Emplacement Mechanisms of a Dyke Swarm Across the Brittle-Ductile Transition

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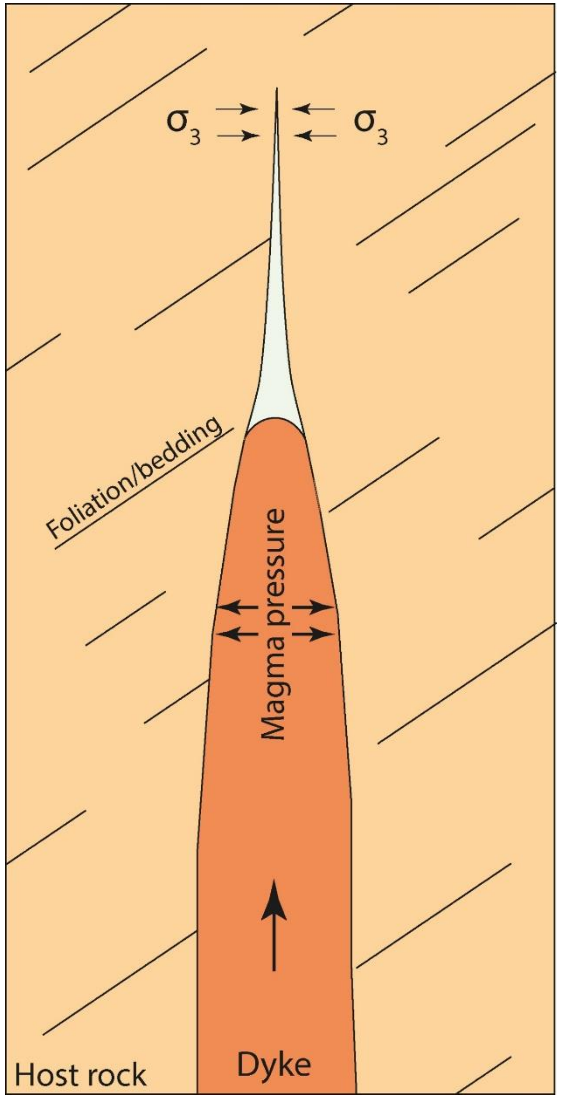
The content of the following presentation has recently been published in EPSL (Kjøll et al., 2019a)

Introduction



After Rubin, 1995

Dyke emplacement is generally assumed to:

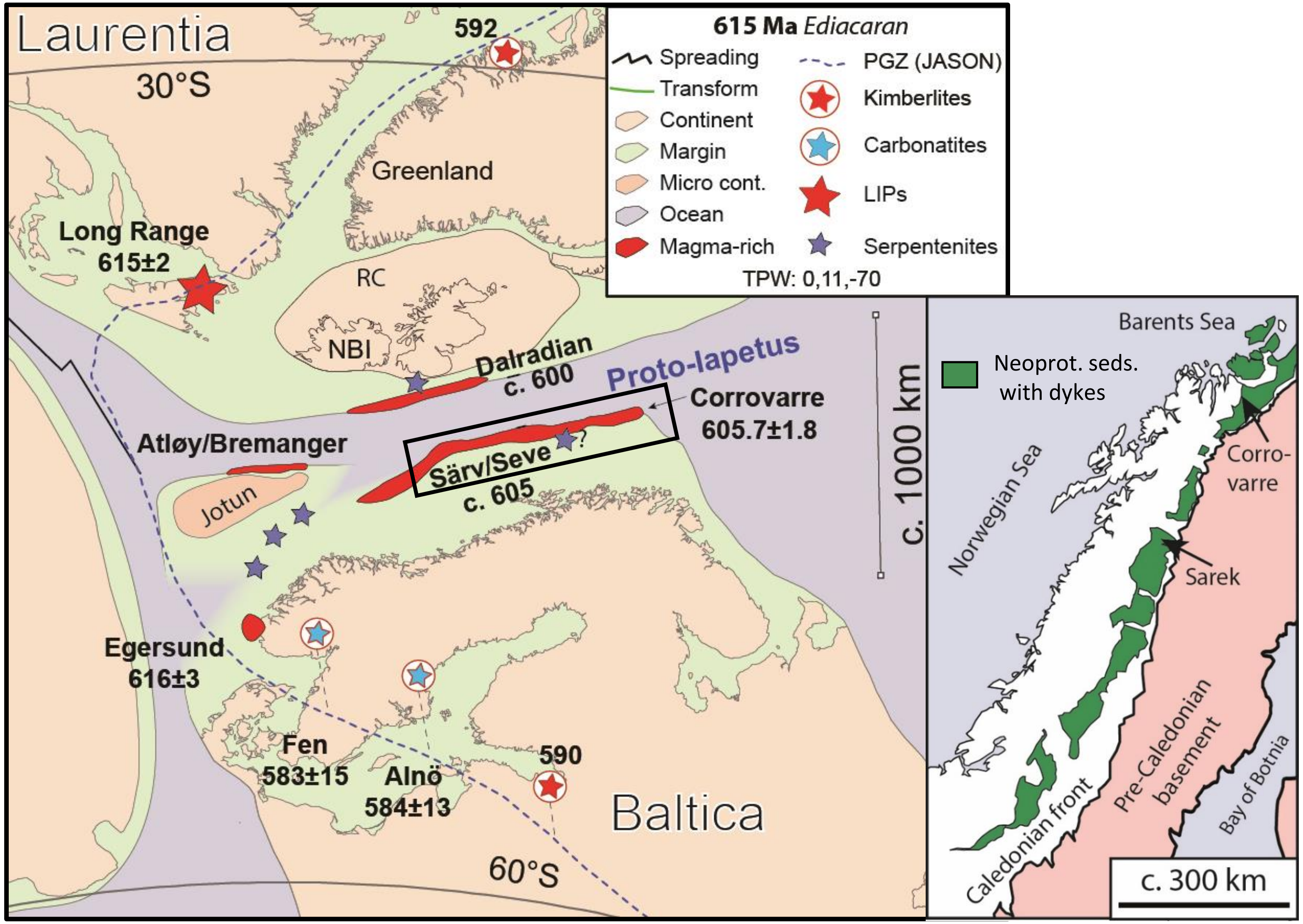
- Form simple vertical sheet-like structures
- Open parallel to extension direction
- Filling in the space provided by the stretching crust
- Governed by brittle mechanisms,
 even in the ductile crust

Questions to be addressed:

- What about the lack of seismicity in the ductile crust?
  - What is the role of ductile deformation?
- How does the emplacement of large quantities of magma, over a geologically short timescale, affect the dynamics related to dyke emplacement?

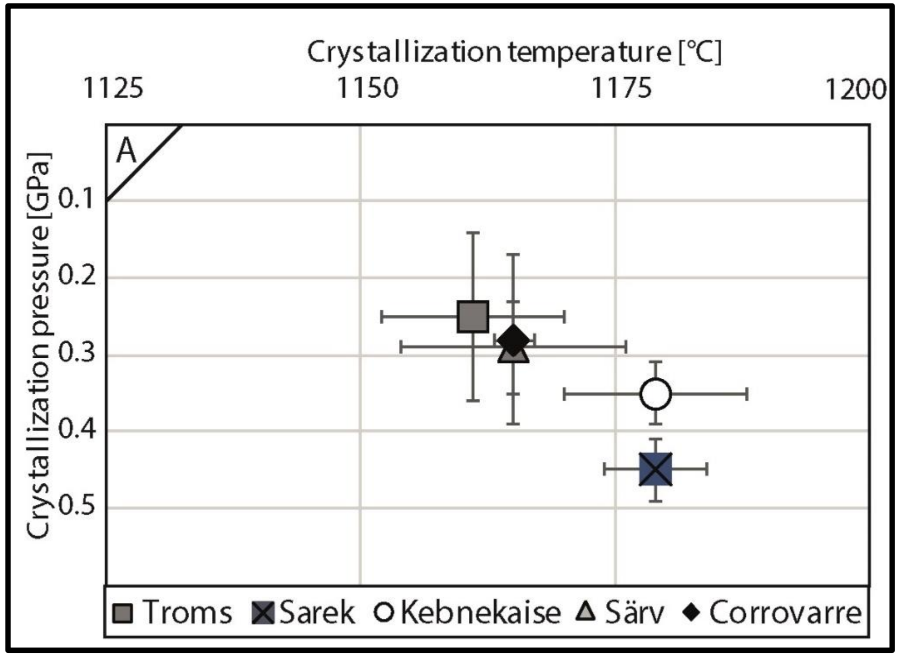
To answer these questions we have studied a dyke complex that developed in the **OCT domain** of a 600 Ma **magma-rich rifted margin**

