

# **THE ISUA SUPRACRUSTAL BELT OF SOUTHWESTERN GREENLAND**

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- General background and geographical location
- Primary lithologies of the Isua Greenstone Belt
- Historical sequence of geologic events
- Metamorphic history of the Isua Greenstone Belt
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- Controversies related to the Isua Greenstone Belt

## GENERAL BACKGROUND AND GEOGRAPHICAL LOCATION

- Archaean aged (3900–3800 My) greenstone belt occurring in southwestern Greenland
- When age of Isua Greenstone Belt was first established in the early 1970s, was considered oldest volcanic and sedimentary rocks in existence
- Largely composed of meta-volcanic amphibolites from island arc tholeiite and picrite protoliths, as well as smaller amounts of clastic and chemical sediments that includes quartz-magnetite banded iron formation, metachert, dolomites, and rare felsic schists and pelites of volcanic-sedimentary origin
- A source of considerable research since initial investigations due to remaining relatively undeformed after Mesoarchaean and preservation of some primary igneous and sedimentary structures
- As such, considerable attention has been paid to regions of least destruction

Ice

**Mesoproterozoic–Phanerozoic**

- Palaeogene magmatic province
- Phanerozoic orogens and basins
- Neoproterozoic–Palaeozoic basins
- Grenville orogen
- Gardar igneous province and Seal Lake Group
- Mesoproterozoic plutonic suites
- Palaeo- to Neoproterozoic basins

**Palaeoproterozoic**

- Julianehåb batholith
- Ketilidian-Makkovik orogen
- Prøven igneous complex, Cumberland batholith, Lac Lomier complex
- De Pas batholith and Narsajuaq arc
- Burwell arc
- Piling, Hoare Bay and Karrat groups
- Lake Harbour Group
- Ramah and Mugford groups
- Cape Smith – New Quebec orogen
- Inglefield orogenic belt and Ellesmere-Devon terrane
- Proterozoic basement in East Greenland

**Archaean**

- Mary River Group
- Archaeon microcontinental fragments
- Rae craton
- North Atlantic craton
- Superior craton

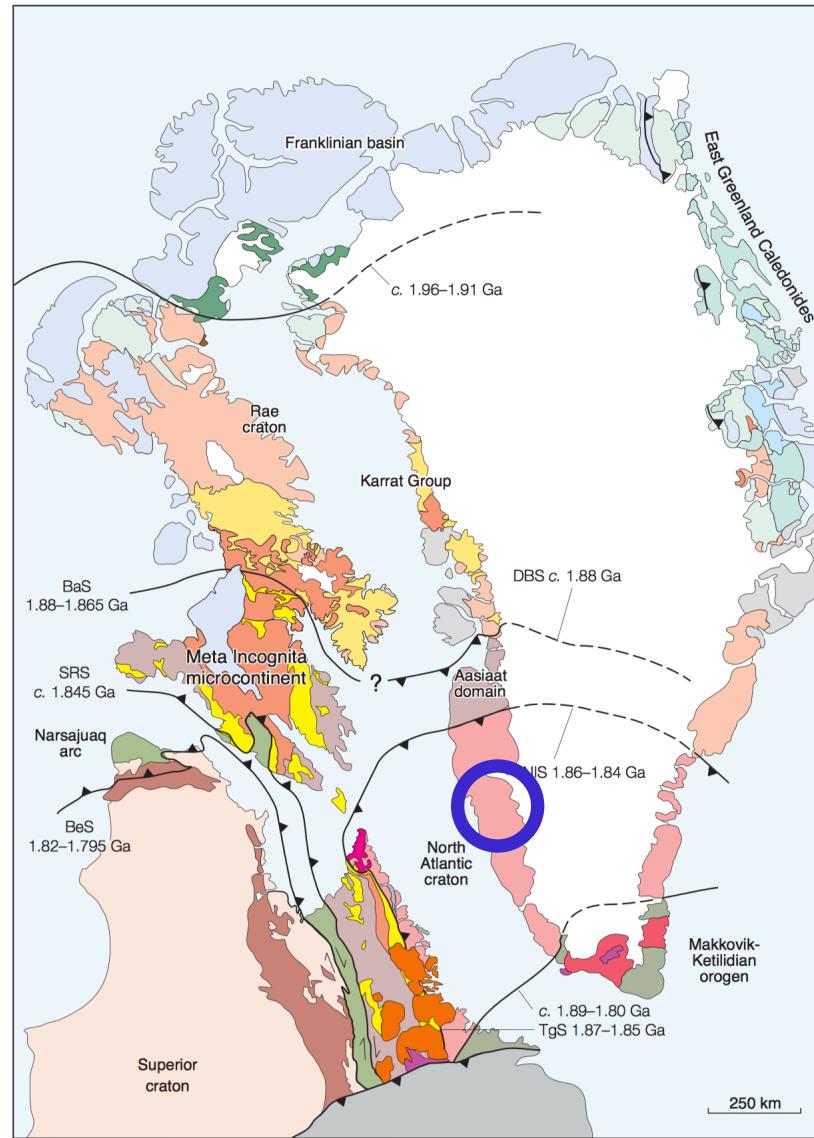


Figure 1  
(Henriksen *et al.*, 2009)

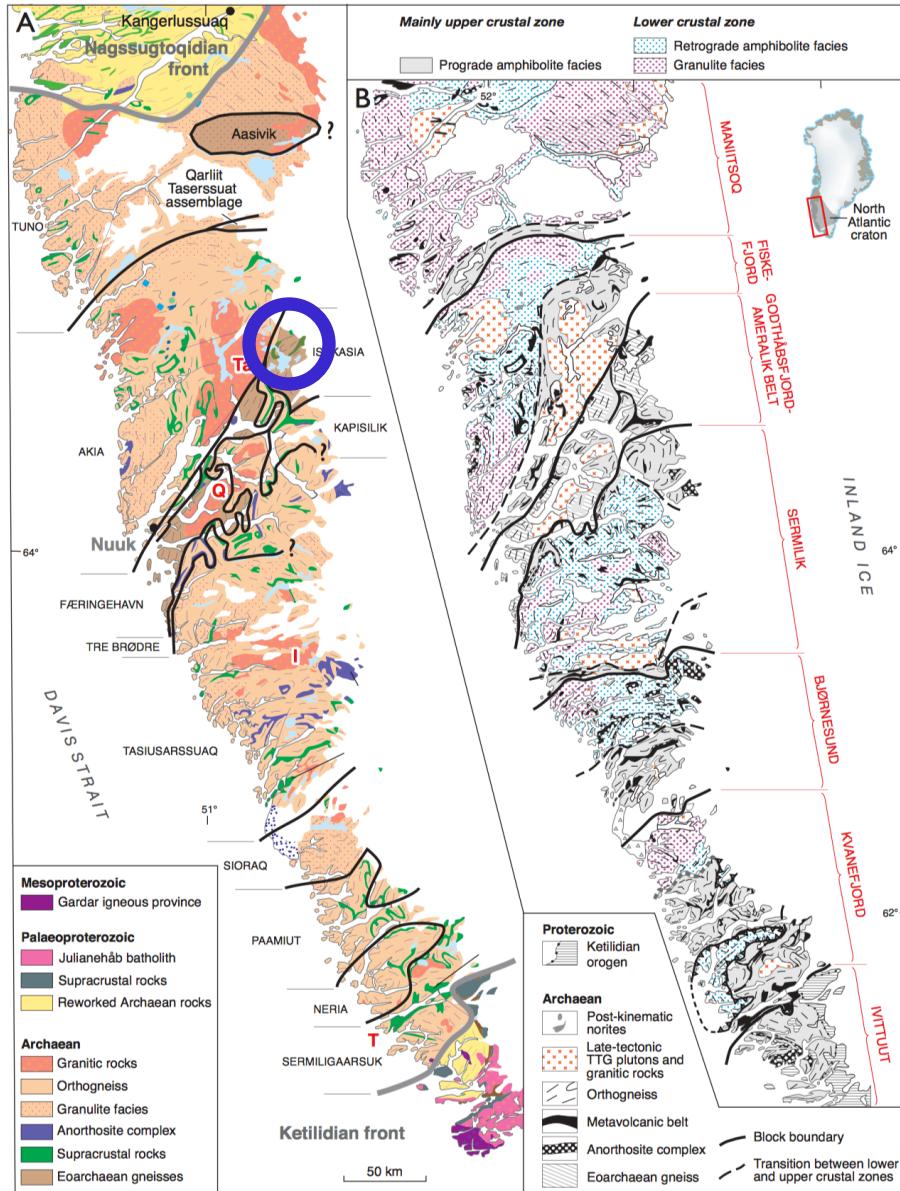


Figure 2  
(Henriksen *et al.*, 2009)

