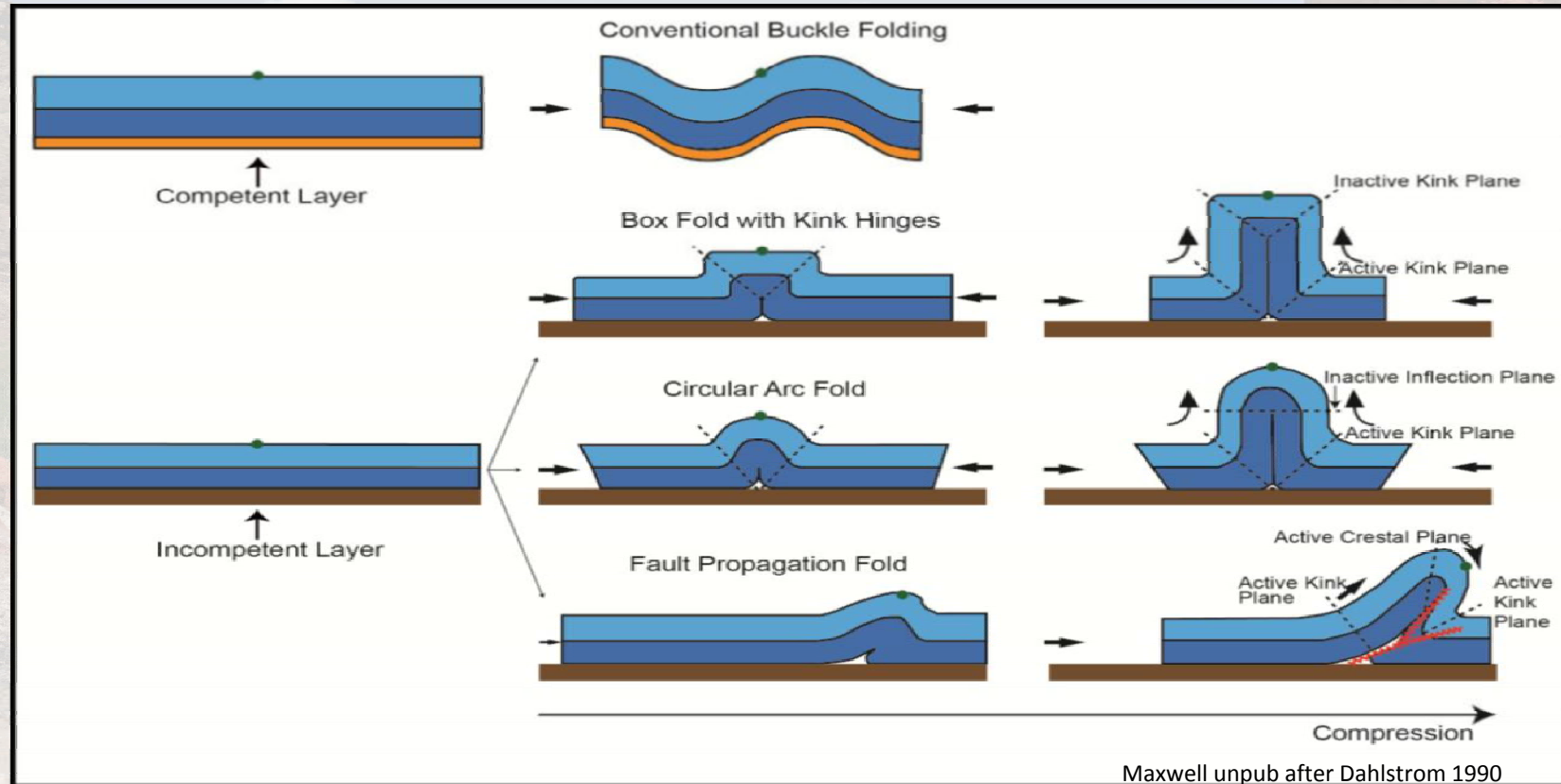




# Background

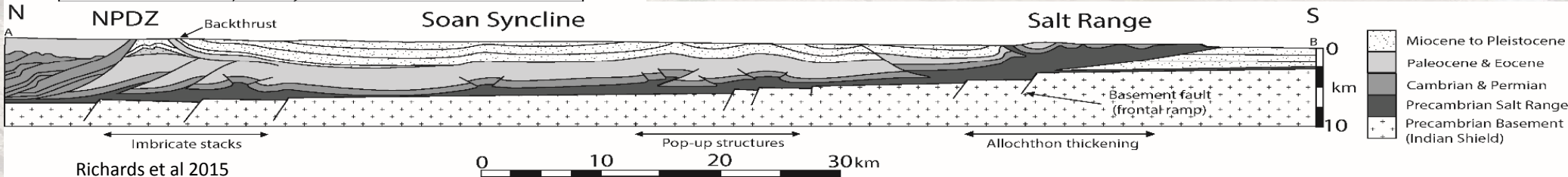
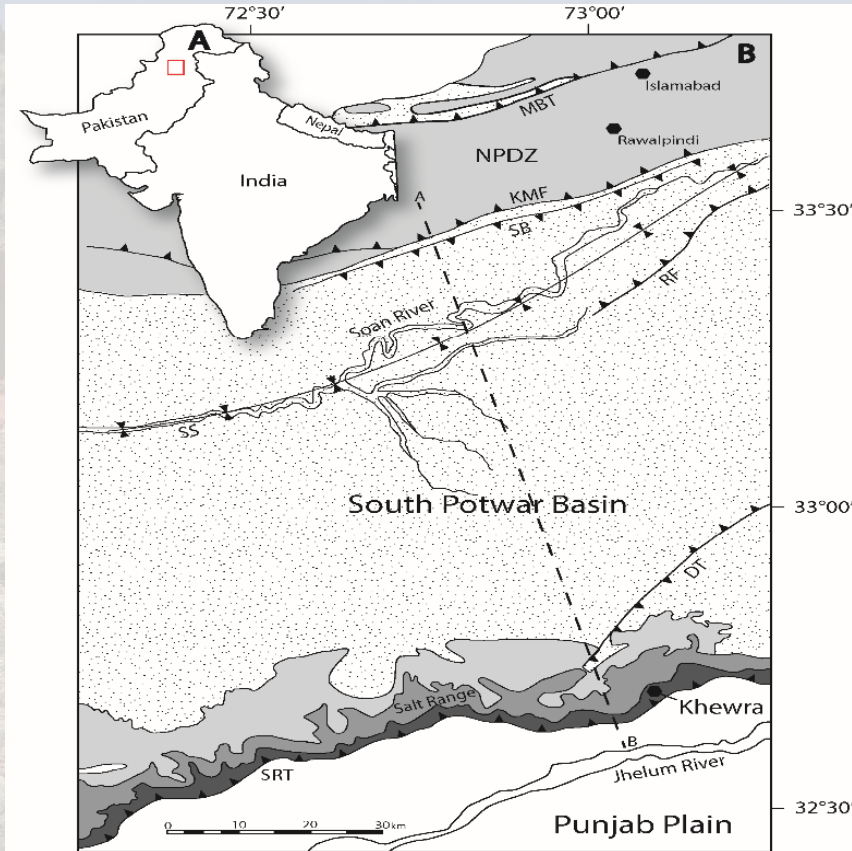
## Factors controlling FTB deformation

- Stress source
- Lithology
- Strength
- Detachment thickness
- Pore pressure
- Dip & dip direction
- Coefficient of friction



