THE ISUA SUPRACRUSTAL BELT OF SOUTHWESTERN GREENLAND

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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

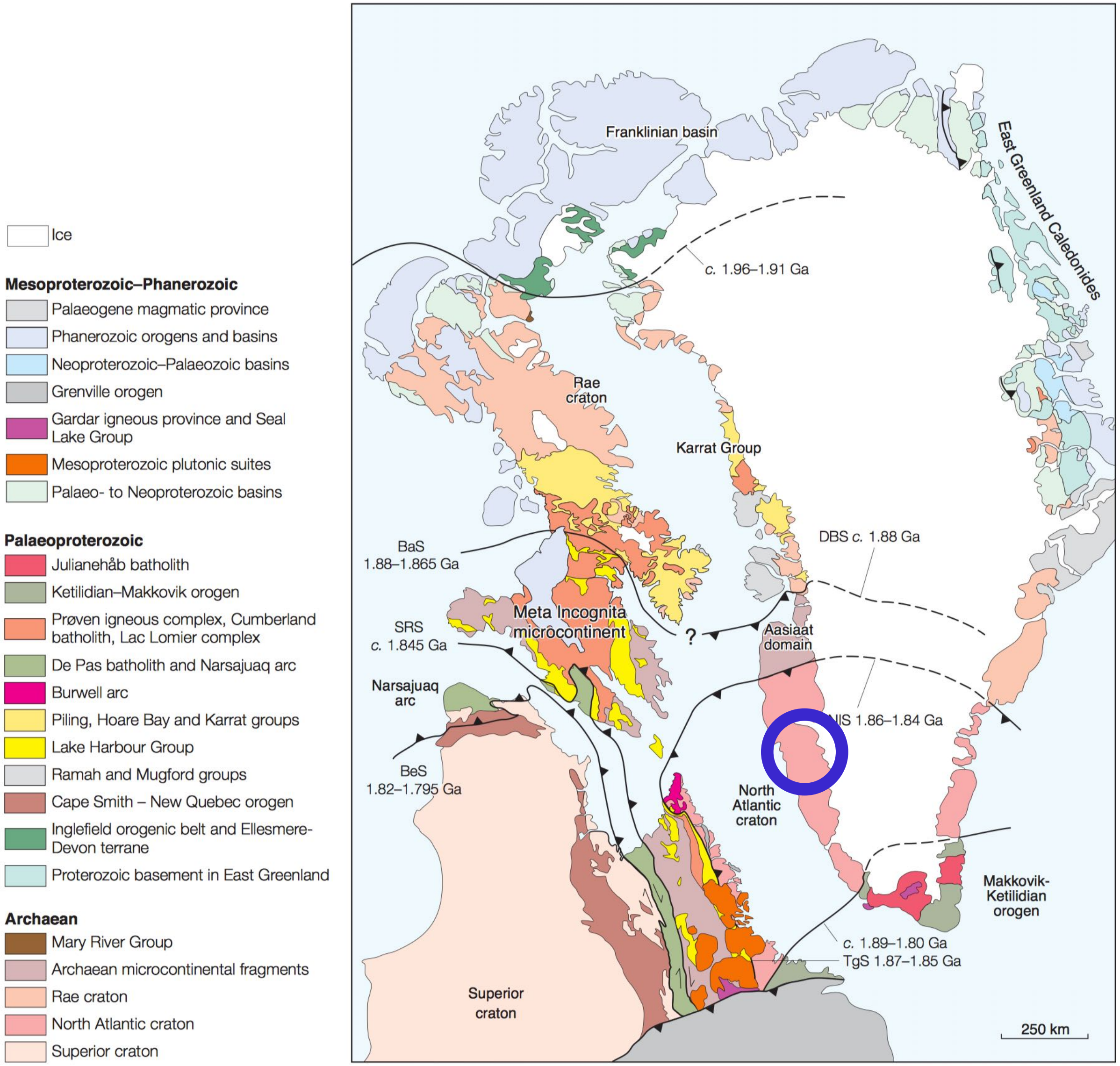

Figure 1
(Henriksen *et al.*, 2009)

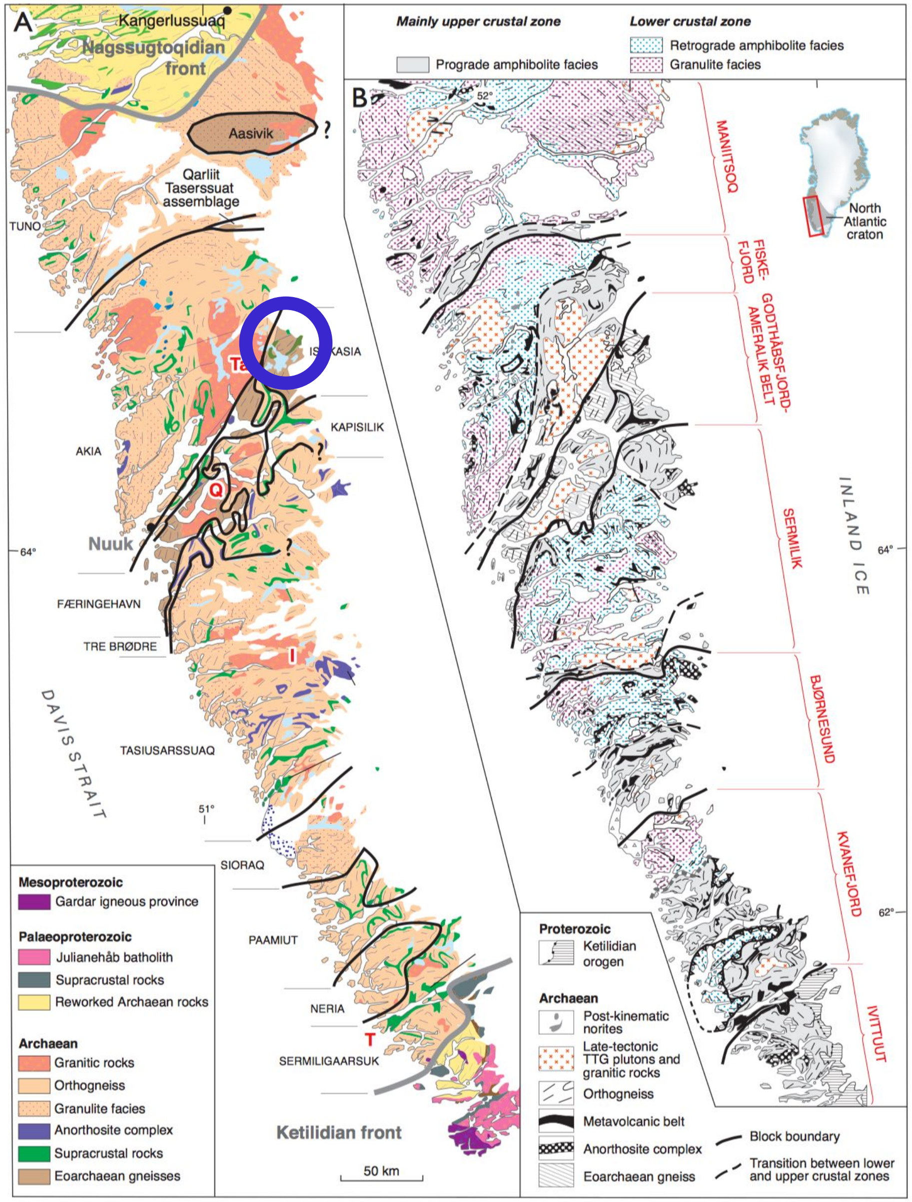

Figure 2
(Henriksen *et al.*, 2009)