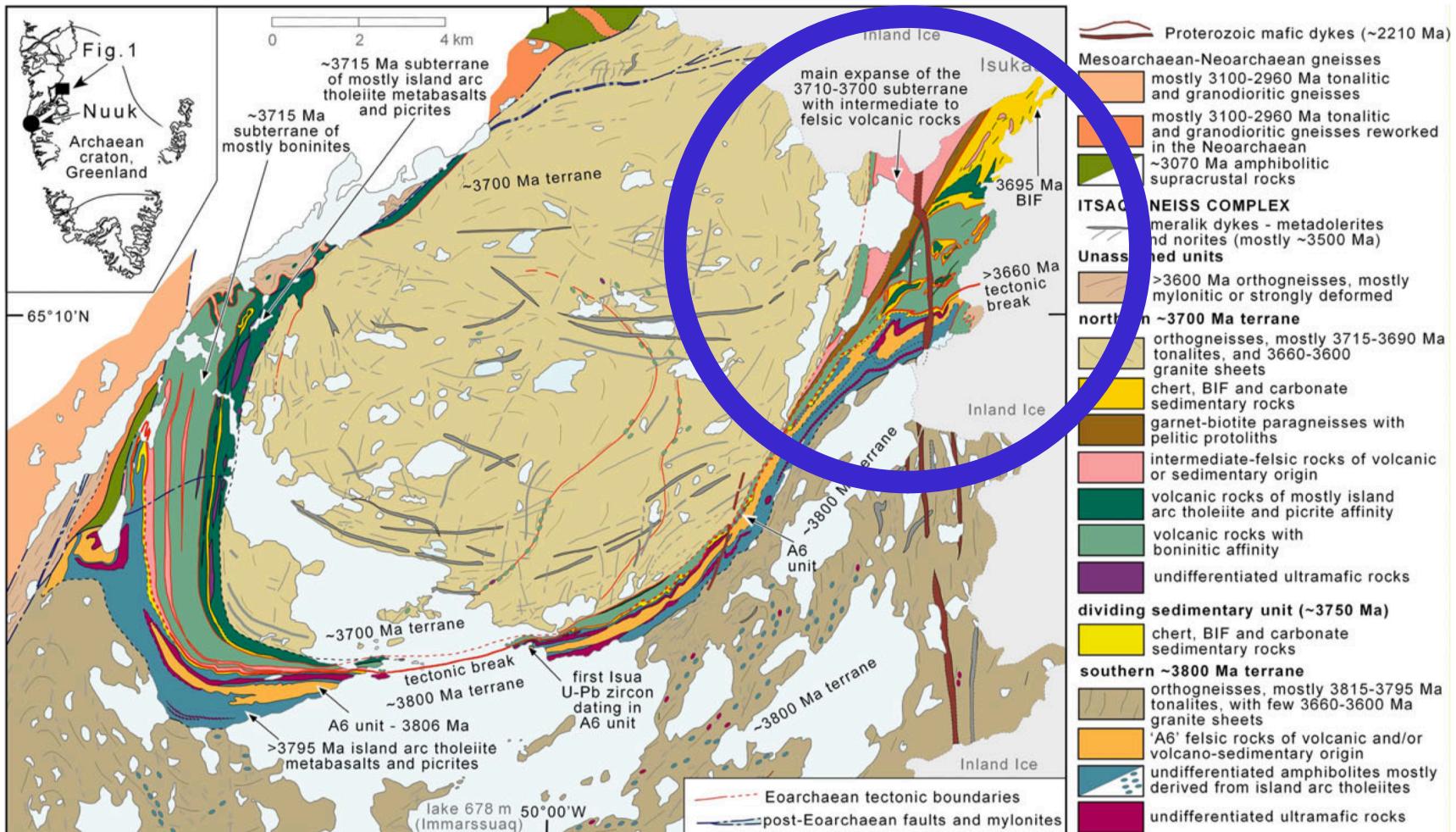


Figure 3  
(Kaczmarek *et al.*, 2016)

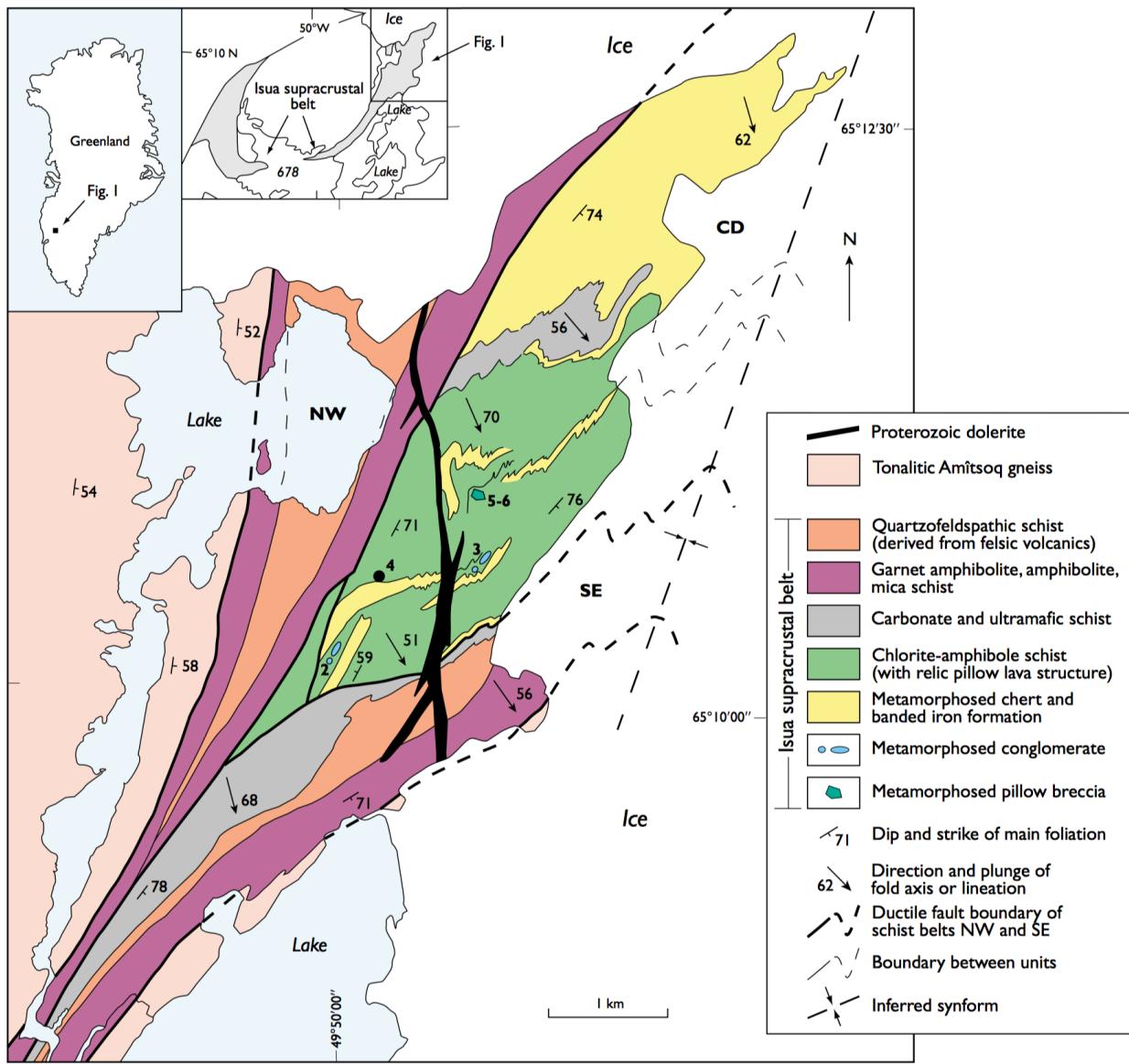


Figure 4  
(Appel *et al.*, 1998)

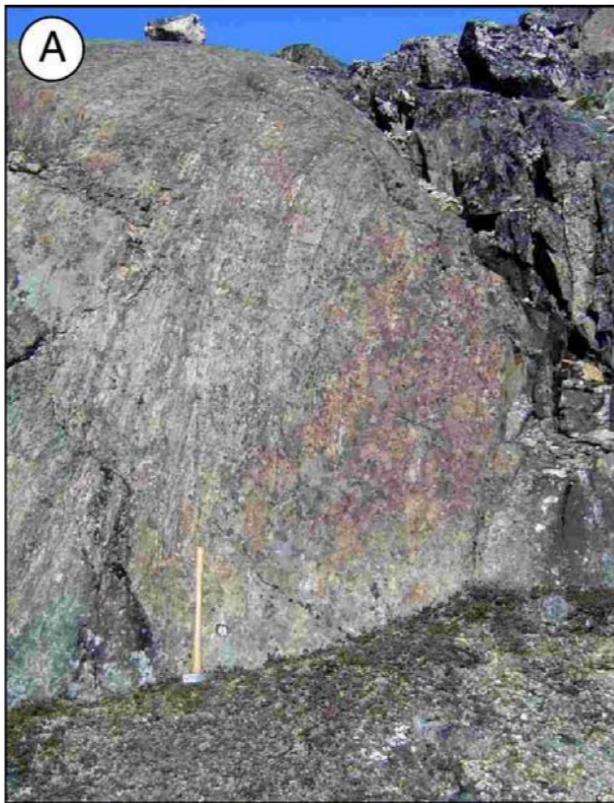
## PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