# Salt Range, Pakistan

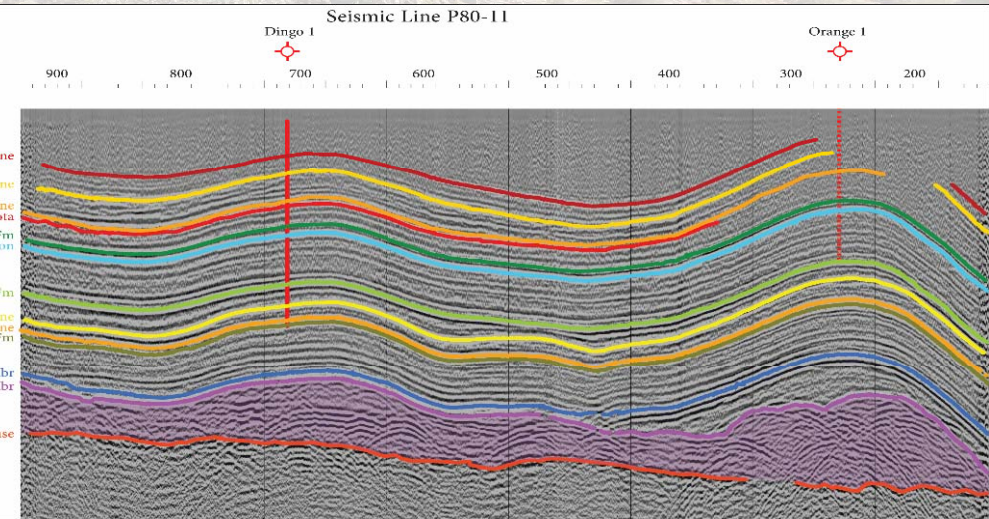
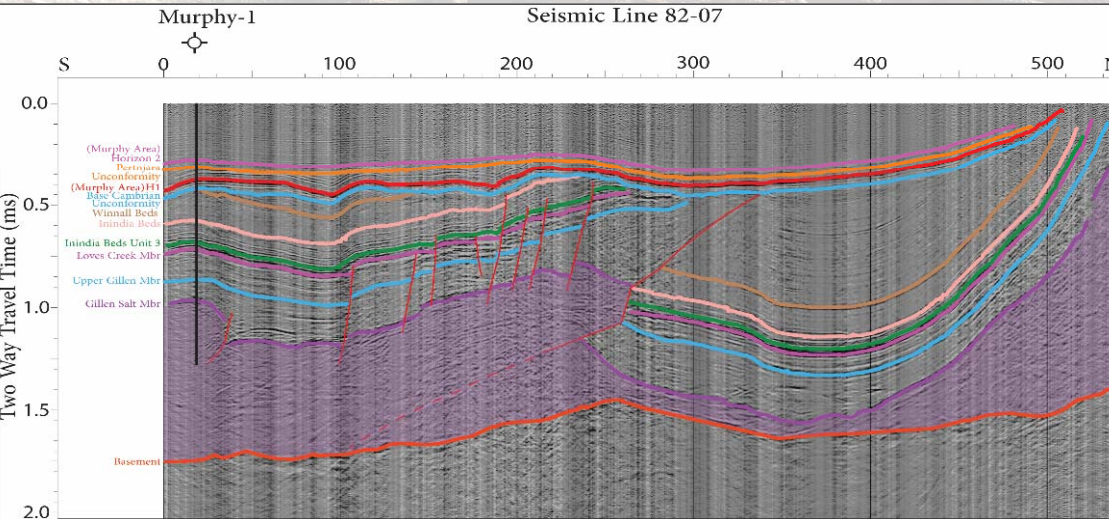
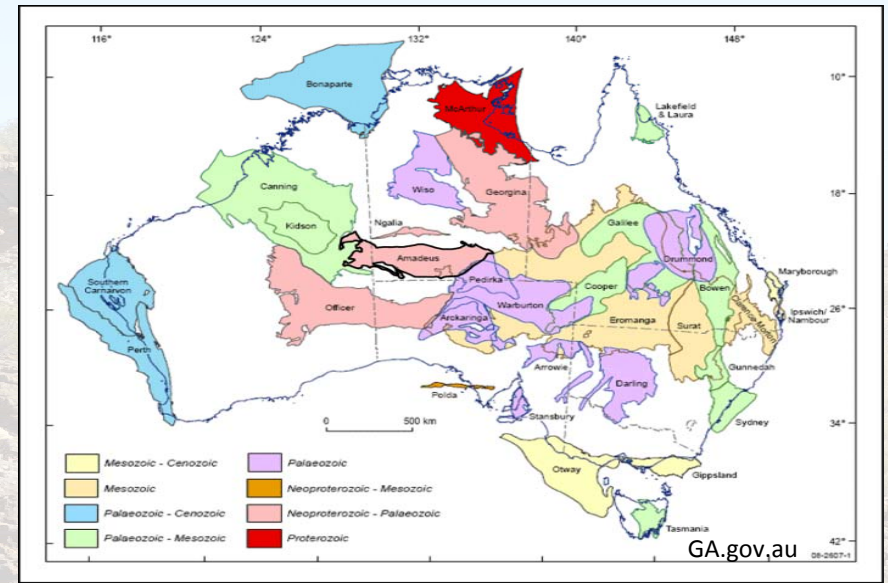
- A foreland Fold-thrust belt
- Rare surface expression of a salt detachment
- Khewra Salt Mine allows for excellent structural analysis and sample collection
- Salt Range Formation acts as the primary detachment





# Amadeus Basin, Australia

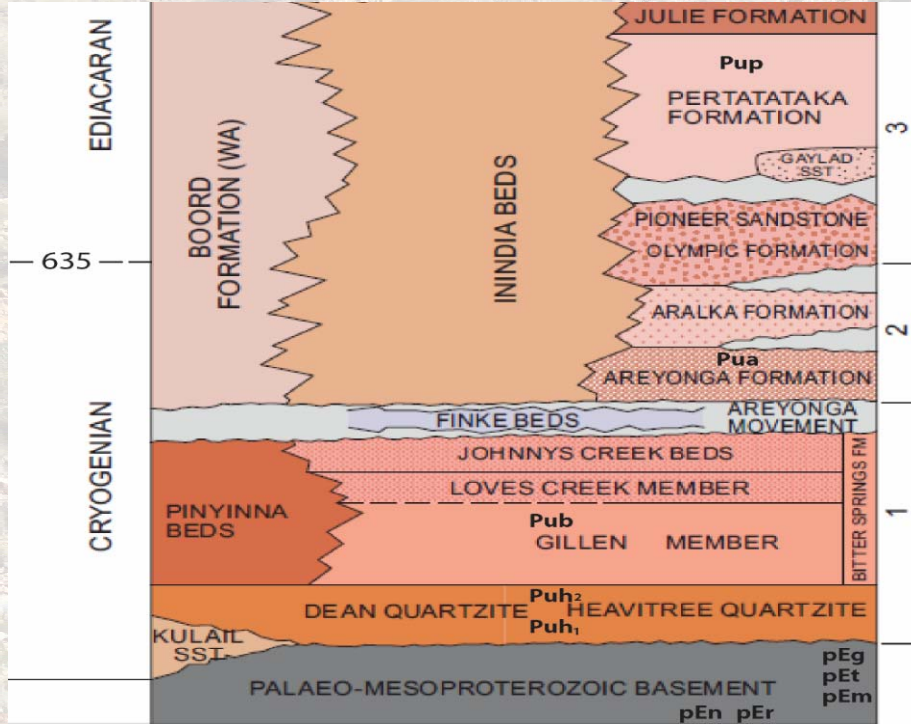
- Cryogenian to Carboniferous intracratonic basin
- N-S compressional tectonic regime



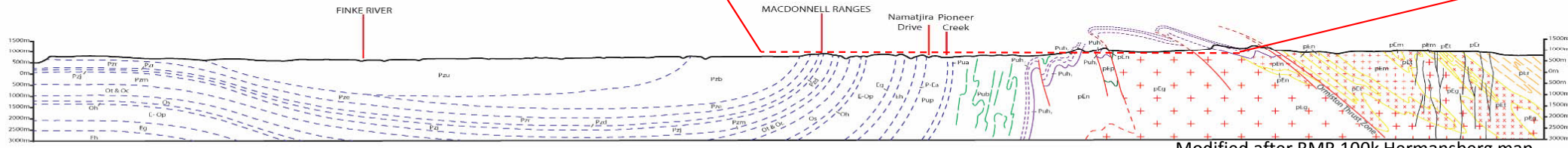


# Amadeus Basin, Central Australia

- Bitter Springs Formation is the main detachment horizon



Modified after Ahmad & Munnson 2013



Modified after BMR 100k Hermansberg map



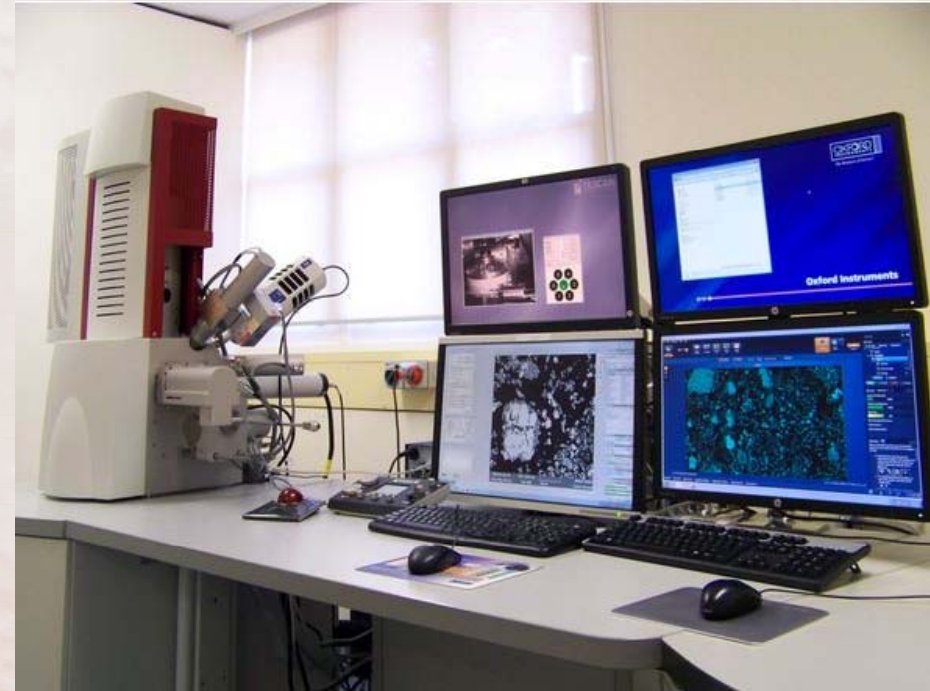
# Analytical Techniques

- Gamma ( $\Gamma$  /  $\gamma$ ) - decorated optical microscopy



John de Laeter Centre, Curtin University

- Electron Backscatter Diffraction (EBSD)