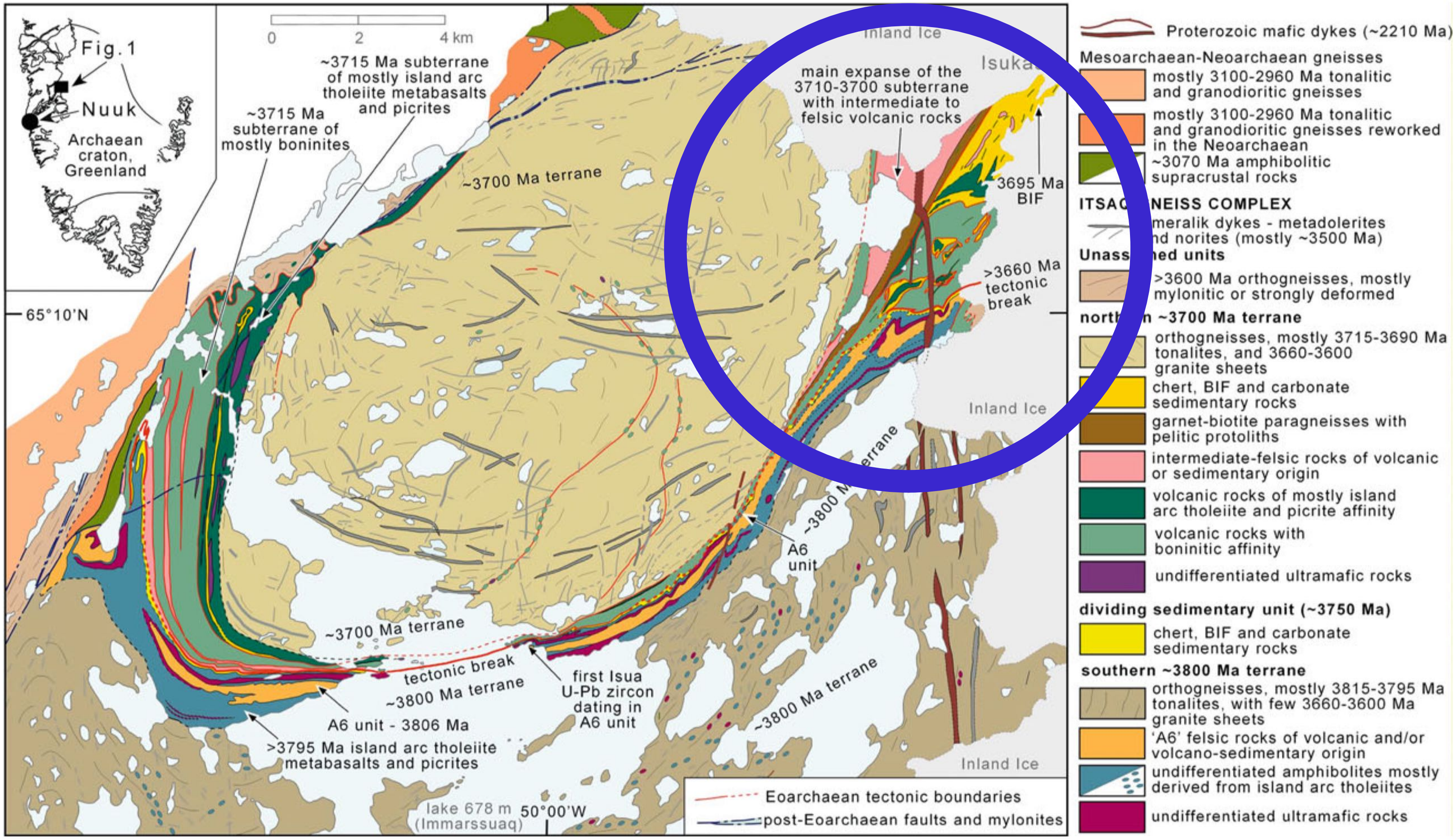

Figure 3
(Kaczmarek *et al.*, 2016)

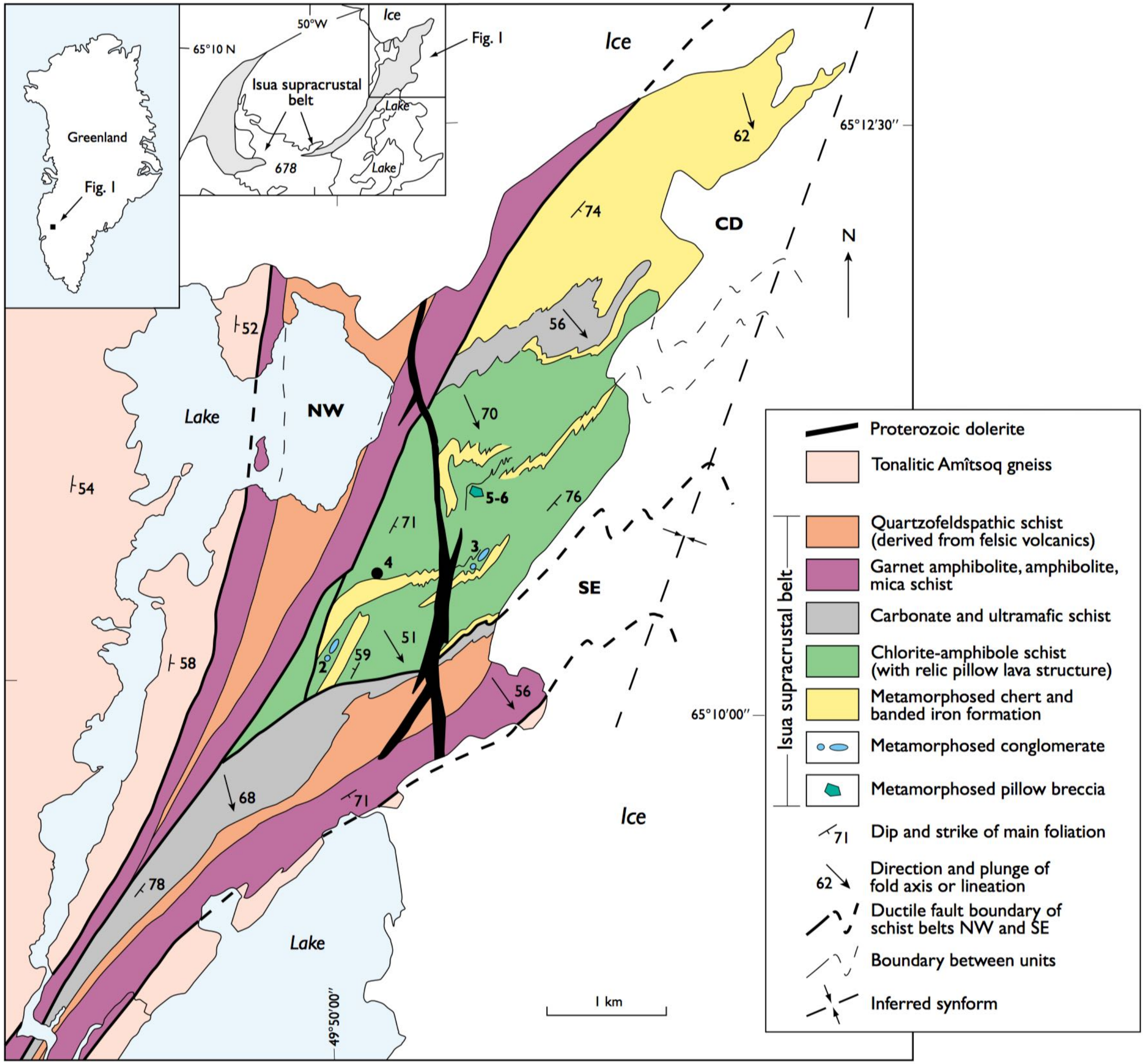

Figure 4
(Appel *et al.*, 1998)