- A number of classifications exist for the lithological units of the Isua Greenstone Belt
- We will primarily rely on those found in Furnes (2009), Rollinson (2002) and Appel (1998)
- The Isua Greenstone Belt is marginally contained by the Ikkattoq gneisses in the north and Tonalitic Amitsoq gneisses that are located between the two limbs and towards the south
- The next several slides will give a quick overview of these main lithologic elements

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

## Garbenschiefer amphibolites

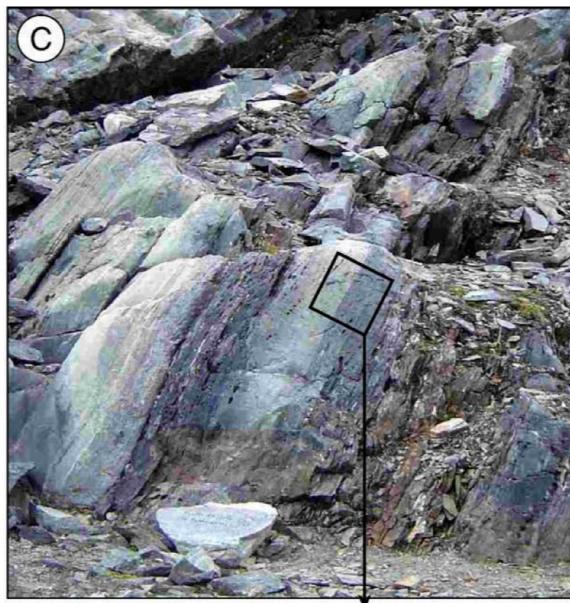
- Encompass a significant part of the greenstone belt
- Characterized by island arc tholeiites and boninite-like rocks
- This unit consists entirely of recrystallized rocks, mostly highly schistose
- Mineral assemblage is primarily composed of a hornblende–garnet–biotite–chlorite
- Interpreting protoliths is difficult, though it is possible discern between metavolcanic/intrusive and metasedimentary protoliths
- Well-preserved sedimentary structures are observable in the lowest-strain domains



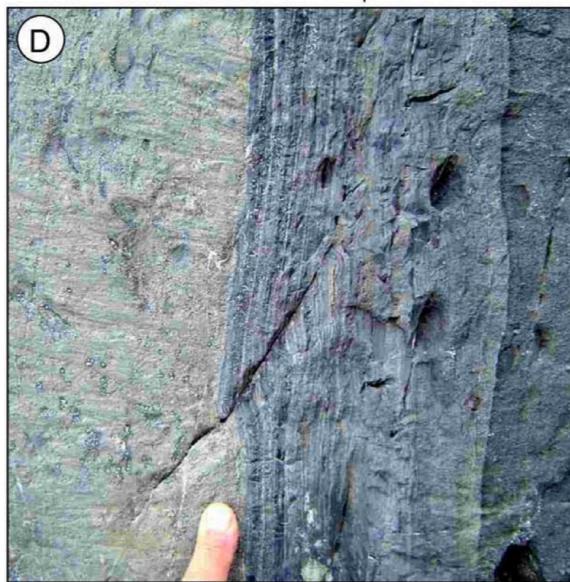
**Figure 5** – General view of the Garbenschiefer amphibolite from the western arm of ISB (Furnes *et al.*, 2009)



**Figure 6** – Close-up of Garbenschiefer amphibolite showing cm-long amphibole sheaves (Furnes *et al.*, 2009)



**Figure 7** – Volcaniclastic sediments showing graded bedding from Garbenschiefer amphibolites from the western arm of ISB (Furnes *et al.*, 2009)



**Figure 8** – Close-up from picture C. Finger points to the grey graphite-bearing pelitic top of a graded bed (younging to the left) from Garbenschiefer amphibolites from the western arm of ISB (Furnes *et al.*, 2009)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

## Undifferentiated amphibolites

- Contains all major lithological units typical of a Penrose-type ophiolite sequence
- The undifferentiated amphibolites includes a number of lithological components to be briefly discussed in following slides



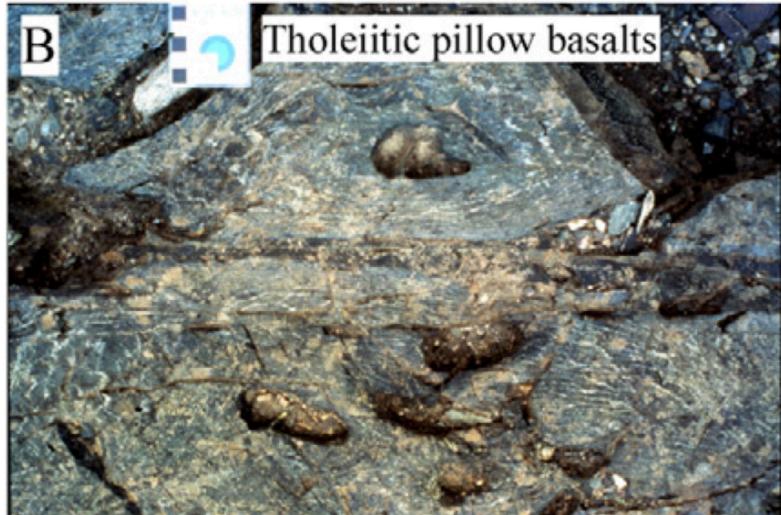
**Figure 9** – Amphibolites from the central tectonic domain (Hoffmann *et al.*, 2010)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

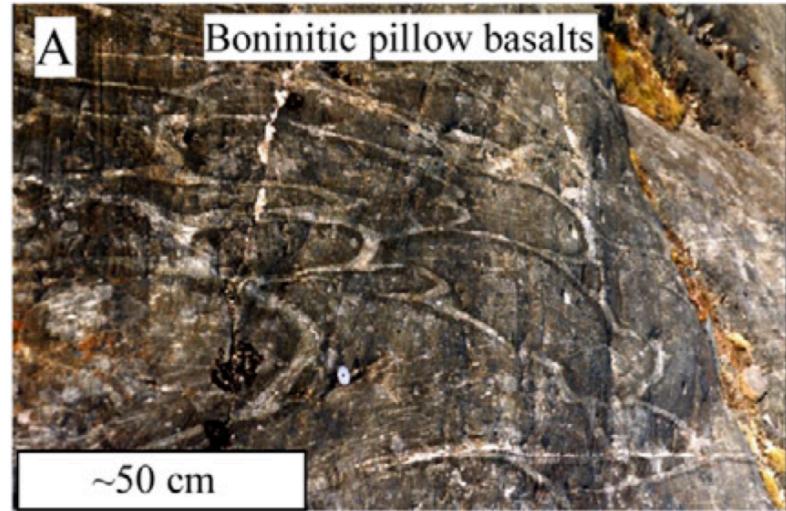
## Undifferentiated amphibolites

### Pillow lava

- Degree of deformation is variable throughout appearances in the greenstone belt
- Range in size up to 50 x 75 cm
- Some pillows have amygdaloidal centres
- Typically pillows are densely packed, but in some places interstitial chert is present



**Figure 10** – Tholeiitic pillow basalts from the central tectonic domain (Hoffmann *et al.*, 2010)



**Figure 11** – Boninitic pillow basalts from the central tectonic domain (Hoffmann *et al.*, 2010)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

## Undifferentiated amphibolites

### Pillow breccia

- Best preserved unit of pillow breccia extends over an area about 100 x 150 m
- Consists of grey, amygdaloidal, angular pillow fragments that consist of quartz, biotite, muscovite with small amounts of plagioclase



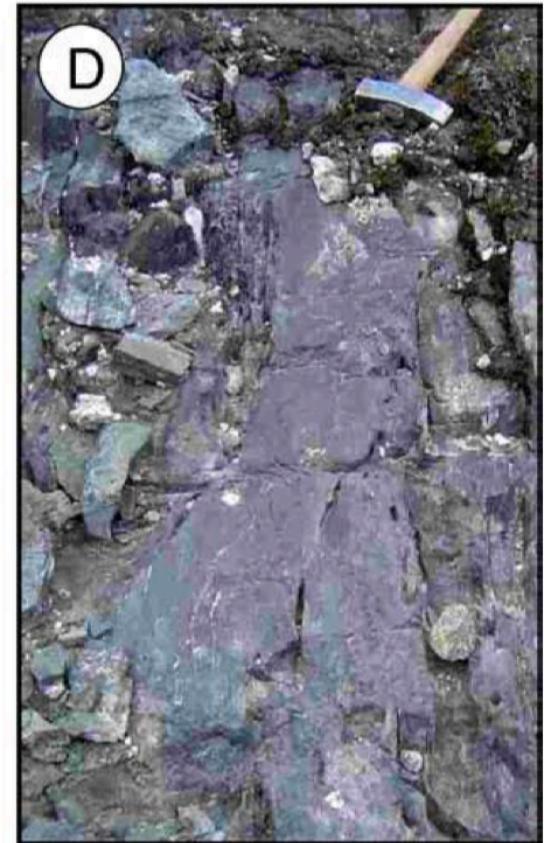
**Figure 12** – Pillow breccia from the central tectonic domain (Hoffmann *et al.*, 2010)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