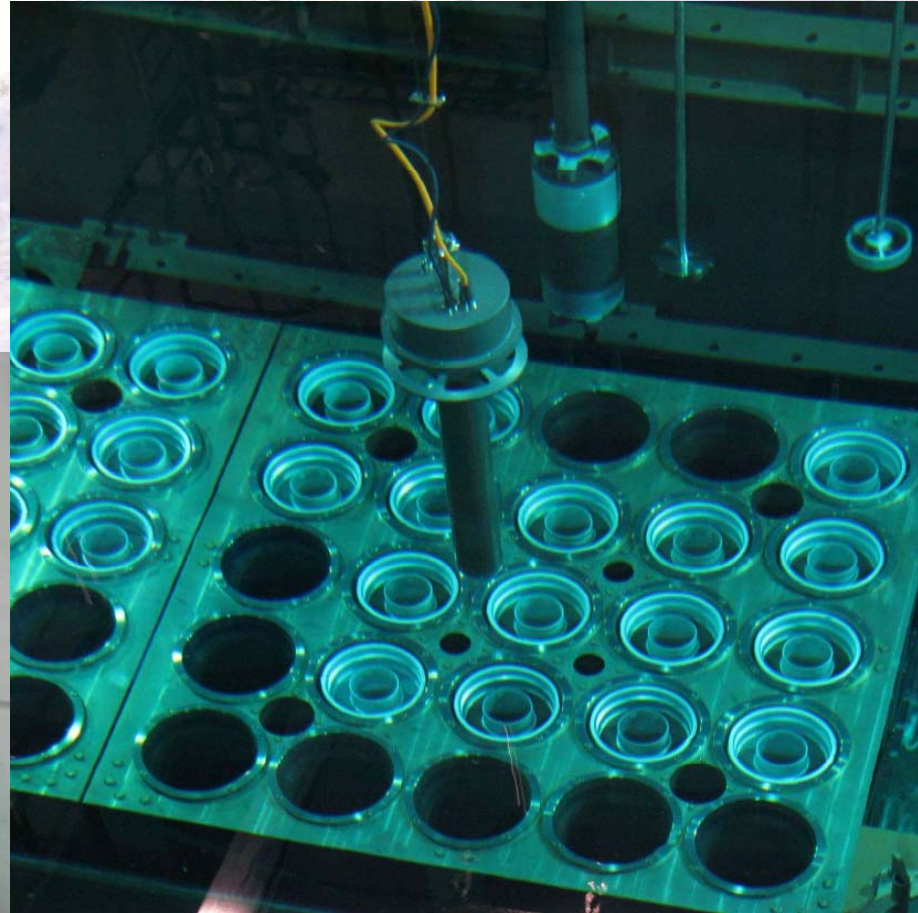


John de Laeter Centre, Curtin University



# $\Gamma$ -Irradiation

$\gamma$ -irradiation absorbed from reactor bath

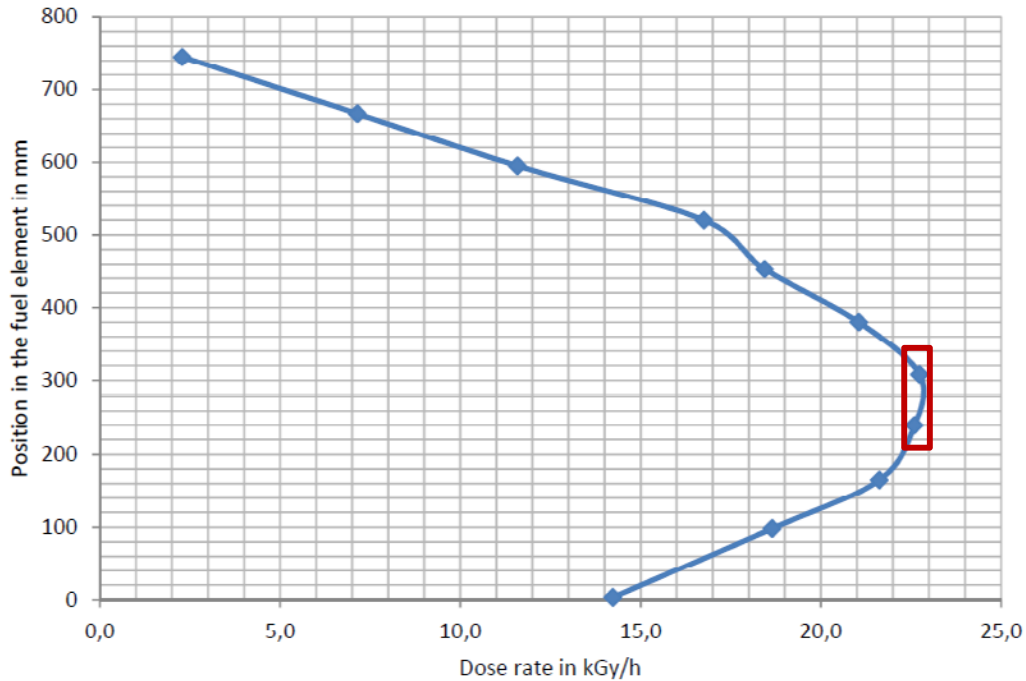




# $\Gamma$ -Irradiation

- Exposure to  $\gamma$ -radiation colours undeformed halite crystal lattice blue

Measurement in JBE10

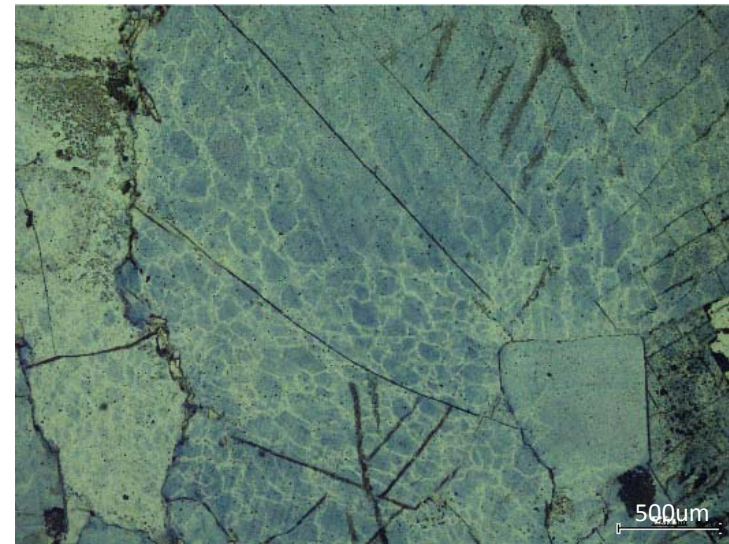
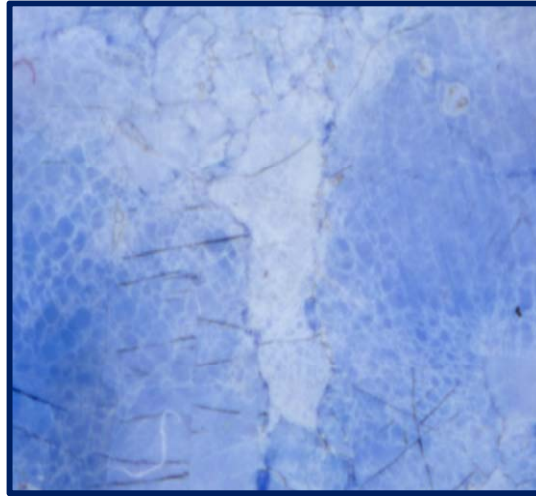
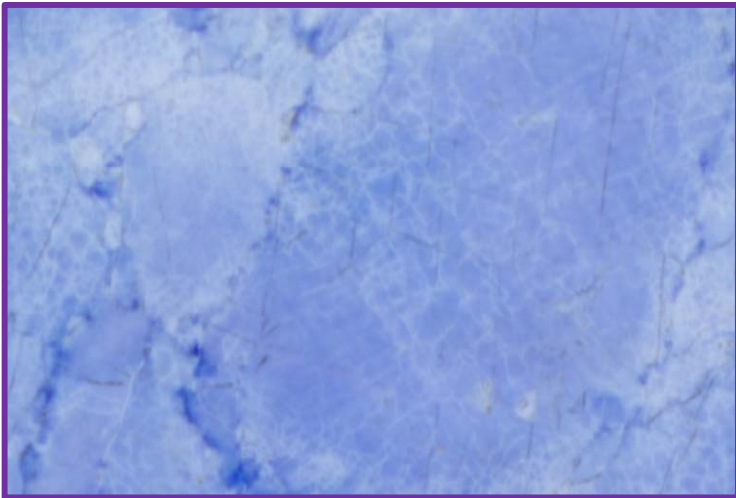