The Scandinavian dyke complex



After Tegner et al., 2019

- A >900km long dyke swarm emplaced at the distal, **magma-rich margin of Baltica** during the c. **605 Ma breakup** of Baltica and Laurentia.
- Dykes were **emplaced at c. 10-15 km depth** and intruded pre- to syn-rift arkoses.
- The rocks are now preserved within the Scandinavian Caledonides.



From Kjøll et al., 2019b

Brittle structures - Sarek

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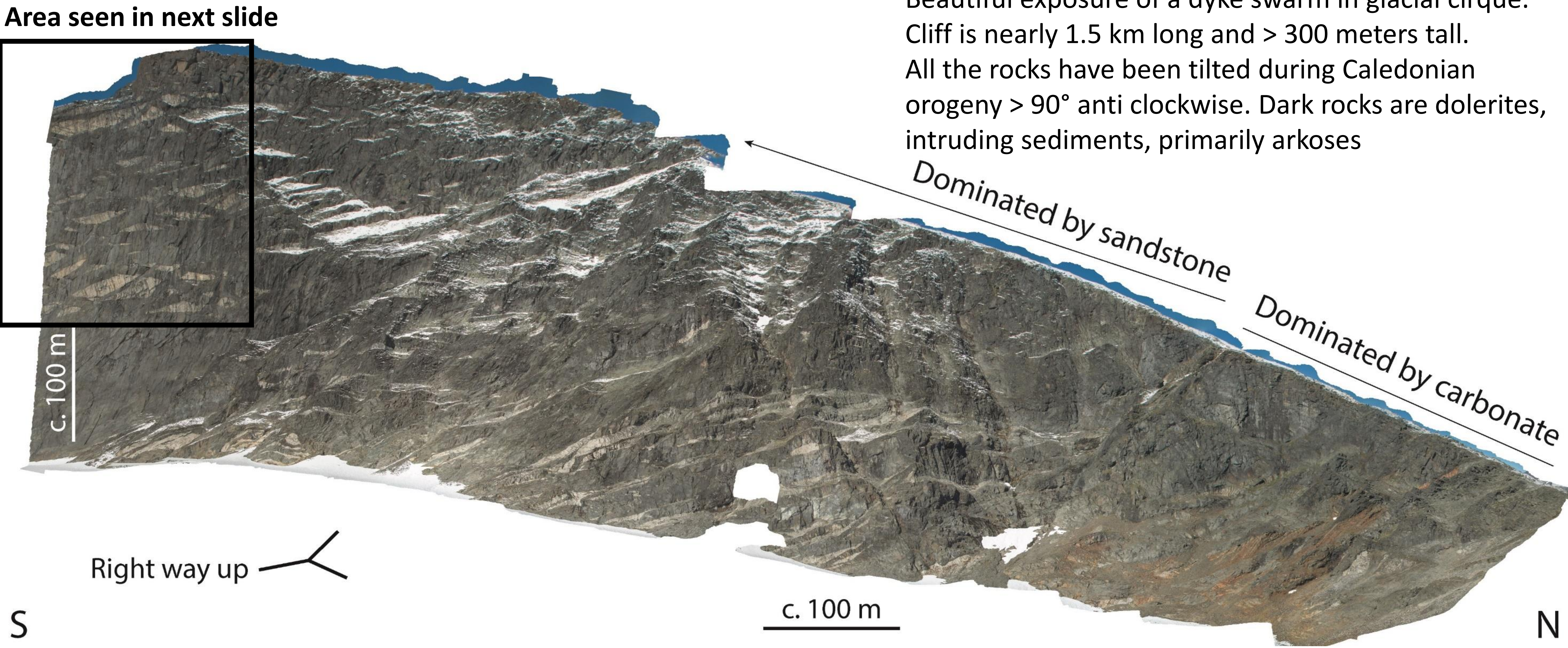
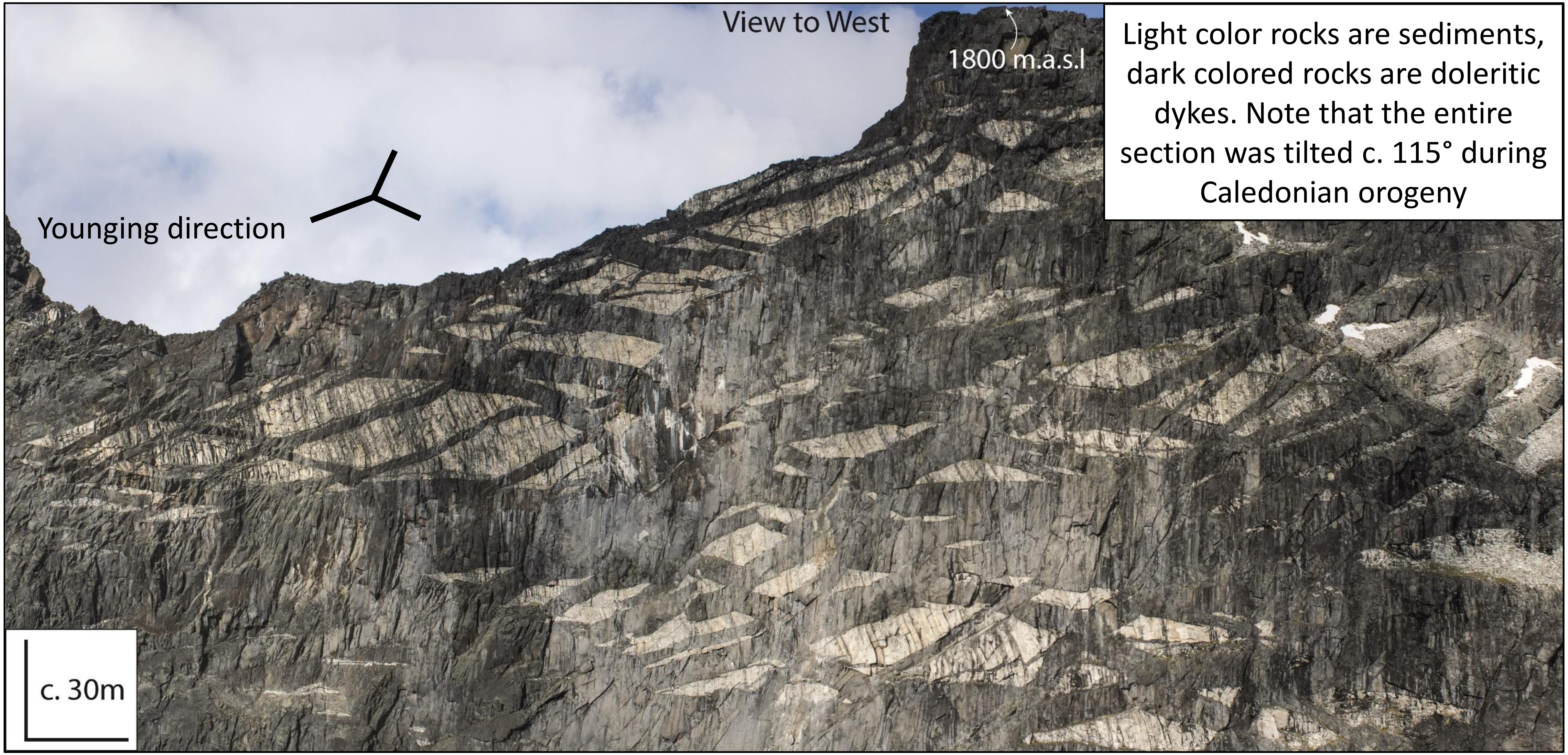
Beautiful exposure of a dyke swarm in glacial cirque.
Cliff is nearly 1.5 km long and > 300 meters tall.
All the rocks have been tilted during Caledonian orogeny > 90° anti clockwise. Dark rocks are dolerites, intruding sediments, primarily arkoses



Cliff is located in Sarek national park in northern Sweden.