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

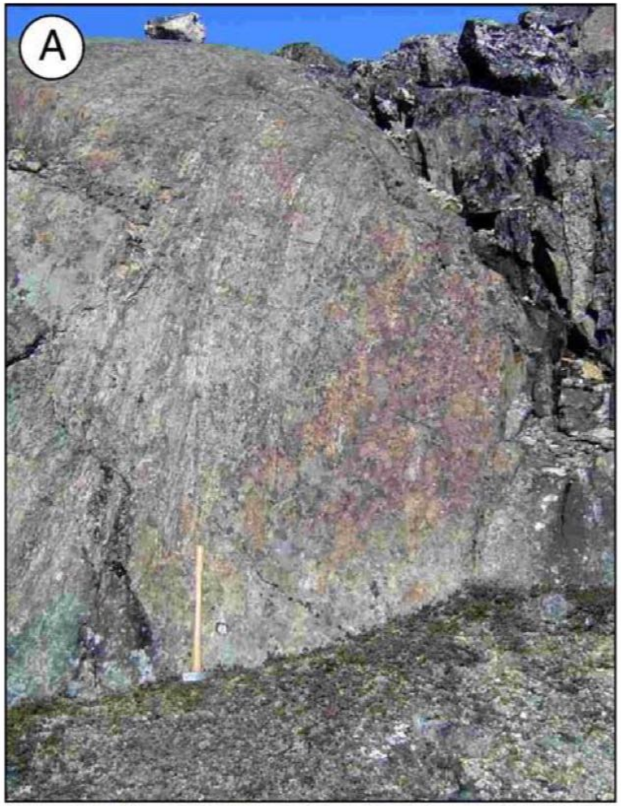

Figure 5 – General view of the Garbenschiefer amphibolite from the western arm of ISB (Furnes *et al.*, 2009)

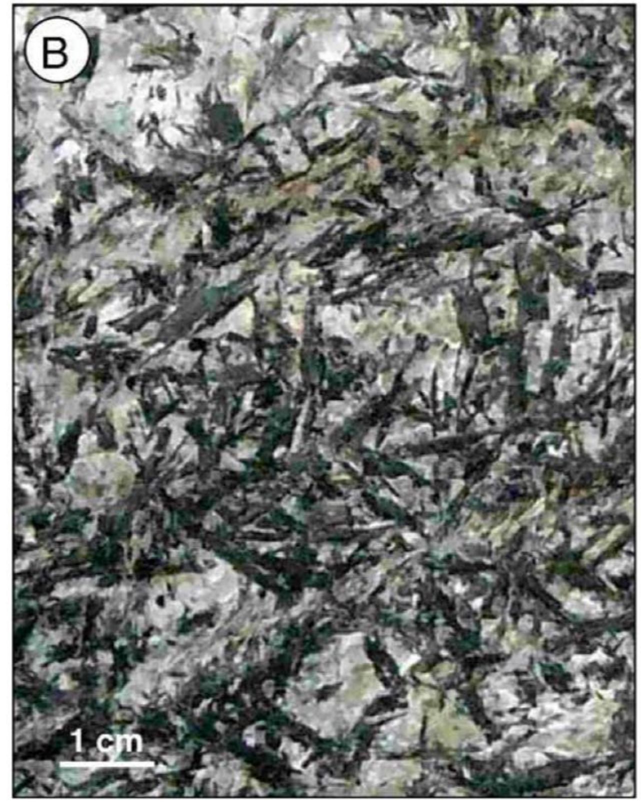

Figure 6 – Close-up of Garbenschiefer amphibolite showing cm-long amphibole sheaves (Furnes *et al.*, 2009)

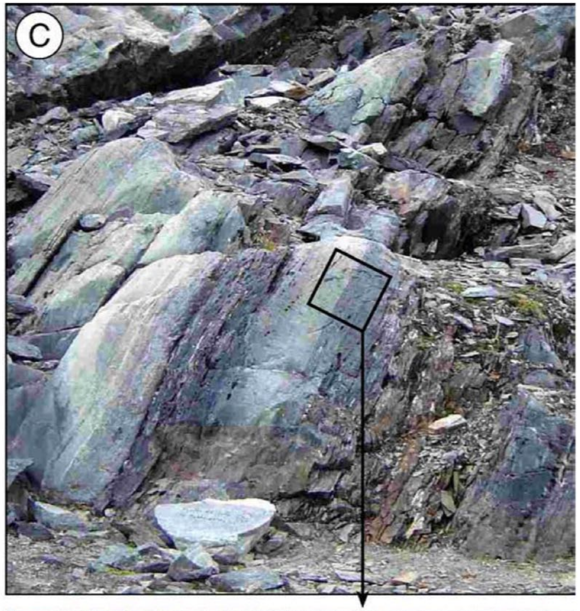

Figure 7 – Volcaniclastic sediments showing graded bedding from Garbenschiefer amphibolites from the western arm of ISB (Furnes *et al.*, 2009)

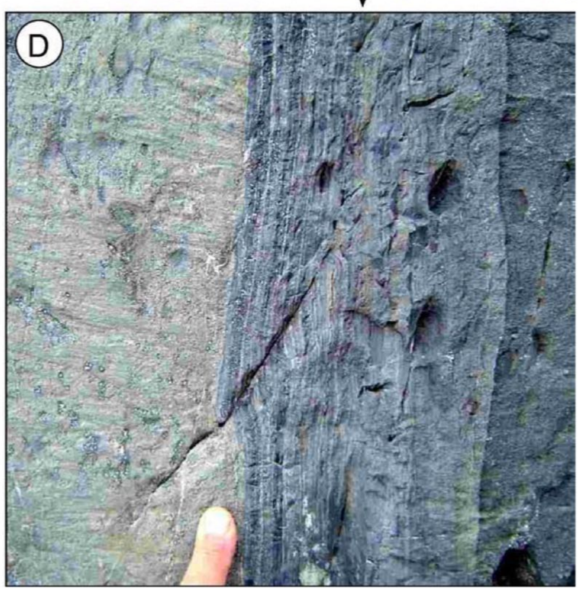

Figure 8 – Close-up from picture C. Finger points to the grey graphite-bearing pelitic top of a graded bed (younging to the left) from Garbenschiefer amphibolites from the western arm of ISB (Furnes *et al.*, 2009)