# $\Gamma$ -Decorated Microstructures

Exposed microstructures indicate



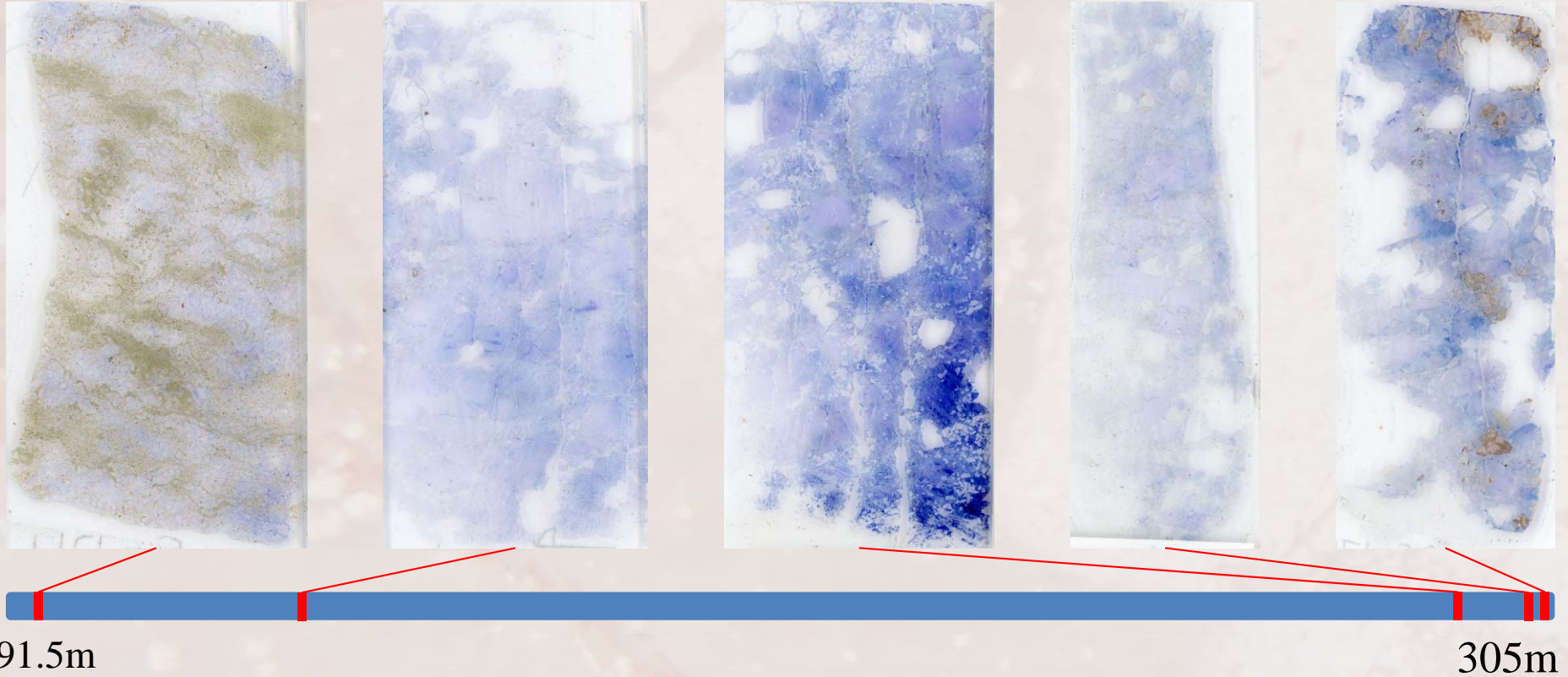
- Subgrain boundaries
- Stress localisation
- Recrystallisation/recovery
- Slip orientation
- Grain boundary migration





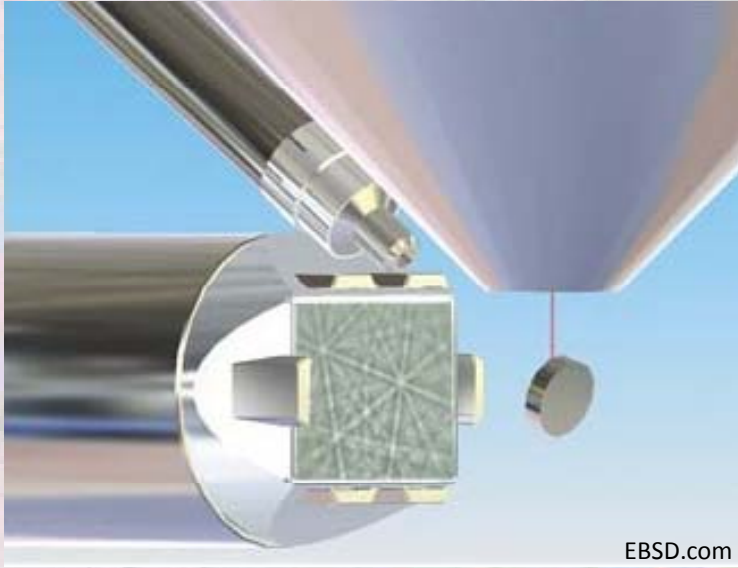
# $\Gamma$ -Decorated Microstructures

## Mt Liebig 1 depth profile

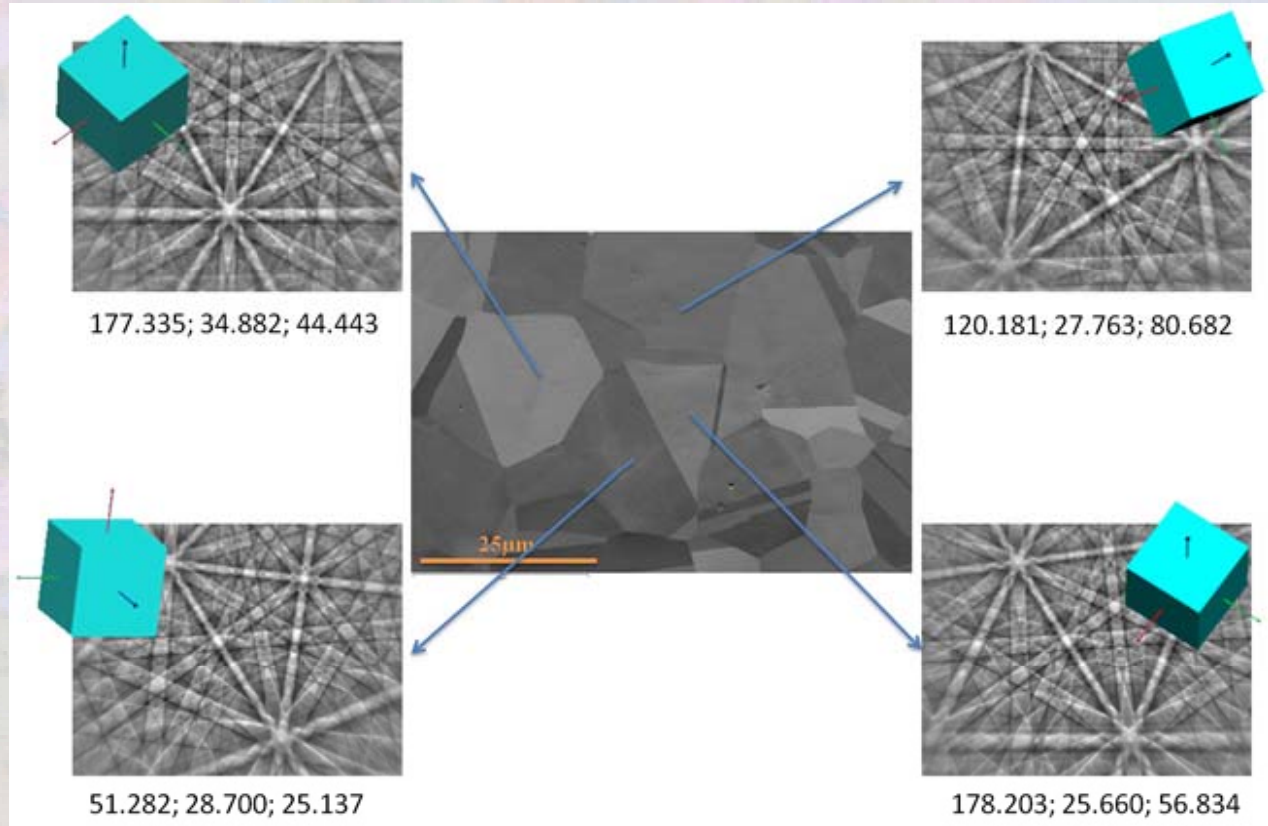
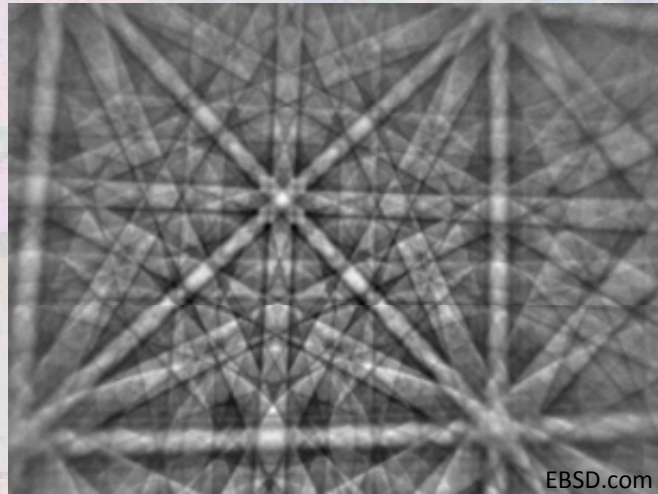