## Undifferentiated amphibolites

### Dikes

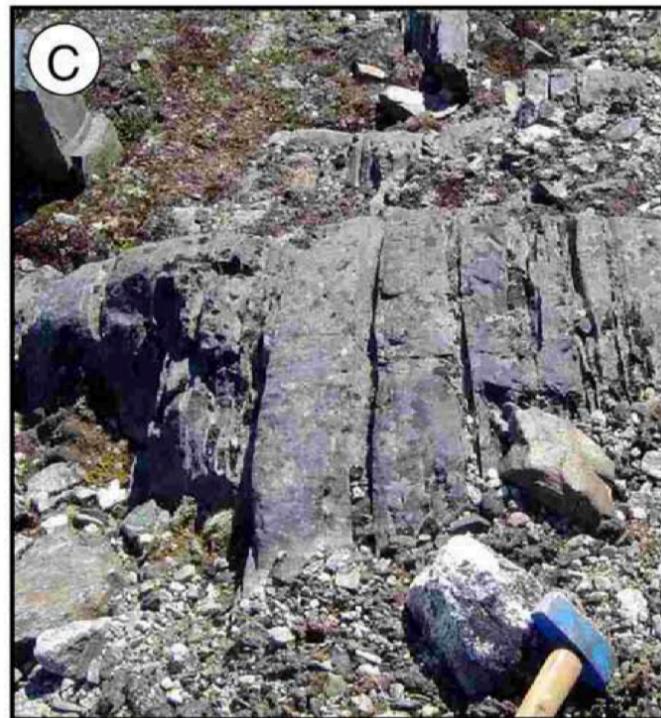
- Central parts of sheeted dykes consist of fine-grained plagioclase and amphibole with minor amounts of biotite
- Cross-cutting dykes do occur
- Marginal zones interpreted as chilled zones



**Figure 13** – Cross-cutting dikes  
(Furnes *et al.*, 2009)



**Figure 14** – Dikes and screens of volcanic rocks from Undifferentiated Amphibolites unit located on western portion of ISB (Furnes *et al.*, 2009)



**Figure 15** – Detail of individual dikes with pronounced chilled margins (Furnes *et al.*, 2009)



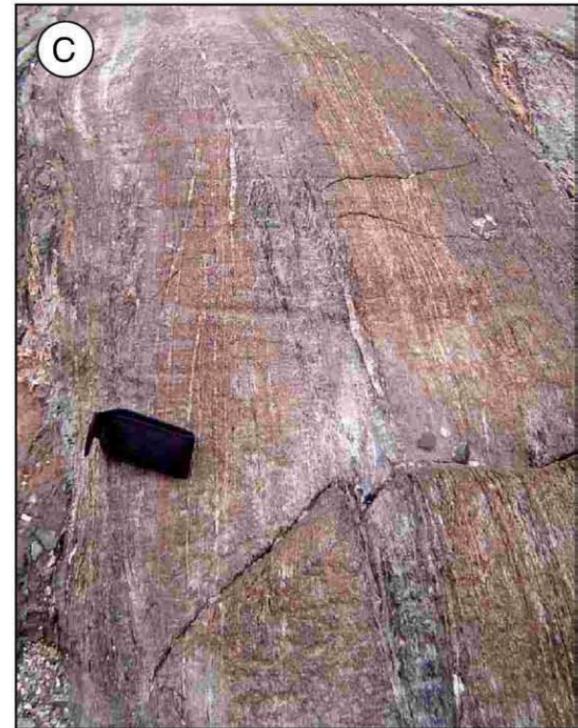
**Figure 16** – Approximately 30 m long continuous outcrop section (in the foreground of the picture) across part of the sheeted dike complex from a dike complex of the Isua Supracrustal belt (Furnes *et al.*, 2009)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

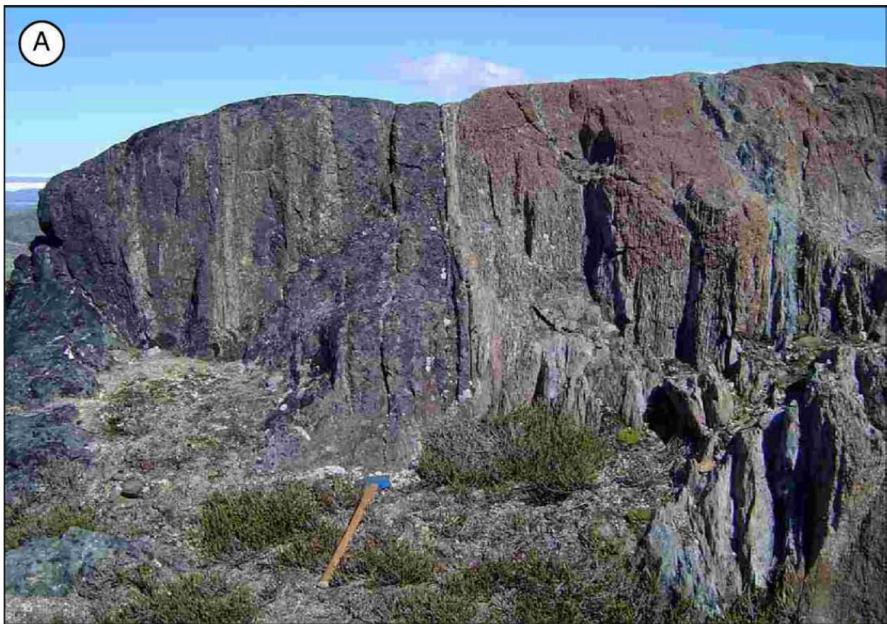
## Undifferentiated amphibolites

### Ultramafic rocks

- Makes up a considerable portion of both the western and eastern arms of the greenstone belt
- Red to grey/black rocks with colour banding and are medium to coarse grained
- Are generally enveloped by calc-silicate rocks which are interpreted to have formed by desilication and carbonation of country rocks by fluids flowing from the ultramafic rocks



**Figure 17** – Small-scale, alternating red and dark grey layers of metaperidotite of ultramafic rocks from the eastern part of the western arm of the ISB (Furnes *et al.*, 2009)



**Figure 18** – Large-scale, alternating reddish-brown (meta-dunitic to -harzburgitic) and black (metapyroxenite-rich) layers of ultramafic rocks from the eastern part of the western arm of the ISB (Furnes *et al.*, 2009)



**Figure 19** – Close-up photograph of the reddish-brown metaperidotite of ultramafic rocks from the eastern part of the western arm of the ISB (Furnes *et al.*, 2009)