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

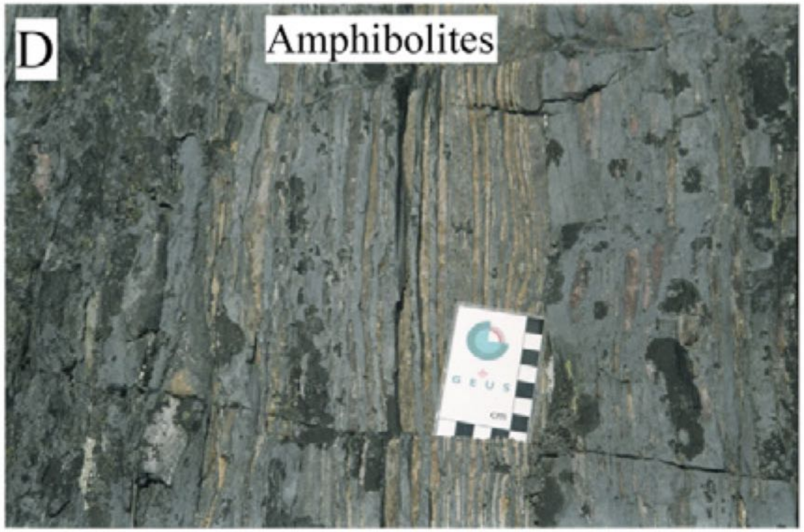

Figure 9 – Amphibolites from the central tectonic domain (Hoffmann *et al.*, 2010)

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)

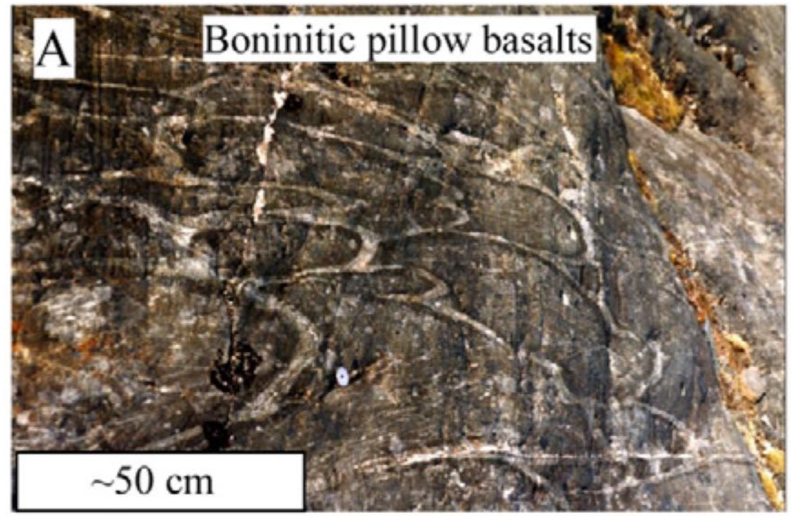

Figure 11 – Boninitic pillow basalts from the central tectonic domain (Hoffmann *et al.*, 2010)

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 interpretted 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)

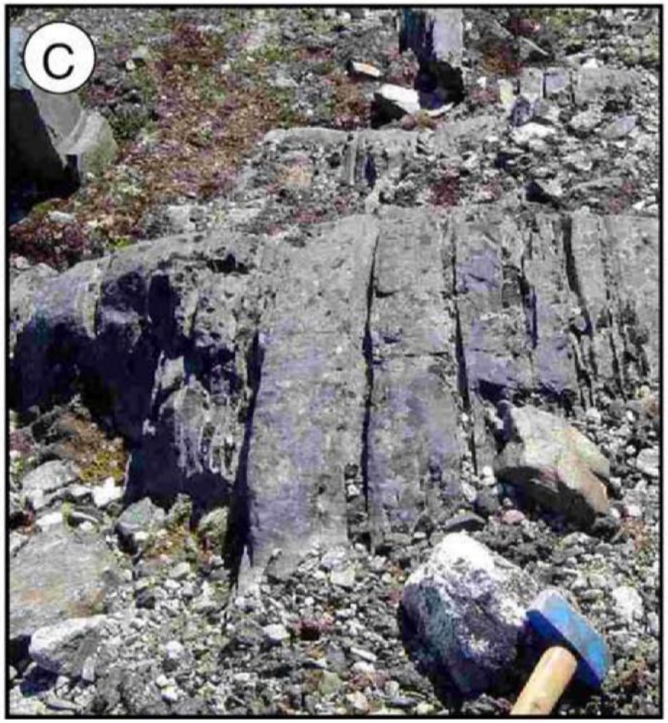

Figure 15 – Detail of individual dikes with pronounced chilled margins (Furnes *et al.*, 2009)

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)

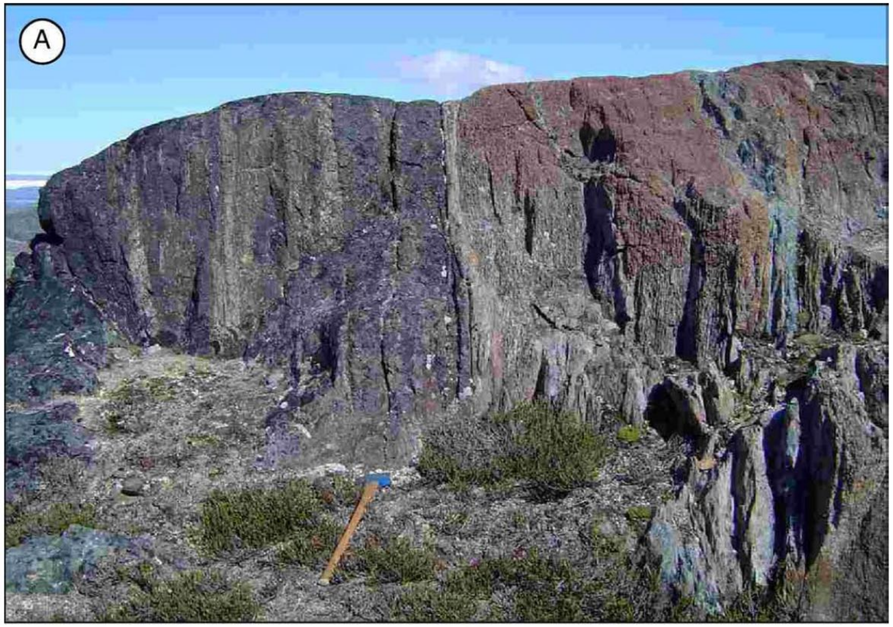

Figure 18 – Large-scale, alternating reddish-brown (meta-dunitic to -harzburgitic) and black (metapyroxenite-rich) layers of ultramafic rocks from the eastern part of the western arm of the ISB (Furnes *et al.*, 2009)

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)