Noticeable change in composition, microstructures, and recovery with depth

# Electron Backscatter Diffraction



- Electron beam diffracted by sample producing Kikuchi band
- Identifies specific mineral & orientation

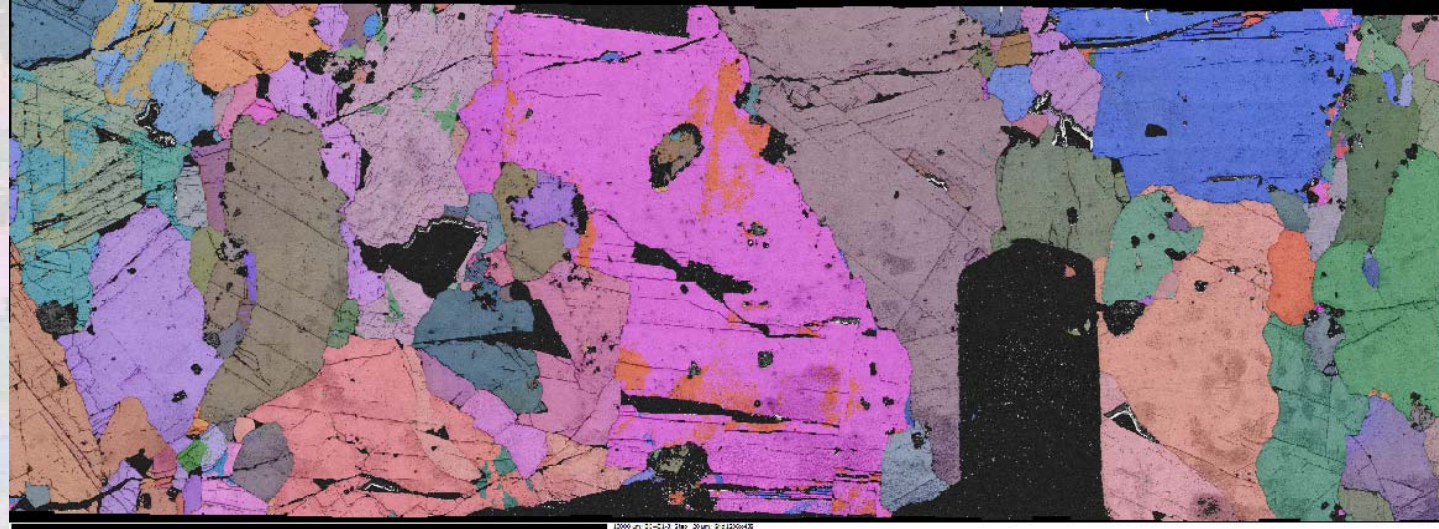




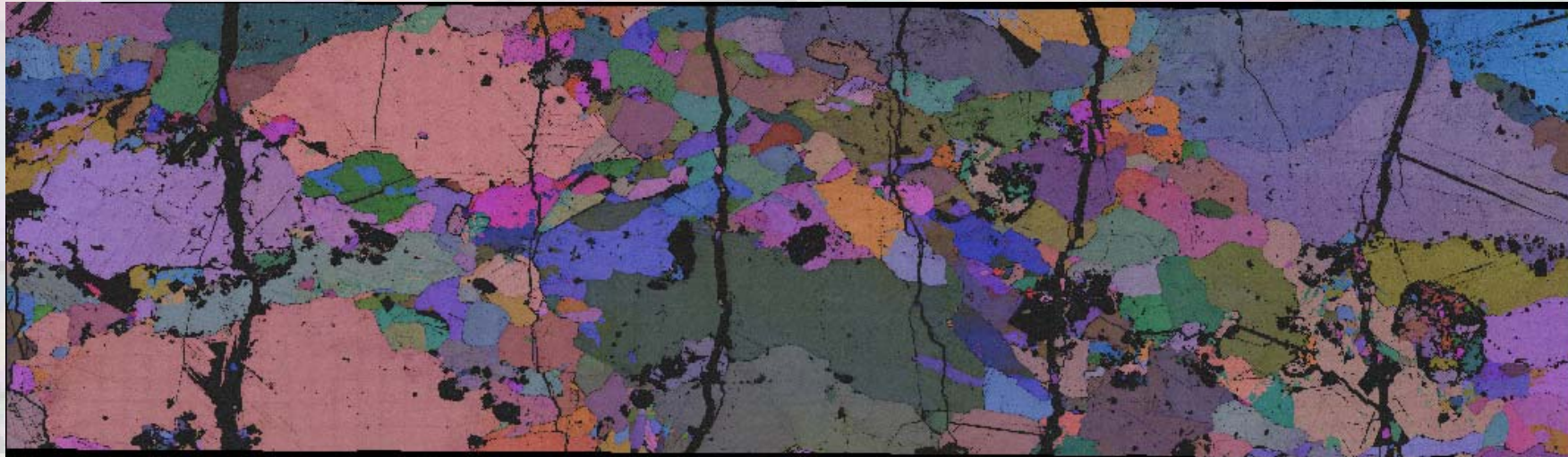
# Electron Backscatter Diffraction

- All Euler map shows grain orientation
- Samples from Mt Liebig 1 well, Amadeus Basin