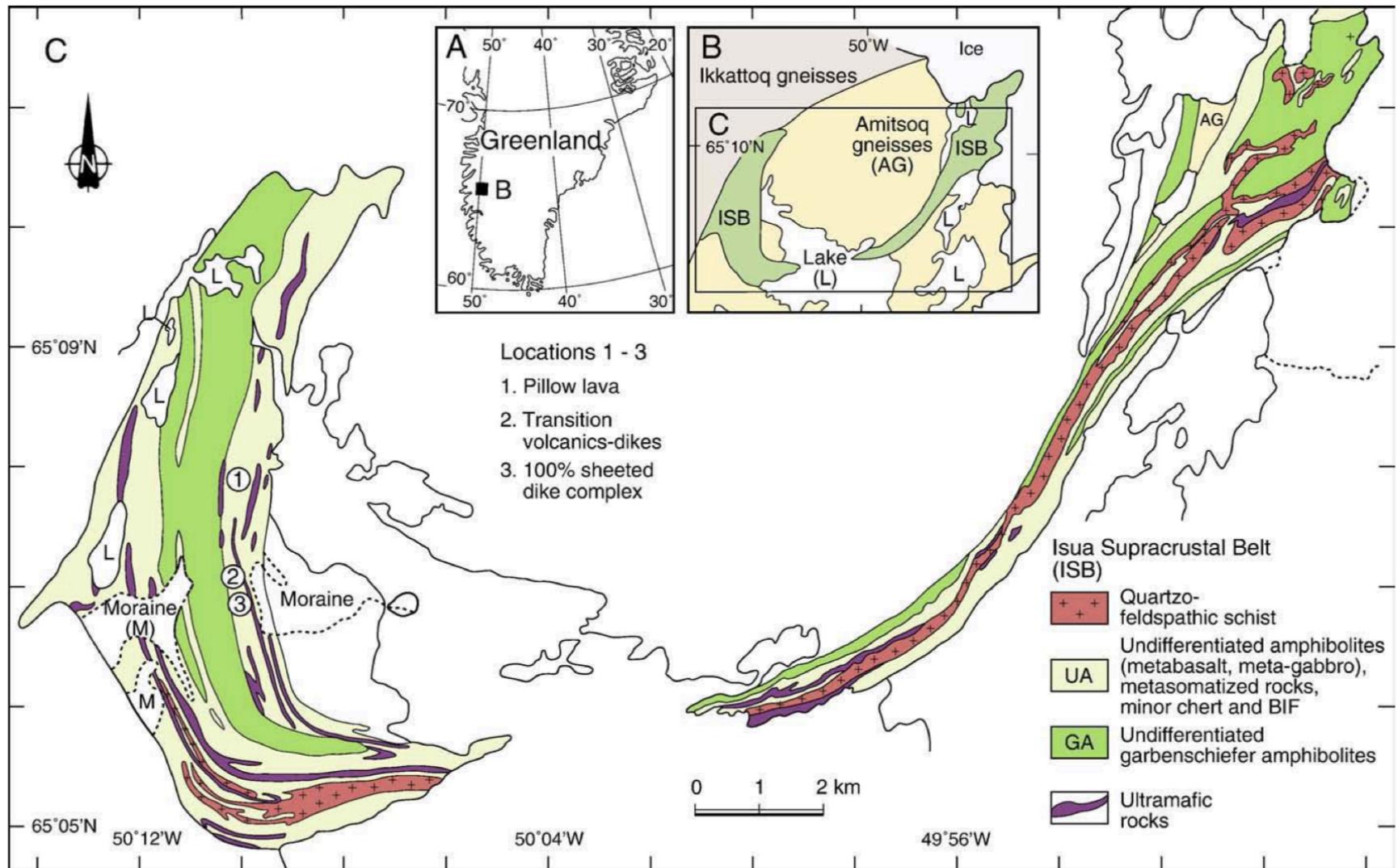


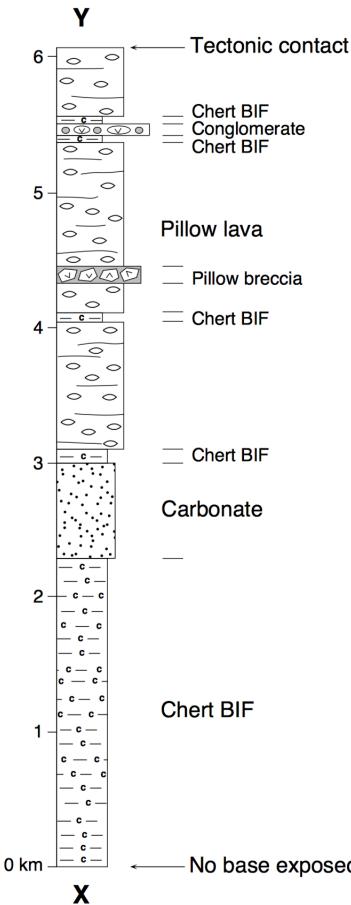
Figure 20  
(Furnes *et al.*, 2009)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

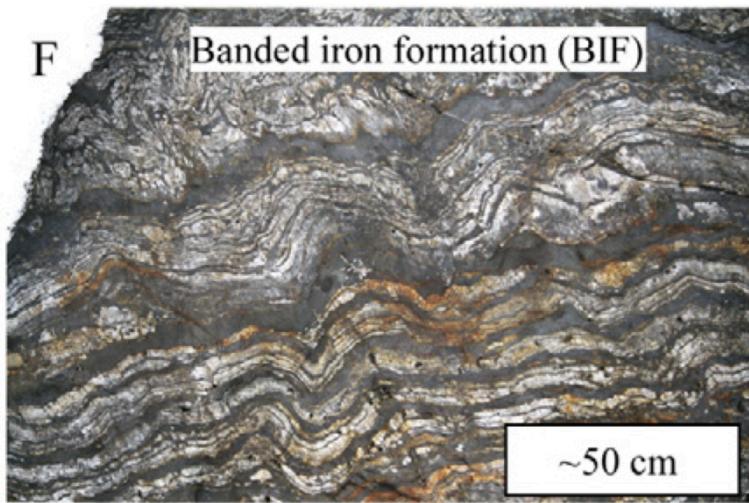
## Metasedimentary lithologies

### Banded iron formation

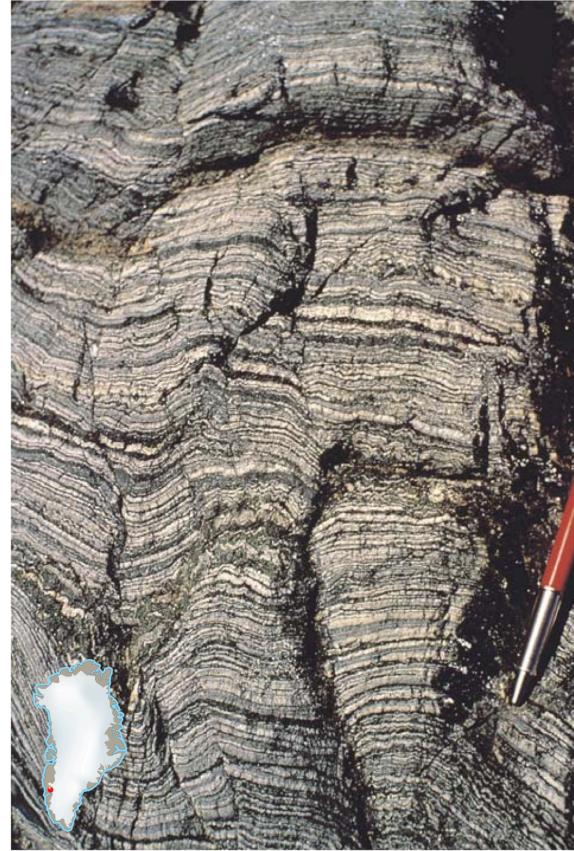
- Major sedimentary unit in the greenstone belt
- Consistent with submarine depositional setting
- Interbedded with chert



**Figure 21** – Stratigraphic column representing the central domain of relatively low strain (Appel *et al.*, 1998)



**Figure 22** – Banded iron formation from central tectonic domain (Hoffmann *et al.*, 2010)



**Figure 23** – Eoarchean banded iron formation consisting of interlayered magnetite (dark layers) and chert (light layers) from the ISB (HenrikSEN *et al.*, 2009)

# PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

## Metasedimentary lithologies

### Polymict conglomerate

- Conglomerates in the Isua Greenstone Belt have been highly debated and many authors point to tectonic origins
- However, Appel *et al.* (1998) noted a particular conglomerate interval approximately 12 m thick with sharp lower and upper contacts with adjacent lithologies includes gravel sized clasts, that display all degrees of rounding indicating that the deposit had a primary clastic origin



**Figure 24** – Conglomerate from the southeastern tectonic domain (Hoffmann *et al.*, 2010)

# HISTORICAL SEQUENCE OF GEOLOGIC EVENTS

The following table is a brief summary of the events from the Archaean in Greenland, adapted from Mowatt & Naidu (1994)

- |   |   |
|---|---|
| 1. Early crust providing source rocks for Isua sediments  | Early earth   |
| 2. Deposition of the Isua supracrustals. Basic and ultrabasic lavas and intrusions, quartzites, siltstones, pelites, ironstones, and calcareous rock. Acid volcanic fragments in a conglomerate   | Isua supracrustals<br>> 3570 My   |
| 3. Intrusion of syntectonic and late tectonic granites (parents of the Amîtsoq gneisses), possibly contemporaneous with upper acid volcanic part of the Isua supracrustals  | Amîtsoq gneisses<br>c. 3750 My  |
| 4. Deformation and metamorphism of the Amitsoq gneisses and Isua supracrustals  |   |
| 5. Intrusion of abundant swarms of basic dykes (Ameralik dykes) during regional stress  | Ameralik dykes  |
| 6. Extrusion of basic and intermediate volcanics (locally pillow lavas); intrusion of ultra-basic bodies and layered basic igneous bodies; deposition of sediments including pelites, aluminous quartzites, minor calcareous units (Maiene supracrustals) | Malene supracrustals<br>> 3040 My<br><i>(possibly 3750 My or earlier)</i> |

# HISTORICAL SEQUENCE OF GEOLOGIC EVENTS

- |     |   |  |
|-----|---|--|
| 7.  | Emplacement of major stratiform anorthosites and gabbro anorthosites  | Anorthosite complexes<br>> 3040 My               |
| 8.  | Major thrusting intercalating the Amîtsoq gneisses, Malene supracrustals and anorthosites   |  |
| 9.  | Emplacement of ultrabasic bodies, mostly between Malene supracrustal rocks and Amîtsoq gneiss units   |  |
| 10. | Intrusion of major suites of syntectonic and late tectonic calc-alkaline rocks as subconcordant sheets (Nûk gneisses)   | Nûk gneisses<br>3040 My                          |
| 11. | Intense deformation with the formation of major nappes, followed by less intense deformation which produced upright folds and widespread dome and basin interference patterns. These were partly modified by sub-linear belts of very intense deformation | Major folding<br>3040–2800 My                    |
| 12. | Emplacement of syn- and late tectonic granites, partly formed by the remobilization of earlier gneisses during increasing regional metamorphism. Emplacement of norites, andesine anorthosites and quartz monzonites                                      | Late granites<br>3000–2800 My                    |
| 13. | High grade metamorphism outlasting (11) and (12) and culminating in the widespread crystallization of granulite facies under late to post-tectonic conditions   | Granulite-facies<br>metamorphism<br>3000–2700 My |

# METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

- Rollinson (2002) subdivides the Isua Greenstone Belt into five distinct domains based on lithological, structural, geochronological and geochemical differences
- Maximum metamorphism in the greenstone belt is amphibolite-facies
- Prior to summarizing the metamorphic history of the Isua Greenstone Belt described by Rollinson (2002), a brief description of these domains is required

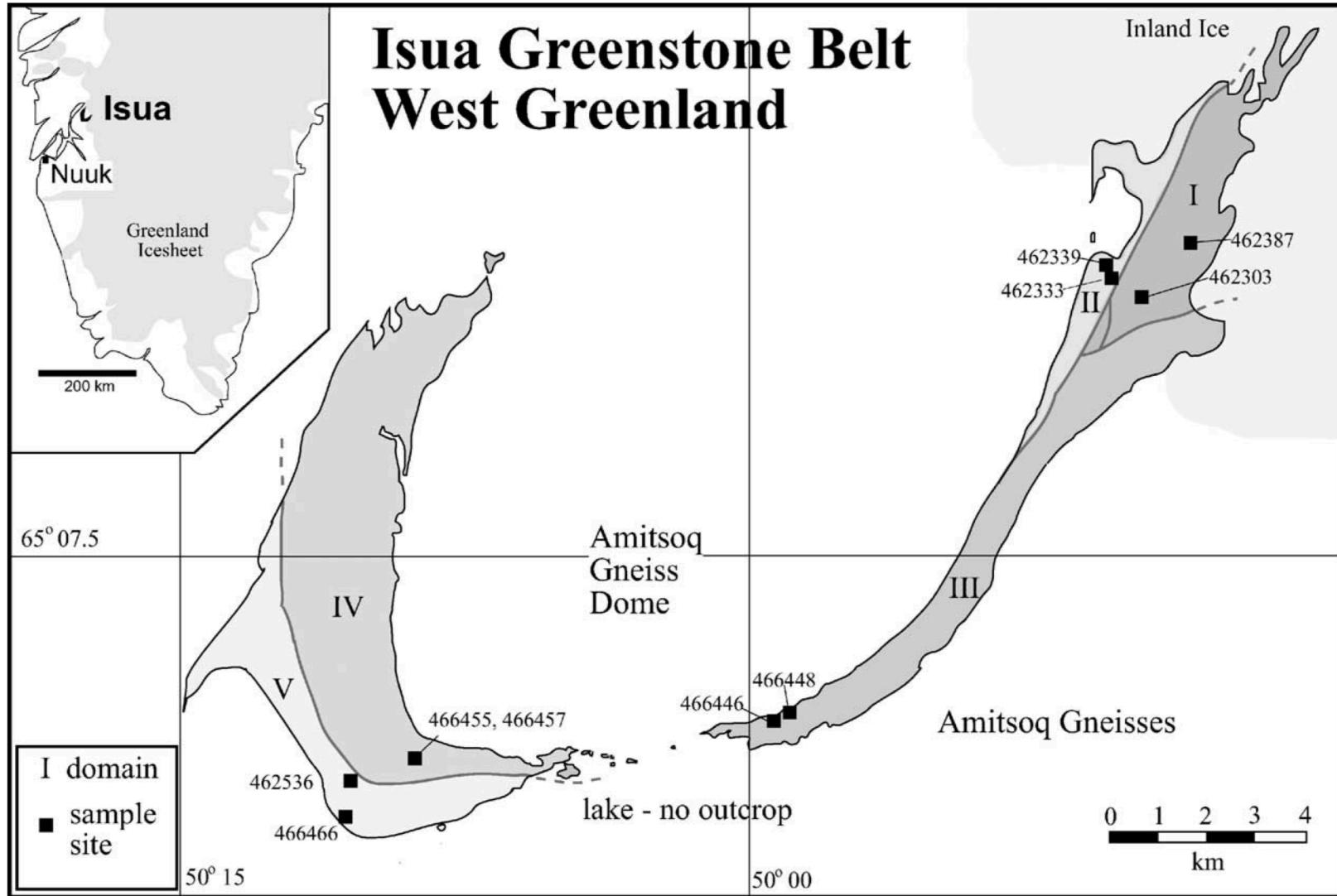


Figure 25  
(Rollinson, 2003)

# METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

## Domain I

- Identified as the low-strain domain and is located in the north east
- Primary lithologies include mafic volcanic rocks, cherts, and banded iron formation, and contains well-preserved, primary igneous and sedimentary features
- Garnets preserve a relatively simple growth history
- Pb-Pb step-leaching age of magnetite from banded iron formation of  $3691 \pm 22$  is interpreted as age of amphibolite-facies metamorphism

# METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

## Domain II

- Lithologically distinct from the rest of the greenstone belt
- Separated from **Domain I** by a major shear zone
- Primary lithologies include pelites, amphiboles and felsic igneous rocks, that have been interpreted as agglomerates but may be deformed tonalities that intruded into the greenstone belt
- Garnets record two growth episodes

# METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

## Domain III

- Narrowest part of the greenstone belt and occurs in the southern portion of the eastern limb
- Primary igneous features are not preserved, which suggests more intensive deformation relative to other domains
- Contains amphiboles, ultramafic schists and pelites and is intruded by tonality sheets
- Some rocks are extensively altered to carbonate
- Zircon in carbonated felsic rock is dated to  $3806 \pm 4$  Ma, but a plagioclase-hornblende pair from an amphibolite yielded an Sm–Nd mineral isochron of  $2849 \pm 116$  Ma, that implies a later Archaean metamorphic event
- Garnets record three episodes of growth

# METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

## Domain IV

- Dominated by thick sequence of metamorphosed pillows lavas
- Generally highly deformed although isolated low-strain lacunae are present
- Occurs in the eastern part of the western limb
- Records three growth episodes of garnet, as found in **Domain III**

# METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

## Domain V

- Believed to be oldest part of the greenstone belt and occurs in the southwest
- Minimum age is based off of U-Pb dating of 3800 My, but it believed to be as old as 3900 My
- Most rocks in this domain are mafic or ultramafic
- Felsic rocks are considered as intruded sheets
- 3740 Ma metamorphism in this domain closely associated with a fluid infiltration event in which fluids rich in LREE, Th and U were emplaced

## METAMORPHIC HISTORY OF THE ISUA GREENSTONE BELT

Thus, the metamorphic history of the Isua Greenstone Belt can be summarized as follows:

- **Domains II-V** record two early metamorphic events. Evidence from **Domain V** suggest that the average age of the two events is around 3.74 Ga
- **Domain I** records a distinct, single, early Archaean metamorphic event at 3.69 Ga. Correlation with other domains is not understood
- **Domains III and IV** record a late Archaean metamorphism at c. 2.8 Ga

## MAGMATIC HISTORY

- Furnes *et al.* (2009) propose a geodynamic model for magmatic development of the Isua Greenstone Belt
- They propose a magmatic evolution similar to of suprasubduction zone (SSZ) ophiolites in the Mediterranean region
- SSZ was first introduced in 1984 to describe ophiolites with crustal components and architecture of oceanic crust with geochemical signatures related to subduction
- Their model suggests that the Undifferentiated Amphibolies (UA) unit described earlier represents the oldest unit.
- This unit displays a MORB-like geochemistry with a wide compositional range from primary to highly-fractionated magmas, from mantle-generated melt during seafloor spreading and not necessarily related to any influence of subduction zones
- The Garbenschiefer Amphibolites (GA) are depleted in incompatible elements
- The GA unit formed during a later stage in which magmas were generated from subduction-affected, depleted and hydrated mantle