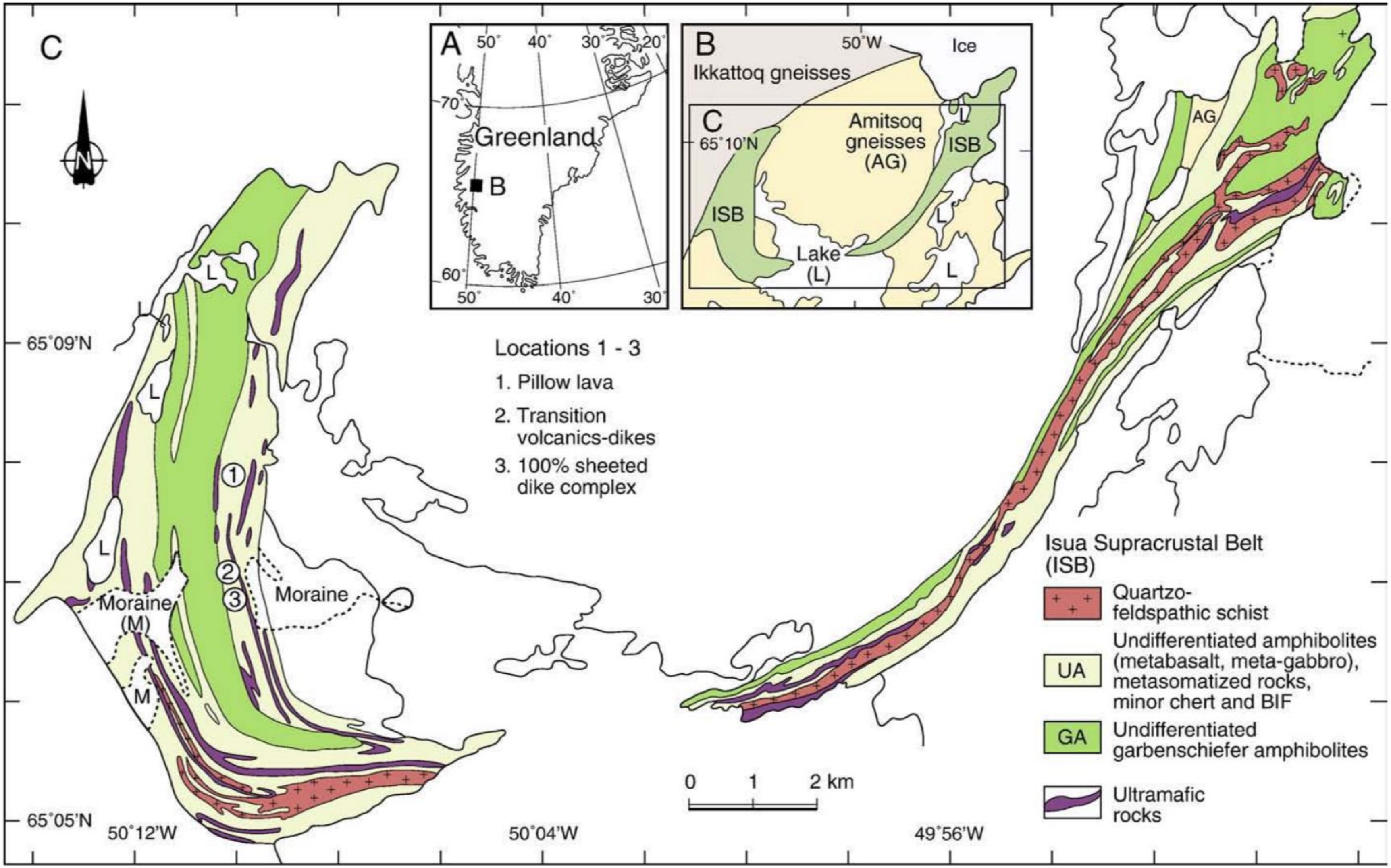

Figure 20
(Furnes *et al*., 2009)

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

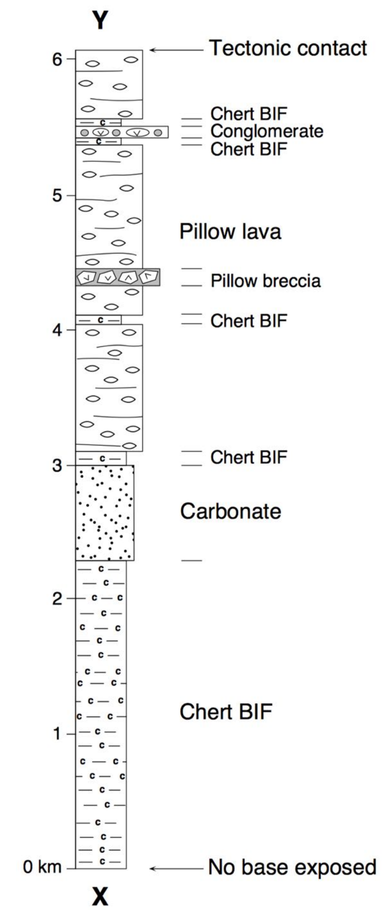

Figure 21 – Stratigraphic column representing the central domain of relatively low strain (Appel *et al.*, 1998)

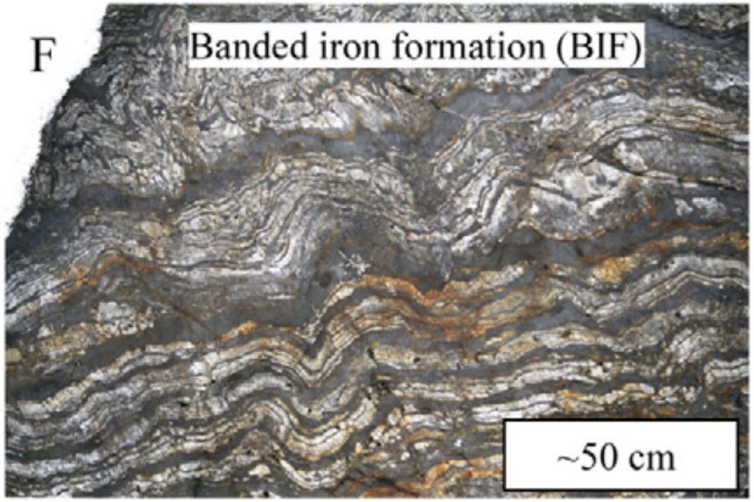

Figure 22 – Banded iron formation from central tectonic domain (Hoffmann *et al.*, 2010)

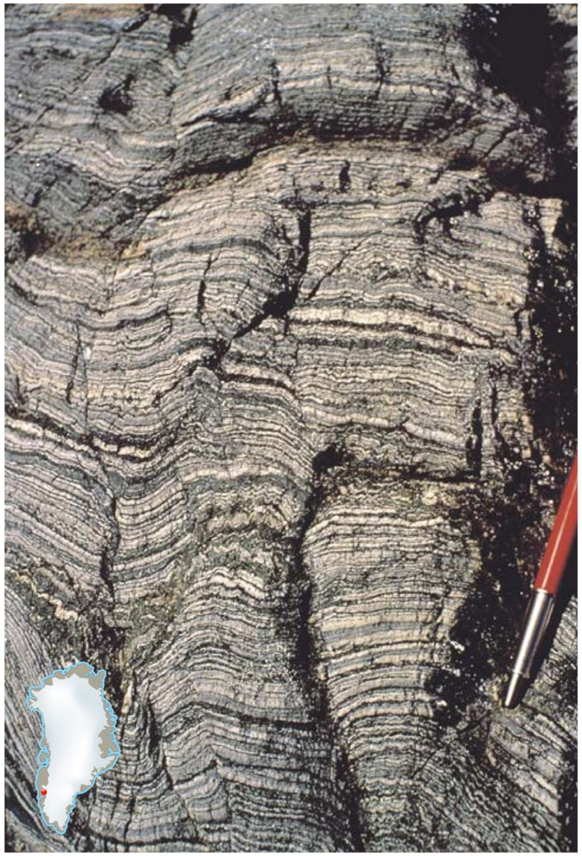

Figure 23 – Eoarchaean banded iron formation consisting of interlayered magnetite (dark layers) and chert (light layers) from the ISB (Henricksen *et al.*, 2009)