ML1-32 step:20um



1cm



2cm

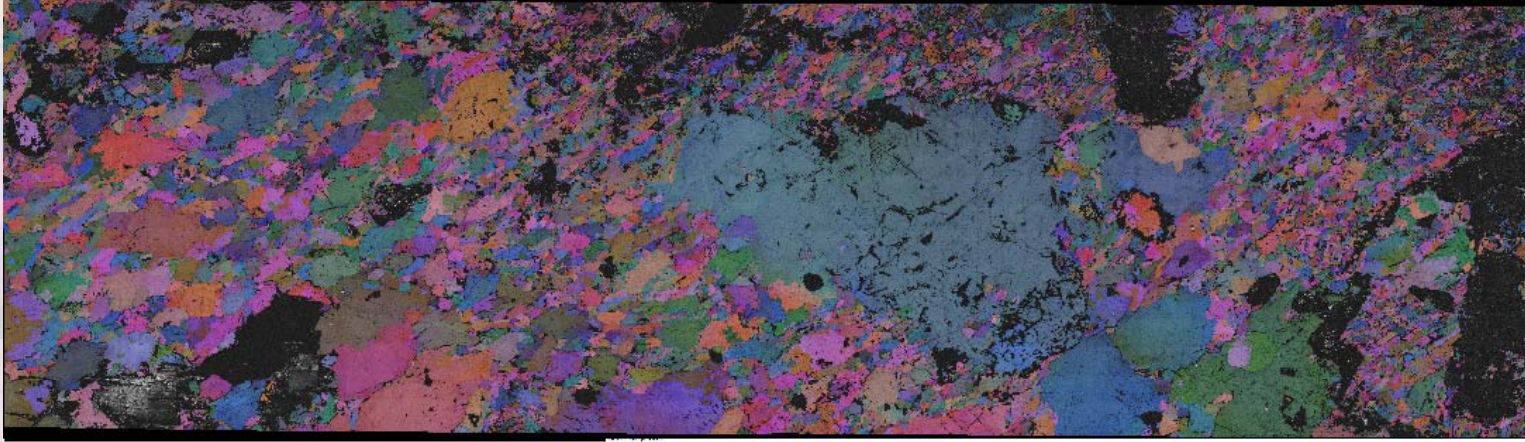
ML1-15 step:11.2um



# Electron Backscatter Diffraction

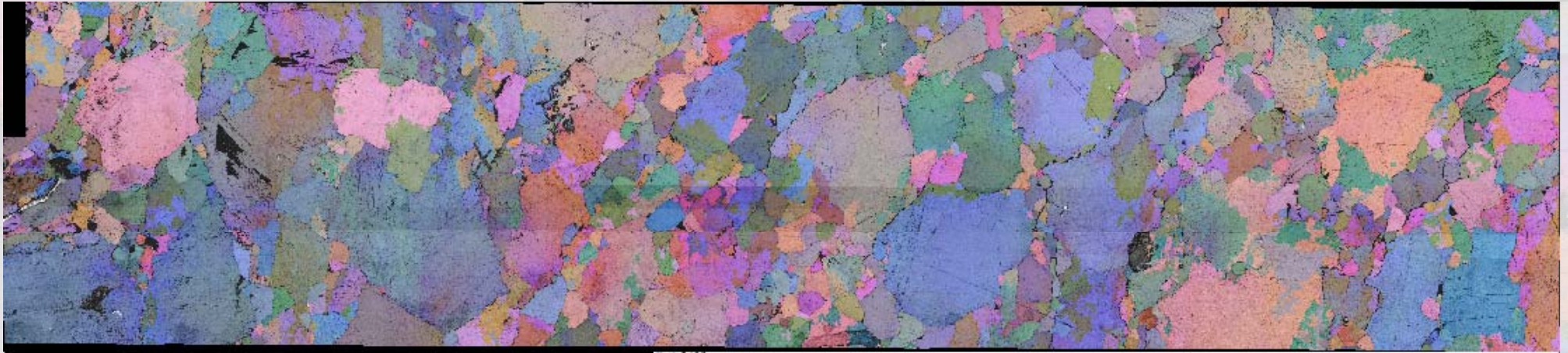
- Samples from Salt Range, Pakistan
- Whole thin section scans

SRLR-06 step size: 15um



2cm

SRLR-05 step size: 12um

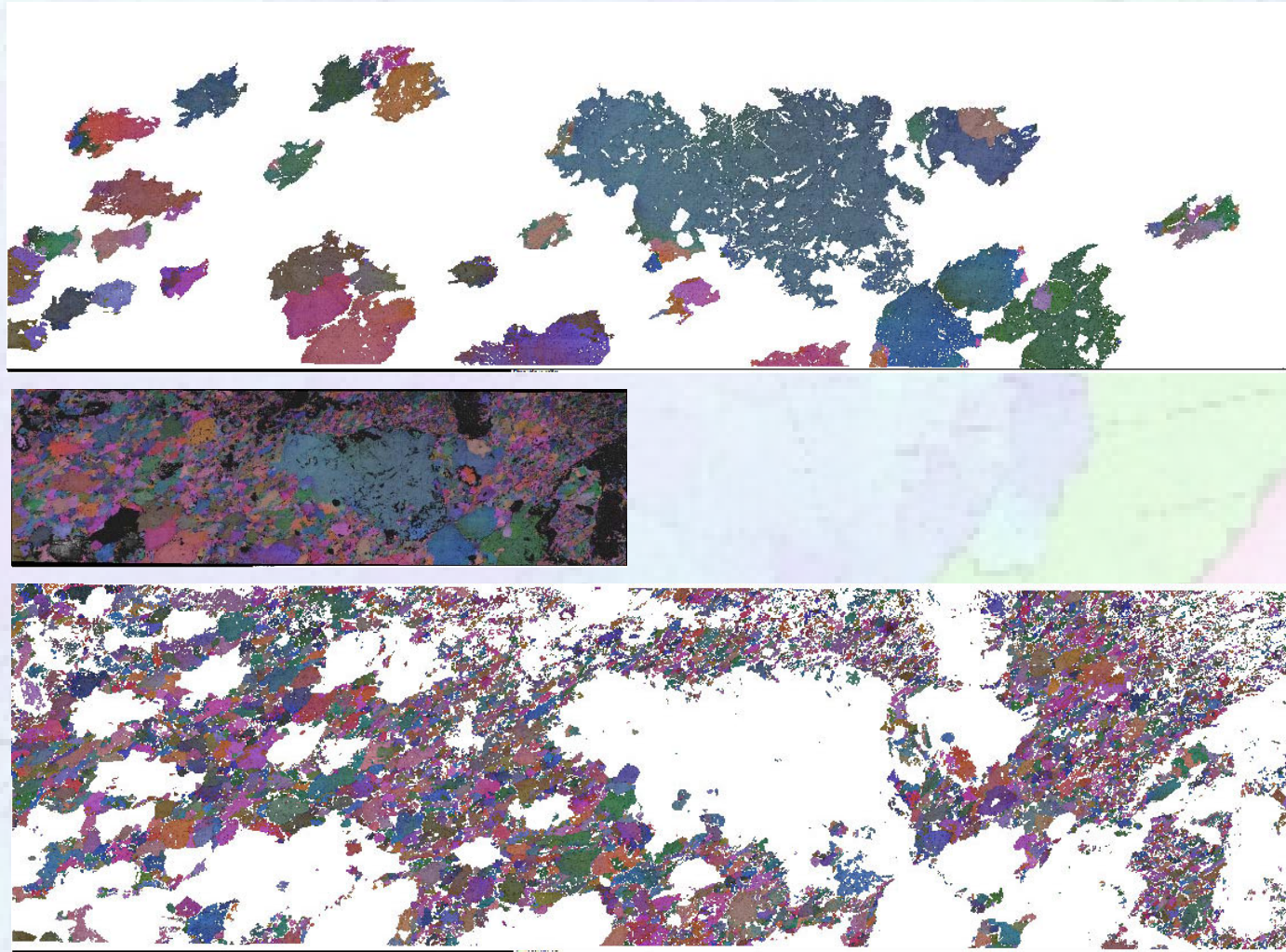


2cm

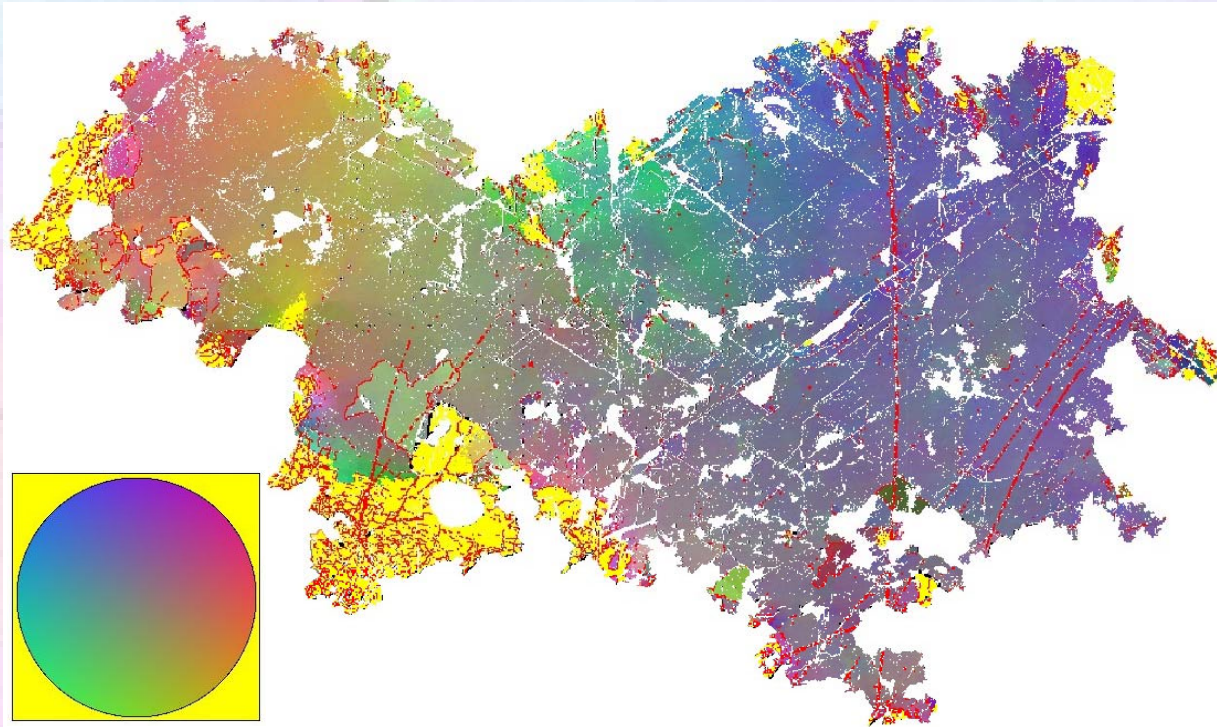
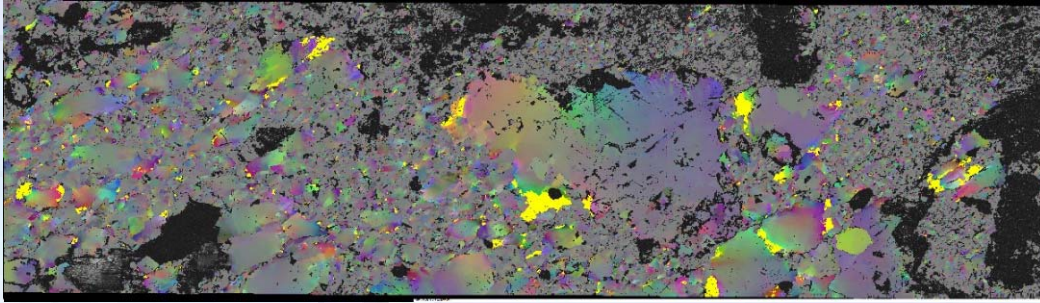