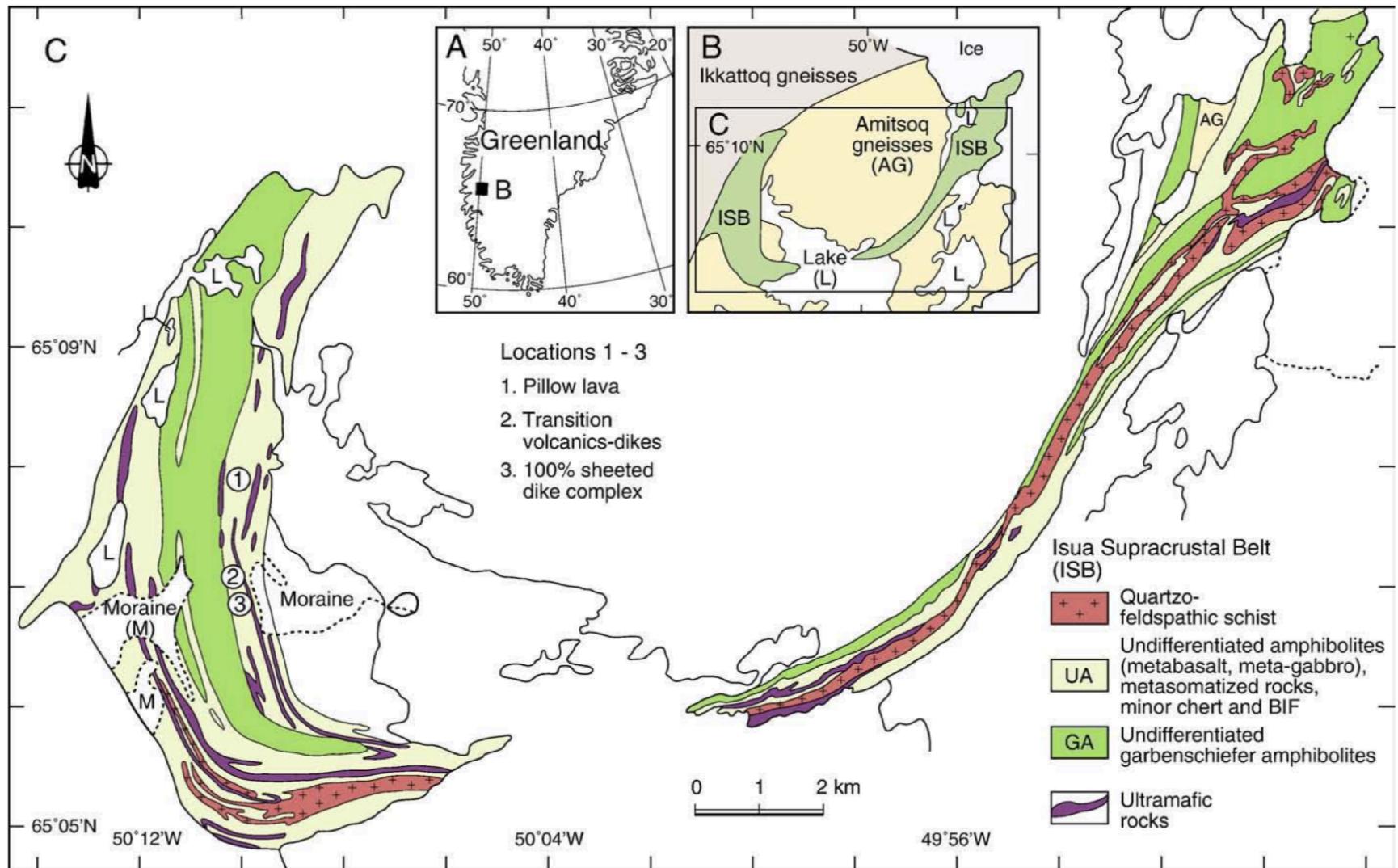


Figure 20  
(Furnes *et al.*, 2009)

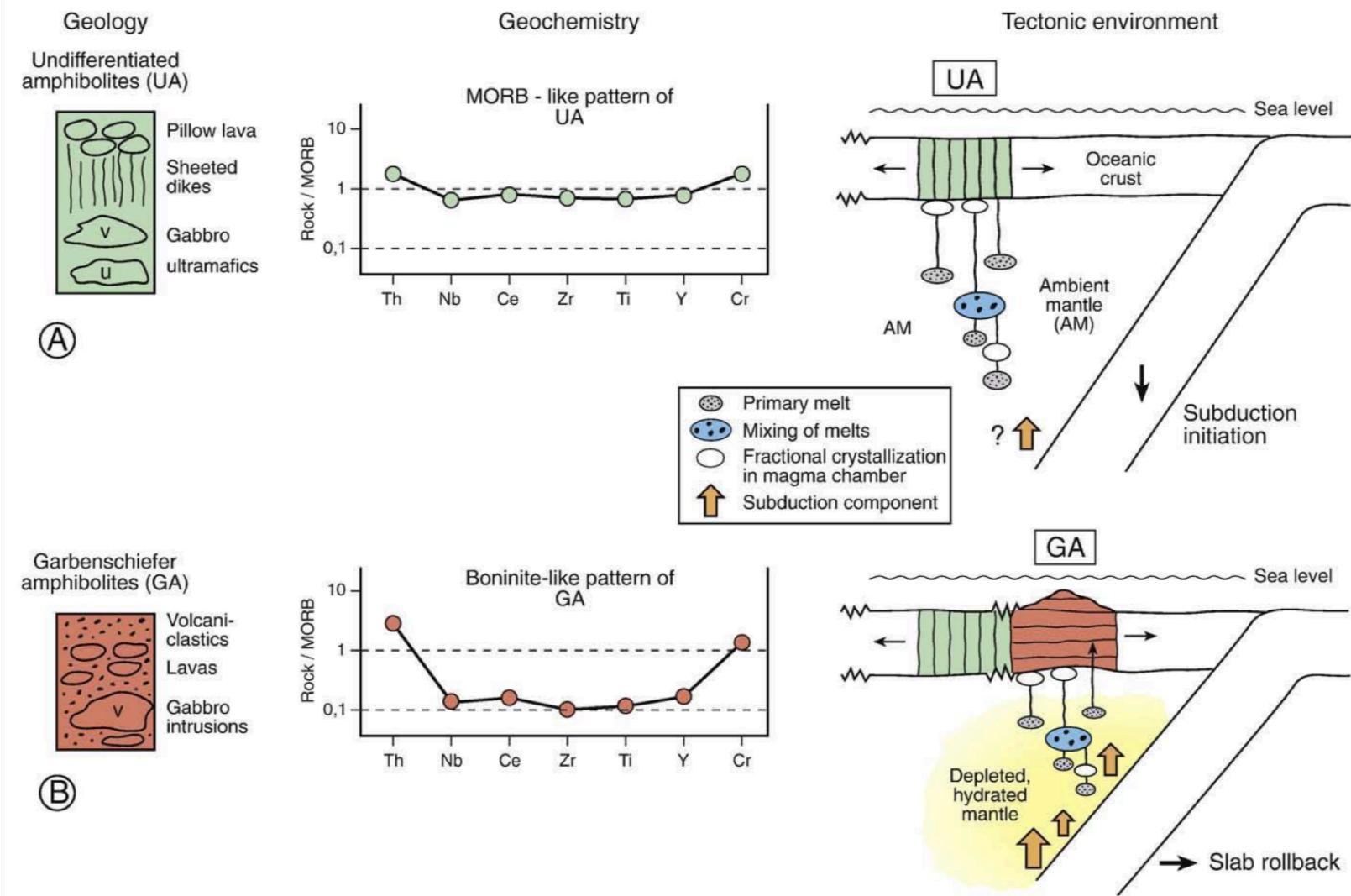
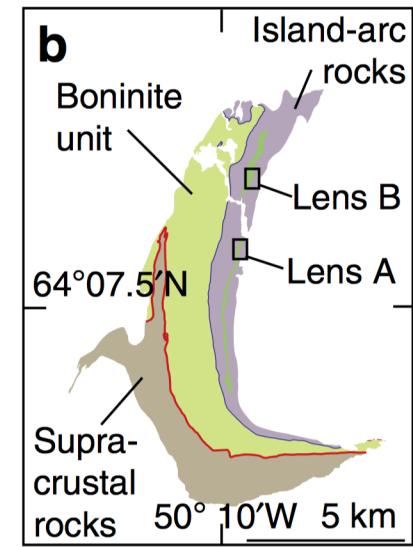


Figure 26  
(Furnes et al., 2009)

# MODELS FOR CRUSTAL DEVELOPMENT AND TECTONISM

- We will now examine two models demonstrating the evolution of the crustal development and evolution of the Isua Greenstone Belt
- The first model is from Kaczmarek *et al.* (2016), in which their model shows the development of their studied area (east side of the western limb, located in **Domain IV** from Rollinson (2002)