PRIMARY LITHOLOGIES OF THE ISUA GREENSTONE BELT

Metasedimentary lithologies

Polymict congomlerate

- 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 > 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 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 > 3040 My *(possibly 3750 My or earlier)*

HISTORICAL SEQUENCE OF GEOLOGIC EVENTS

7.	Emplacement of major stratiform anorthosites and gabbro anorthosites	Anorthosite complexes > 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 (Nük gneisses)	Nük gnesses 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 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 monozonites	Late granites 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 metamorphism 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

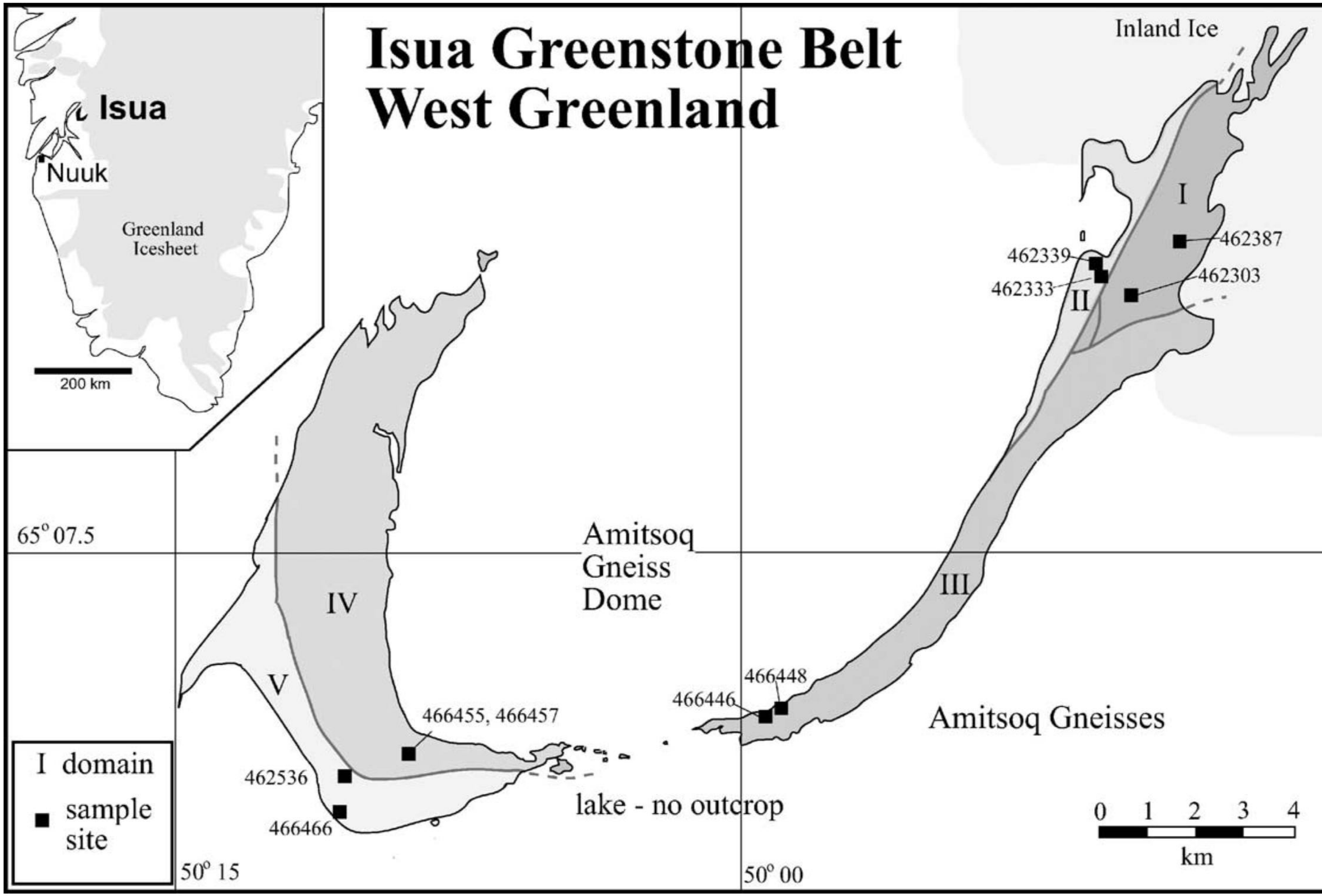

Figure 25
(Rollinson, 2003)

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 ± 22 is interpretted 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 ± 4 Ma, but a plagioclase-hornblende pair from an amphibolite yielded an Sm–Nd mineral isochron of 2849 ± 116 Ma, that implys 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