# EBSD Microstructures: Grain Fabric

- Fabric identified through grain area distribution analysis
- Small grains define fabric, large grains trend similarly



# EBSD Microstructures: Disorientation

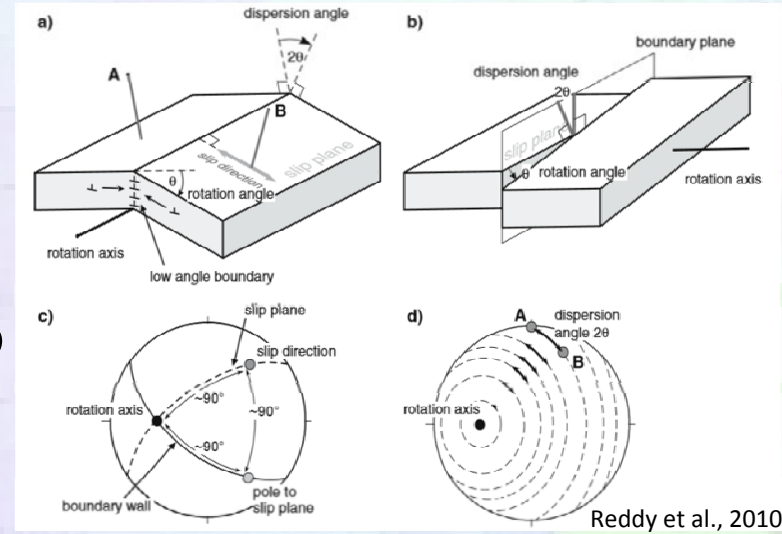
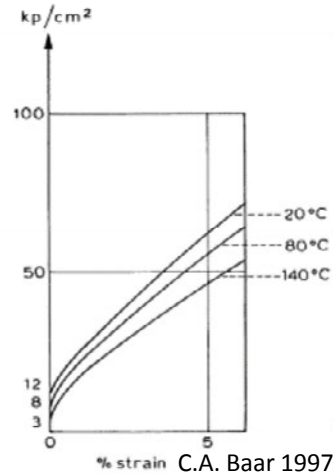
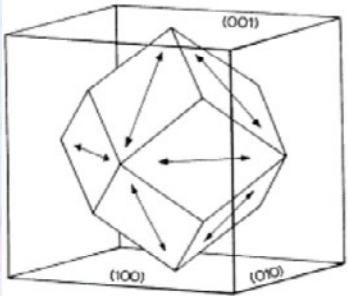


- Disorientation identifies the internal deformation within a single grain (15 )