**Figure 27** – Displaying study area for Kaczmarek *et al.* (2016)

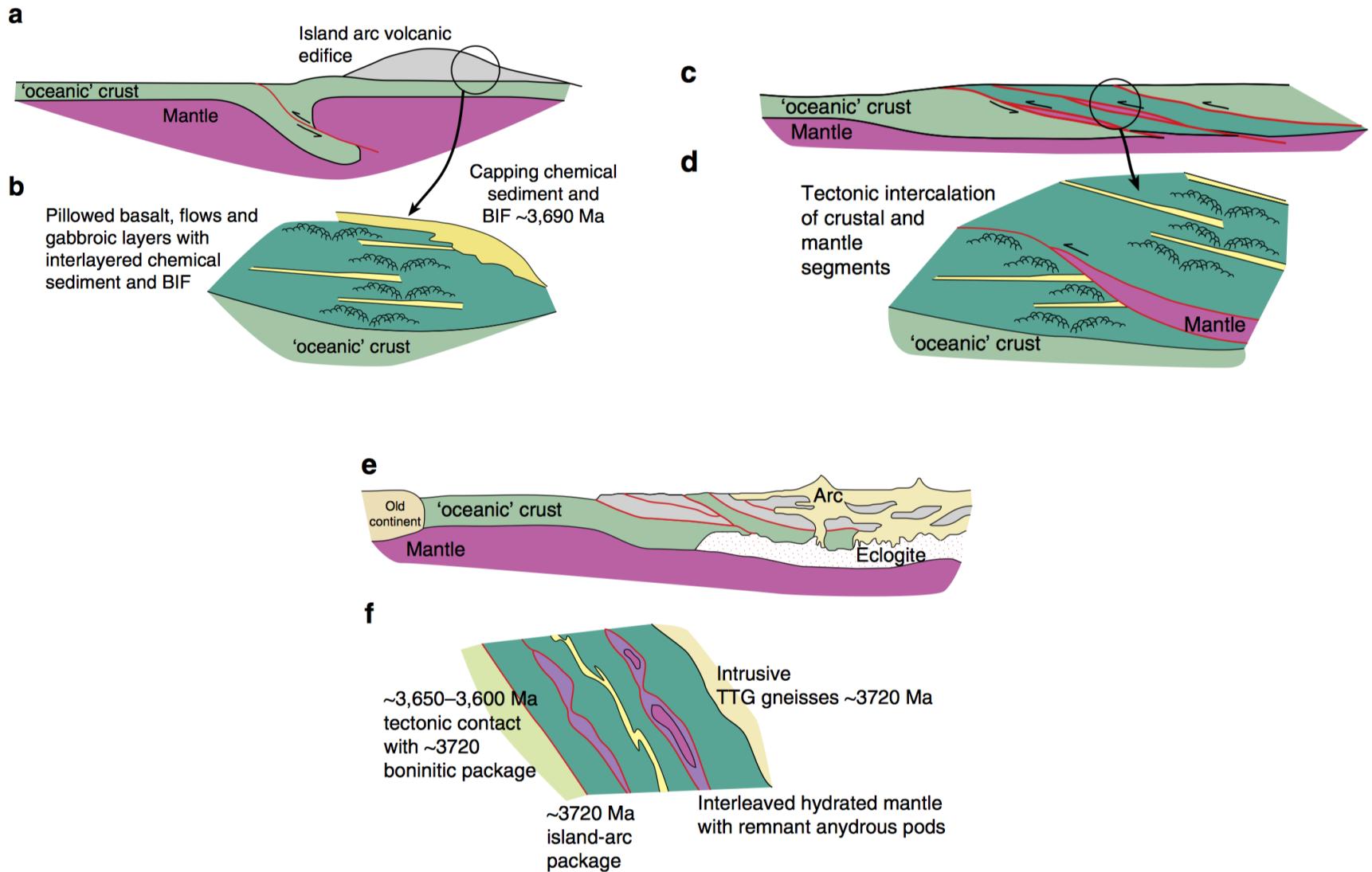


Figure 28  
(Kaczmarek *et al.*, 2016)

## MODELS FOR CRUSTAL DEVELOPMENT AND TECTONISM

- The second model, from Nutman *et al.* (2009), depicts the crustal evolution from 3800–3600 My in the Isua area

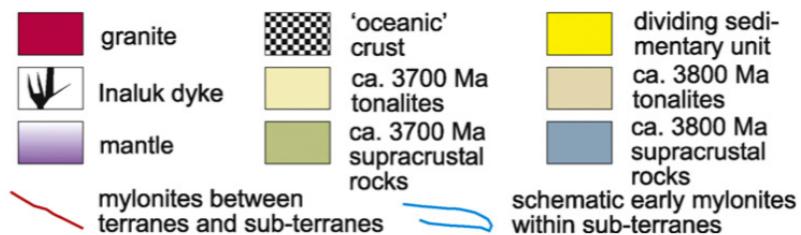
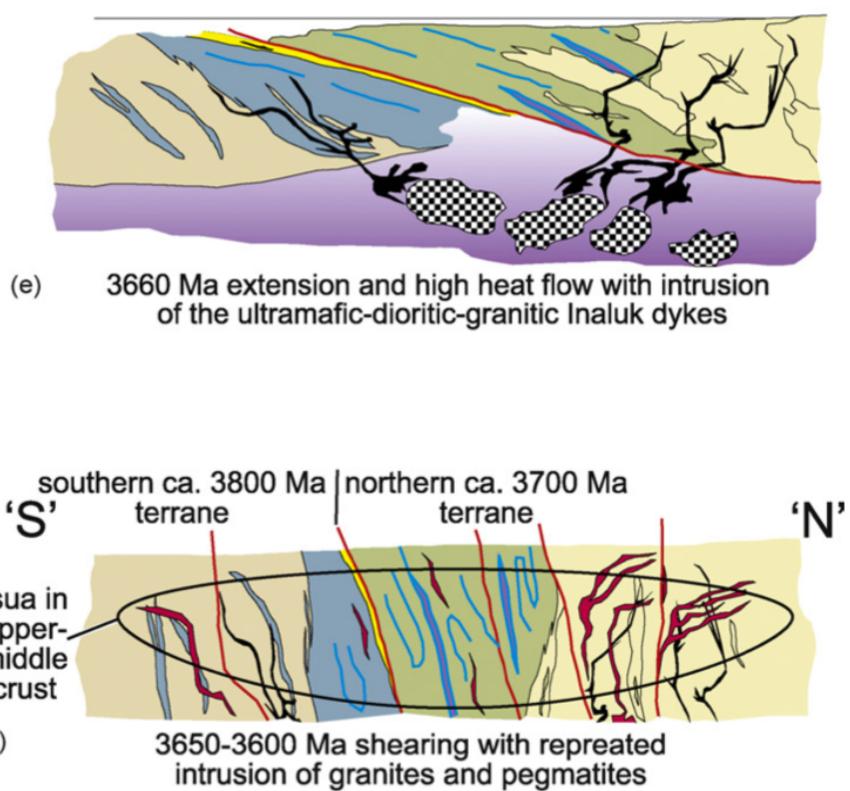
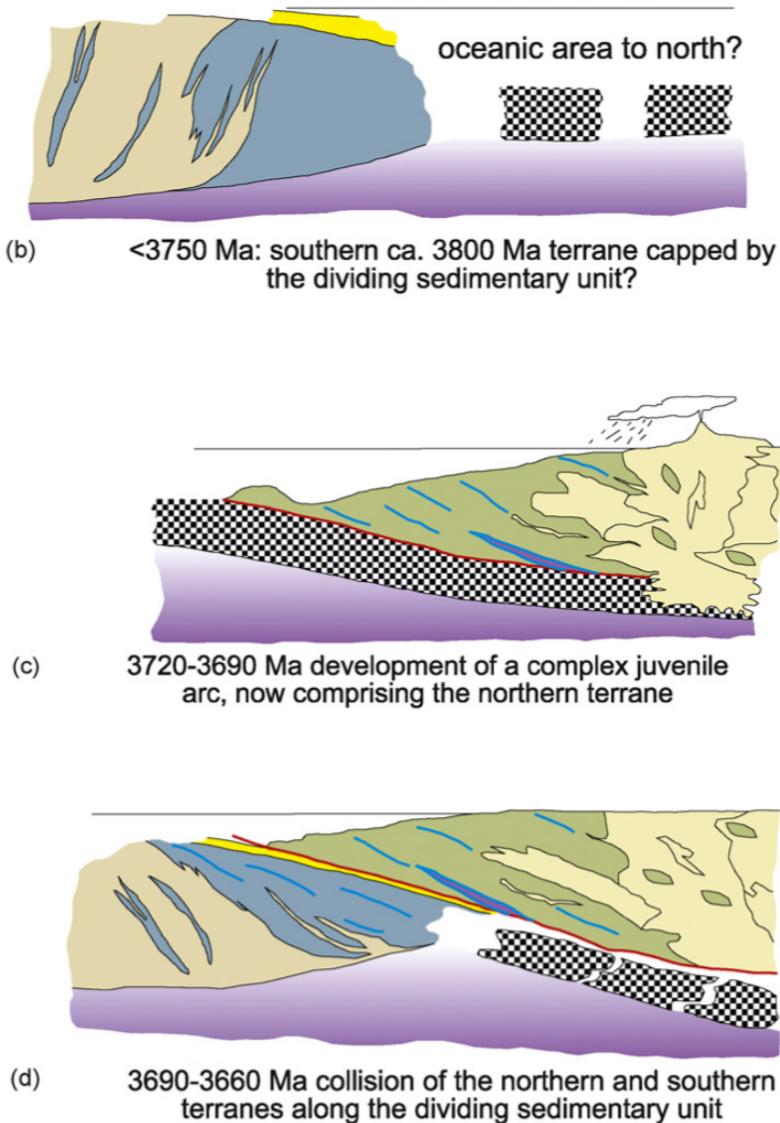


Figure 29  
(Nutman & Friend, 2009)

## CONTROVERSIES RELATED TO THE ISUA GREENSTONE BELT

- Most authors support horizontal plate motion for the Isua region, emphasized by geochemical signatures associated with Phanerozoic subduction zone settings, such as ophiolite sequences and boninites
- However, because horizontal plate tectonic motion has considerable preservation potential, absence of early Archaean rocks from geological record suggests different mechanics were in place
- Alternative models, principally vertical plate tectonics, where early lithospheric evolution operated through sub- and intra-lithospheric diapirism, associated downwelling and volcanism, and basal delamination have been proposed
- However, evidence of obduction at the Isua Greenstone Belt is not supported by vertical tectonics, and can presently, only be explained by horizontal motion
- A more recent model, that suggest volcanism dominated surface heat transport has been proposed, but was not discussed by any authors for this presentation

**THANK YOU**

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