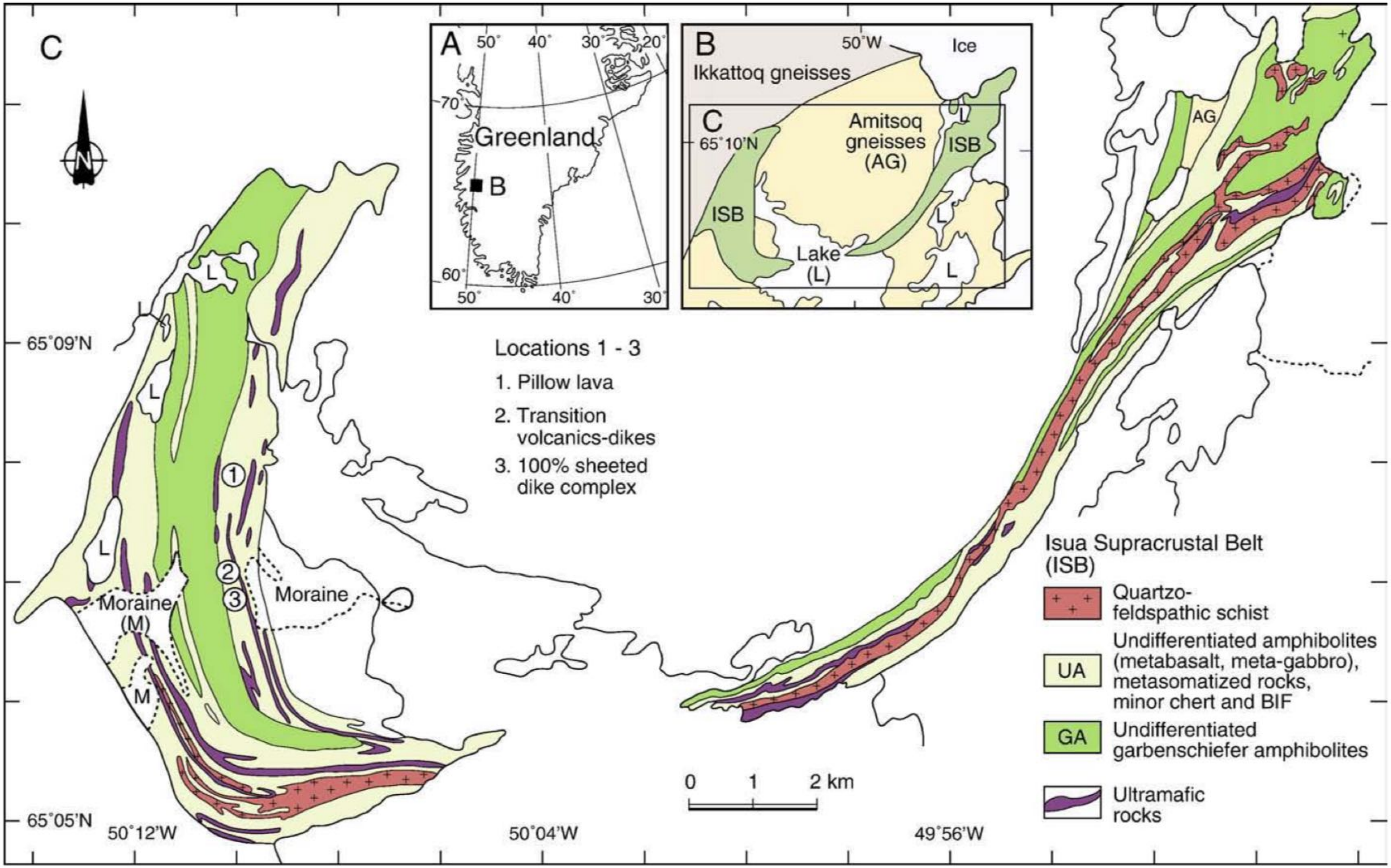

Figure 20
(Furnes *et al*., 2009)

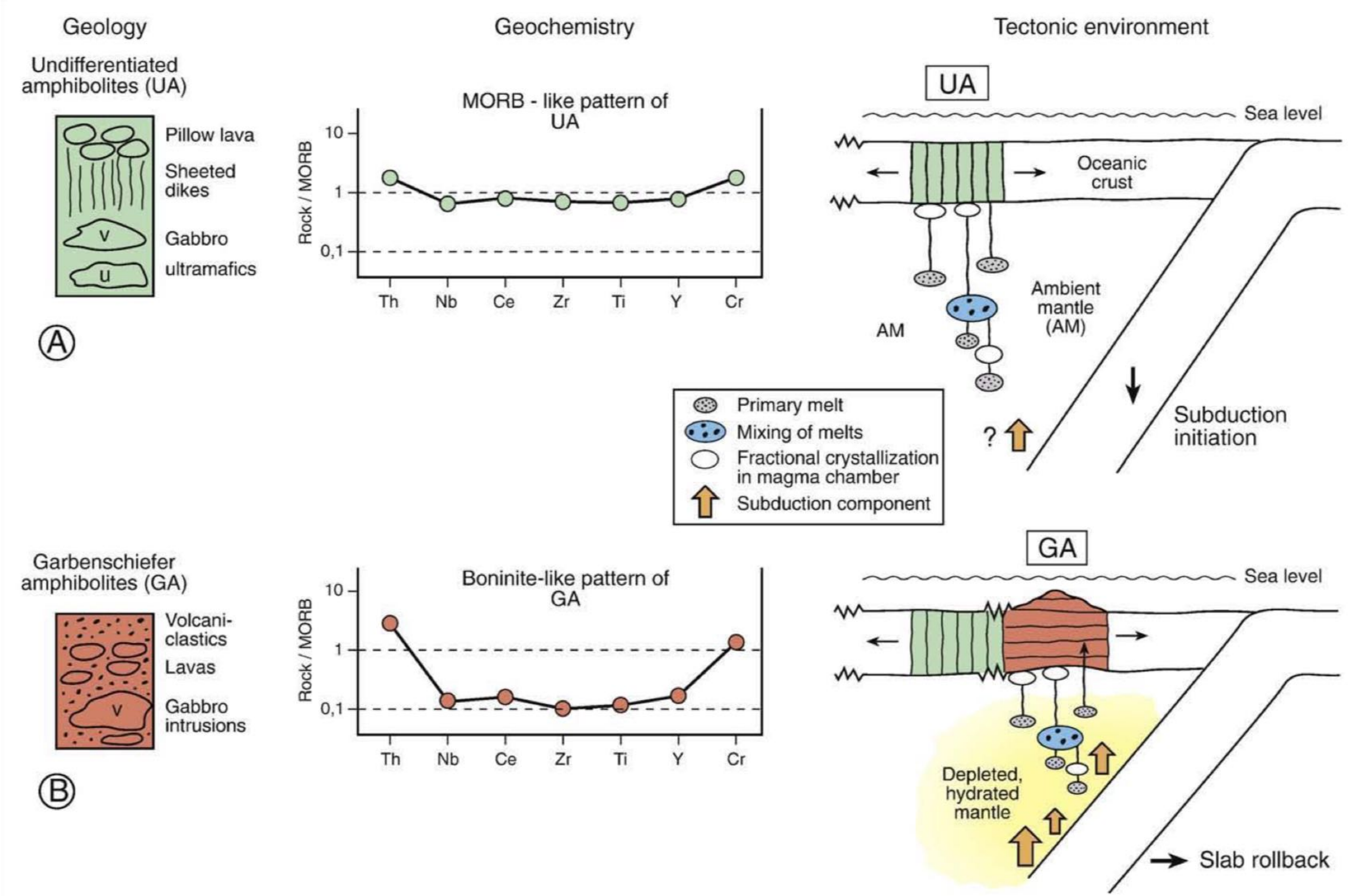

Figure 26
(Furnes *et al*., 2009)

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)

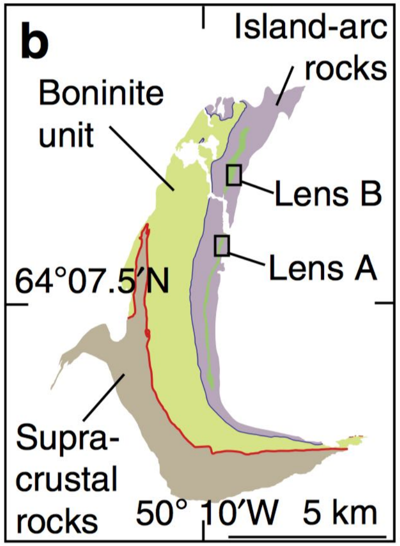

Figure 27 – Displaying study area for Kaczmarek *et al.* (2016)