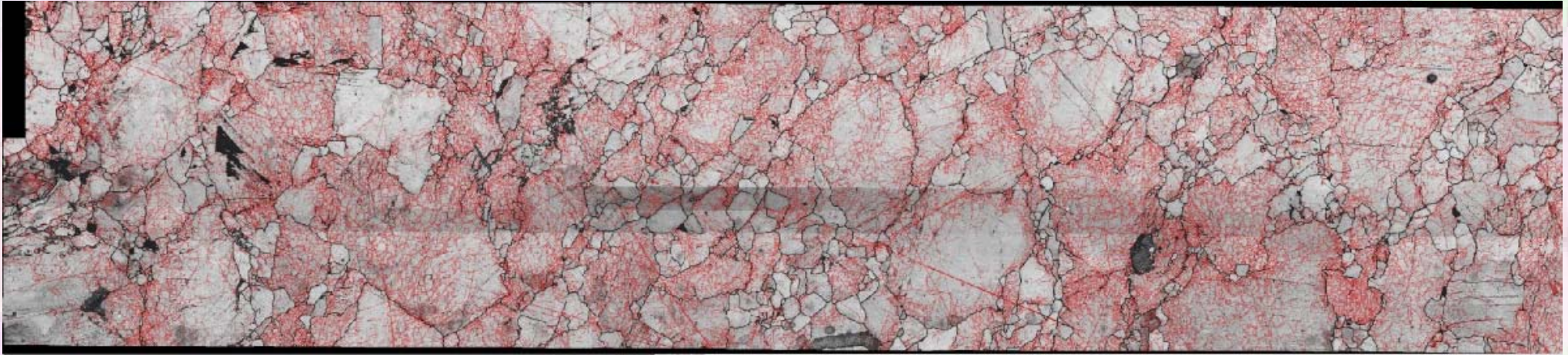


# EBSD Microstructures: Slip Plane

- 6 slip systems in halite
- 2 methods of crystal lattice slip – Tilt or Twist

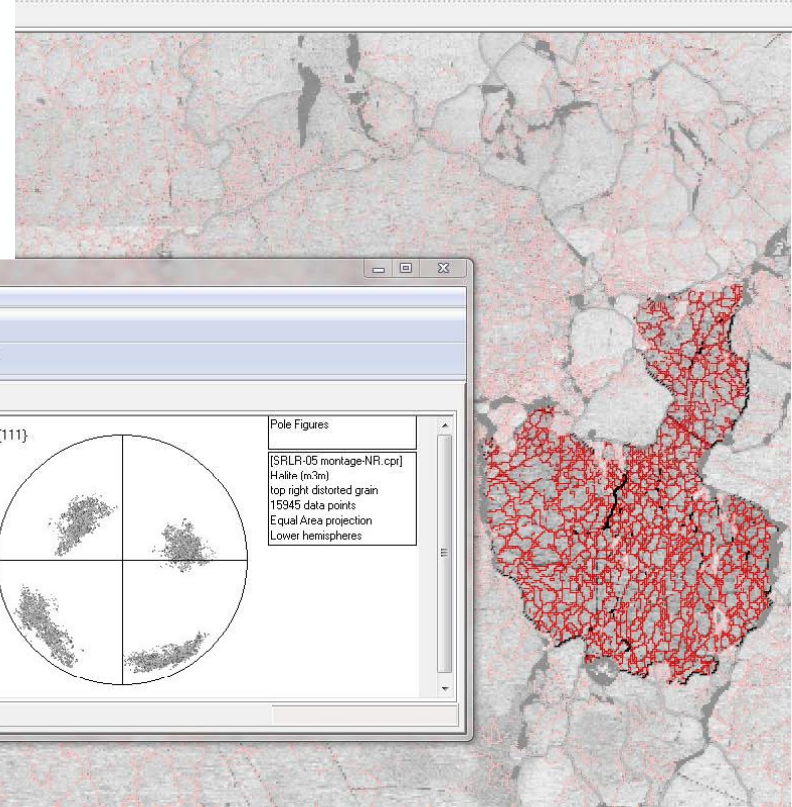
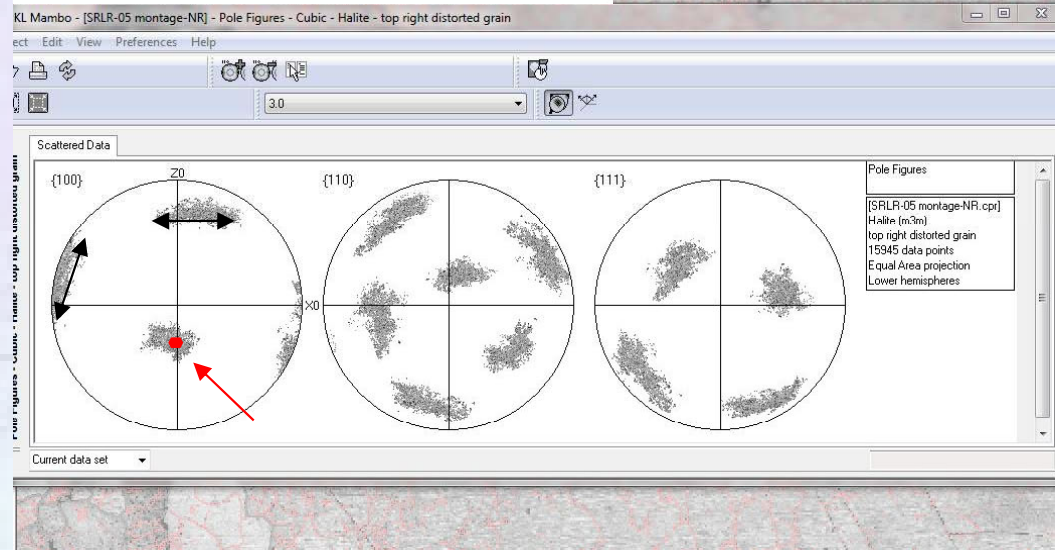
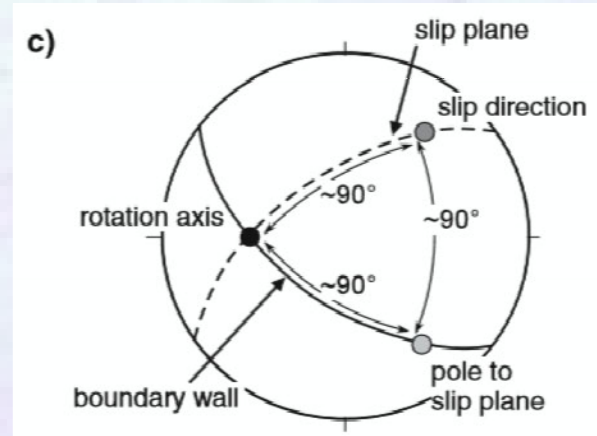


Reddy et al., 2010



# EBSD Microstructures: Slip Plane

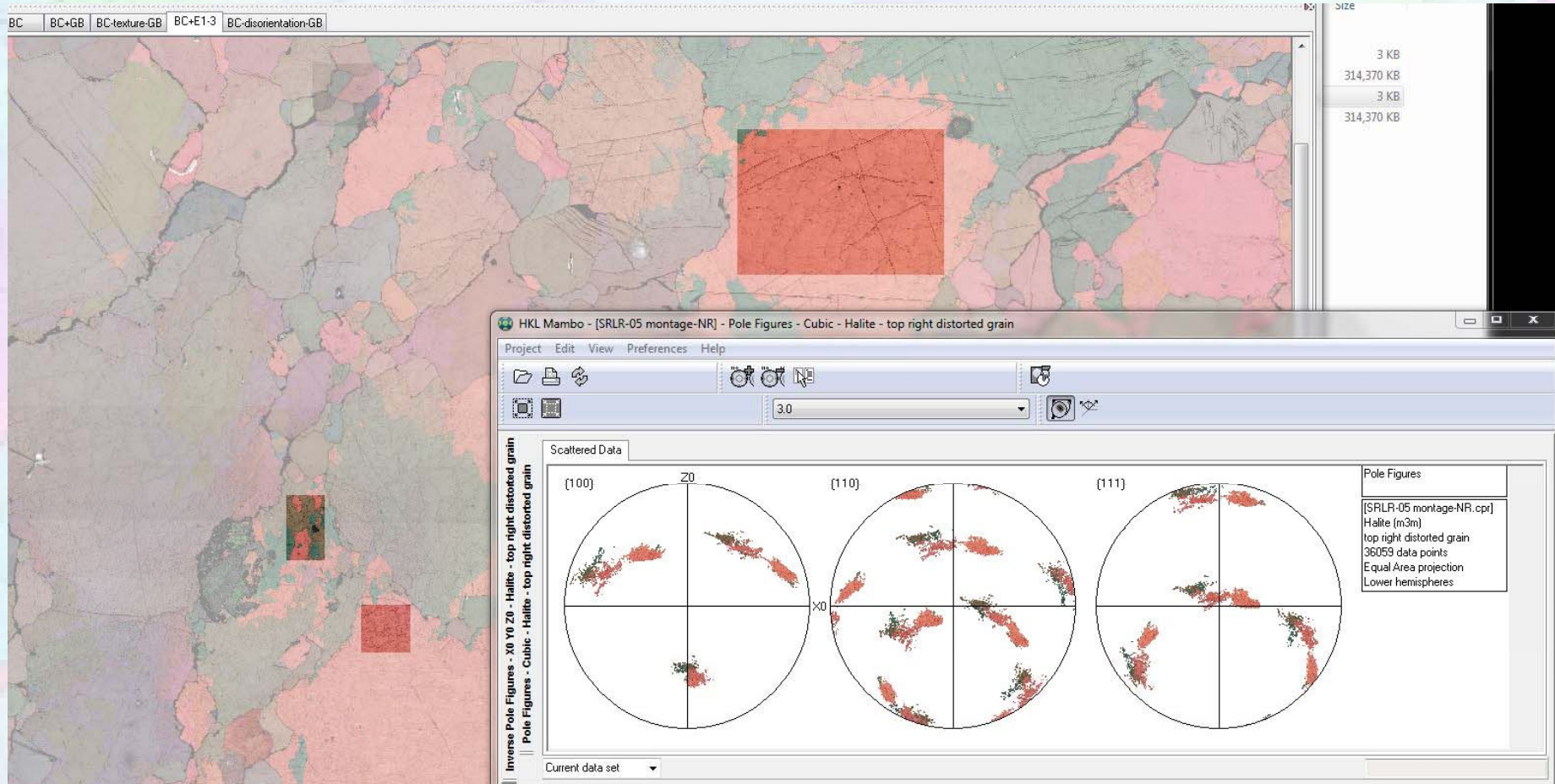
- Highly deformed grain
- $\{100\}$  plane is most appropriate for these samples
- Large smear of data around rotation axis (unsmear data)
- Slip plane and direction at roughly 90





# EBSD Microstructures: Slip Plane

- 3 separate grains show similar orientation and slip along  $\{100\}$  plane



# Summary of Microstructures

Comparative  
microstructural  
history between  
settings

	Amadeus Basin	Salt Range
$\Gamma$ -Irradiation & optical microscopy	<p>Changes in well profile with depth</p> <ul style="list-style-type: none"><li>• Compositionally purer</li><li>• Grain size decrease</li><li>• Rarely observed subgrains</li></ul>	<ul style="list-style-type: none"><li>• Subgrain intricacy varies between grains &amp; internally</li><li>• Partial &amp; complete recrystallization</li><li>• Subgrain boundary migration</li><li>• Multistage deformation</li><li>• Slip orientation</li></ul>
EBSD	<ul style="list-style-type: none"><li>• Large grains</li><li>• Little internal deformation</li><li>• Minor disorientation</li><li>• Strongly recrystallised</li></ul>	<ul style="list-style-type: none"><li>• Fabric forming small grains</li><li>• Large grains show great internal distortion</li><li>• Some large grains show limited deformation or recrystallization</li><li>• Very dense subgrain slip patterns {100} plane</li></ul>



# Conclusions

- Samples taken from salt detachments in Pakistan and Australia demonstrate great disparity in their characteristics and deformation histories
- Amadeus samples show a grain size and compositional purity increase and grain size decrease with depth but remain mostly subgrain free indicating significant recrystallization and subsequent deformation
- Salt Range samples display greater complexity in subgrain history and variation in and between samples with grains being heavily distorted or intensely deformed with very dense subgrains
- Broader characterisation in other regions may aid in understanding specific local deformation histories, particularly in regions where salt is a host to large petroleum accumulations (e.g. South Oman Salt Basin)

# Acknowledgements

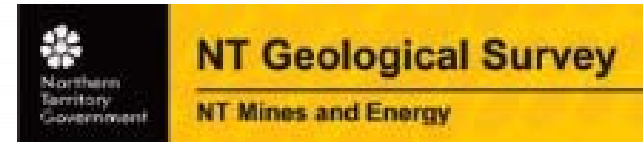


Prof M. A. Khan

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