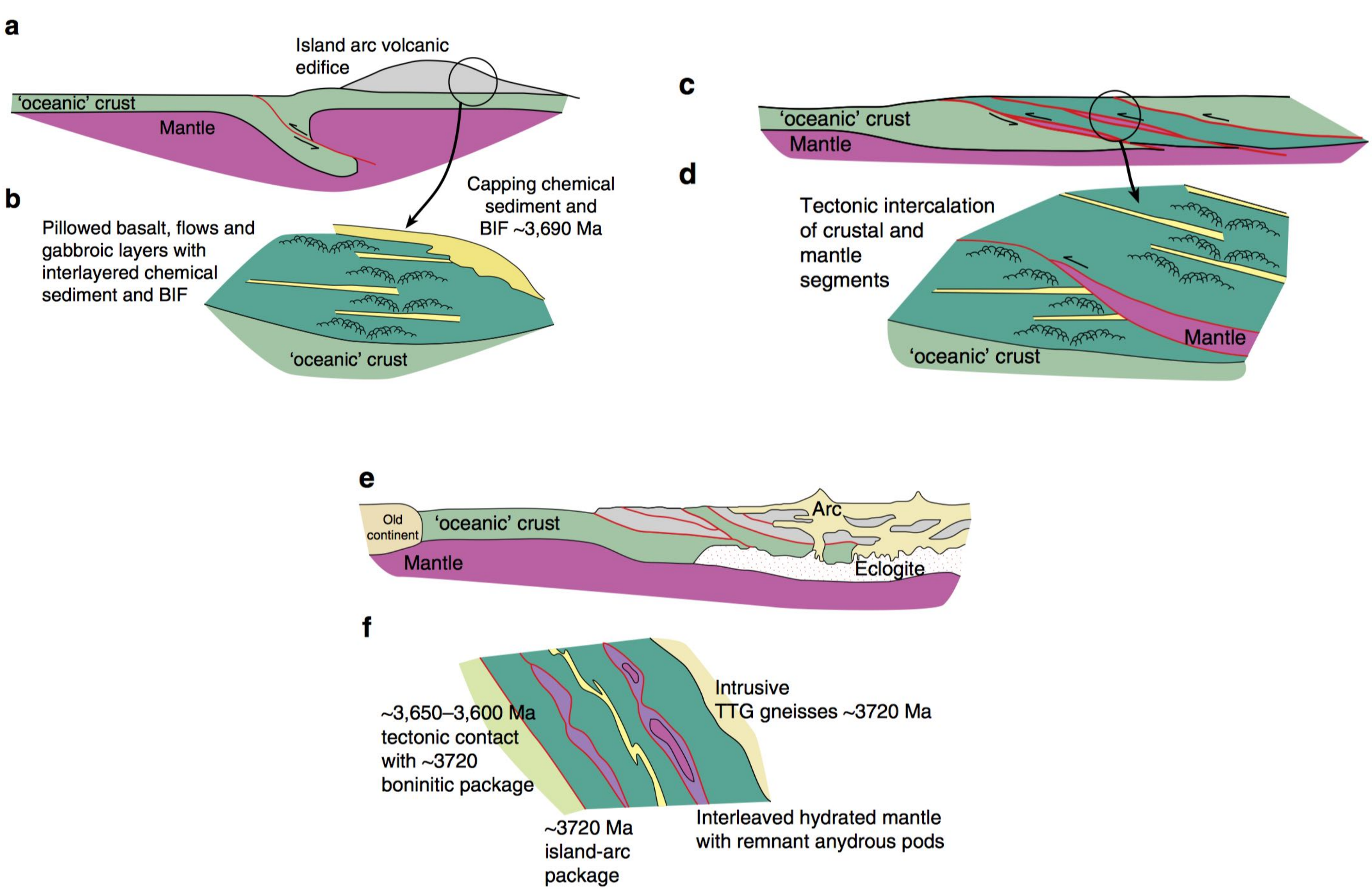

Figure 28
(Kaczmarek *et al.*, 2016)

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

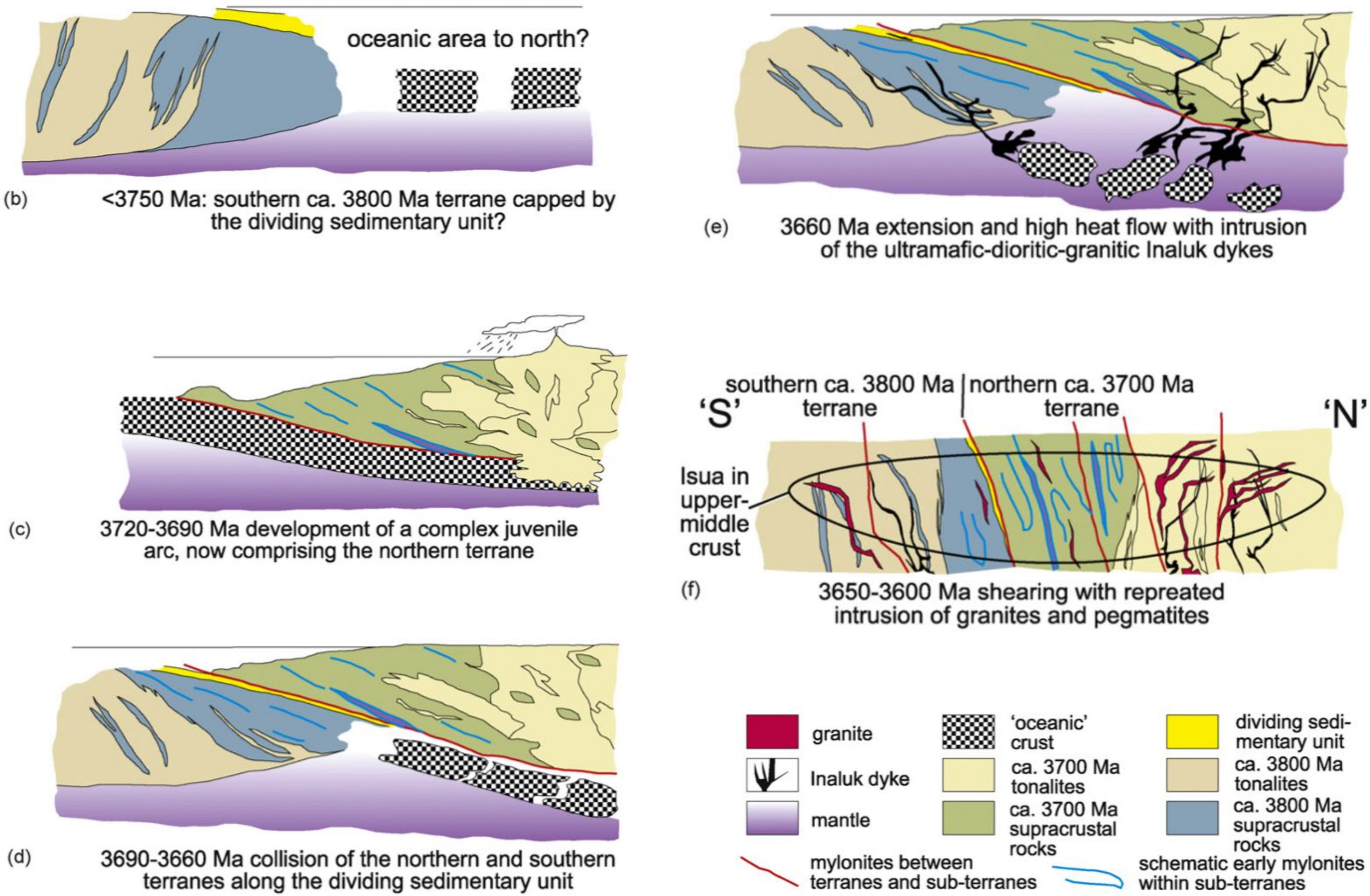

Figure 29
(Nutman & Friend, 2009)

CONSTROVERSIES 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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