Brittle structures - Sarek



Light color rocks are sediments, dark colored rocks are doleritic dykes. Note that the entire section was tilted c. 115° during Caledonian orogeny

Brittle structures - Sarek

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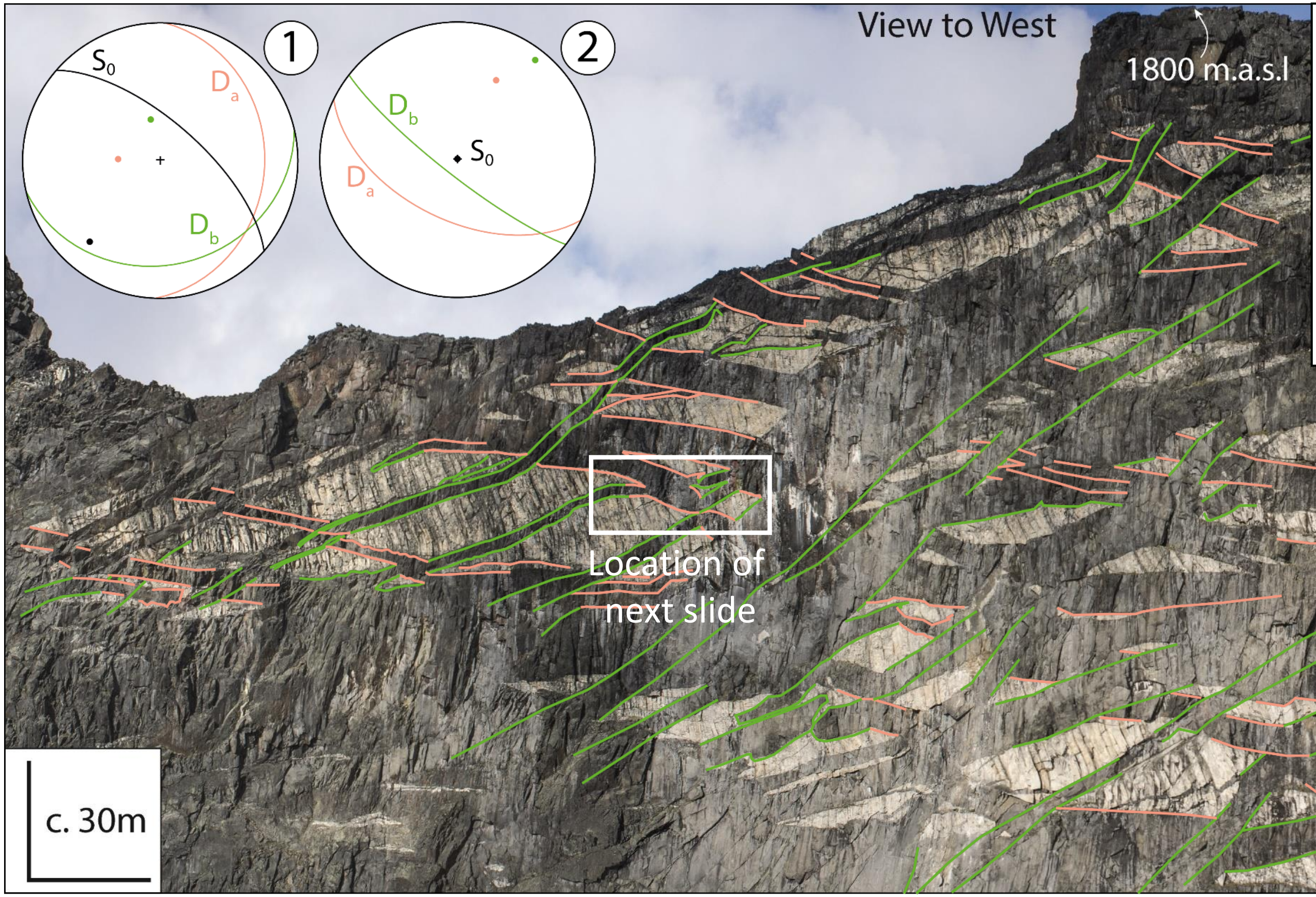
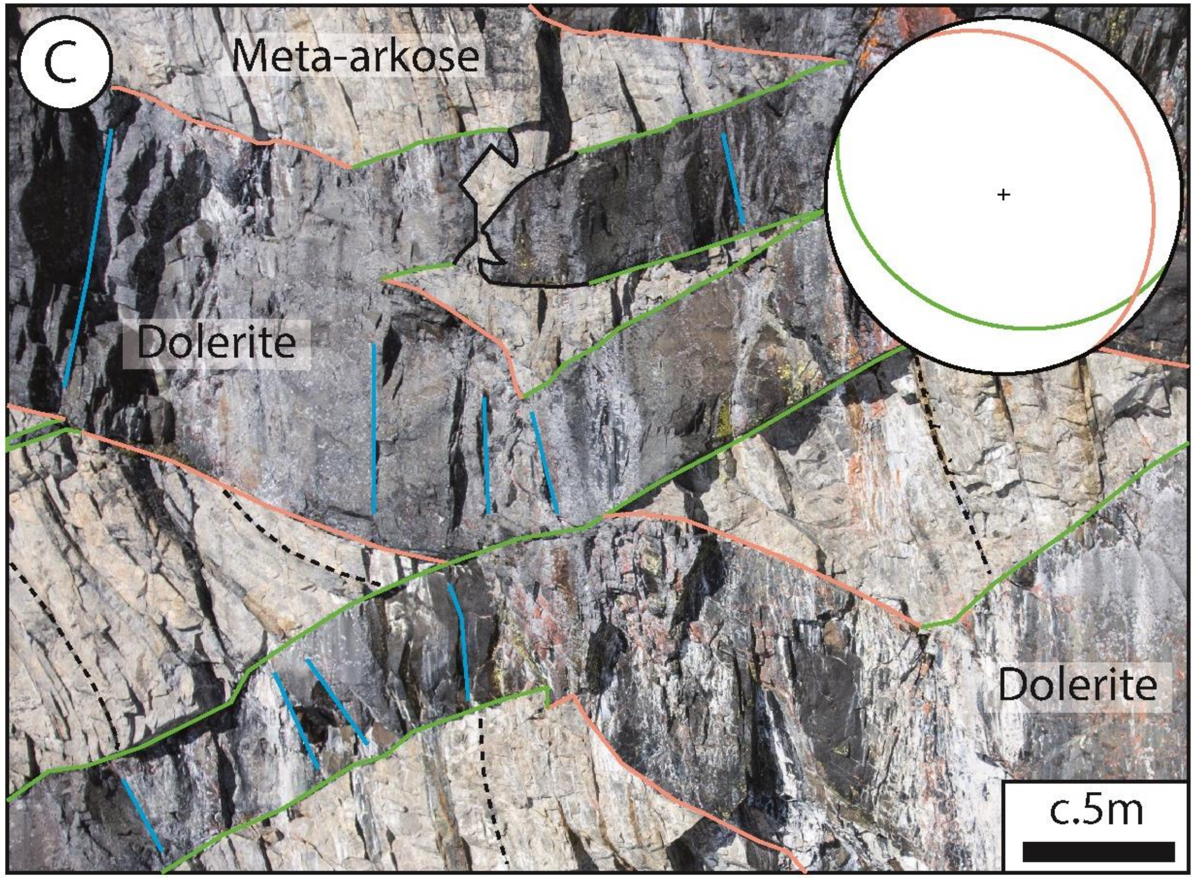


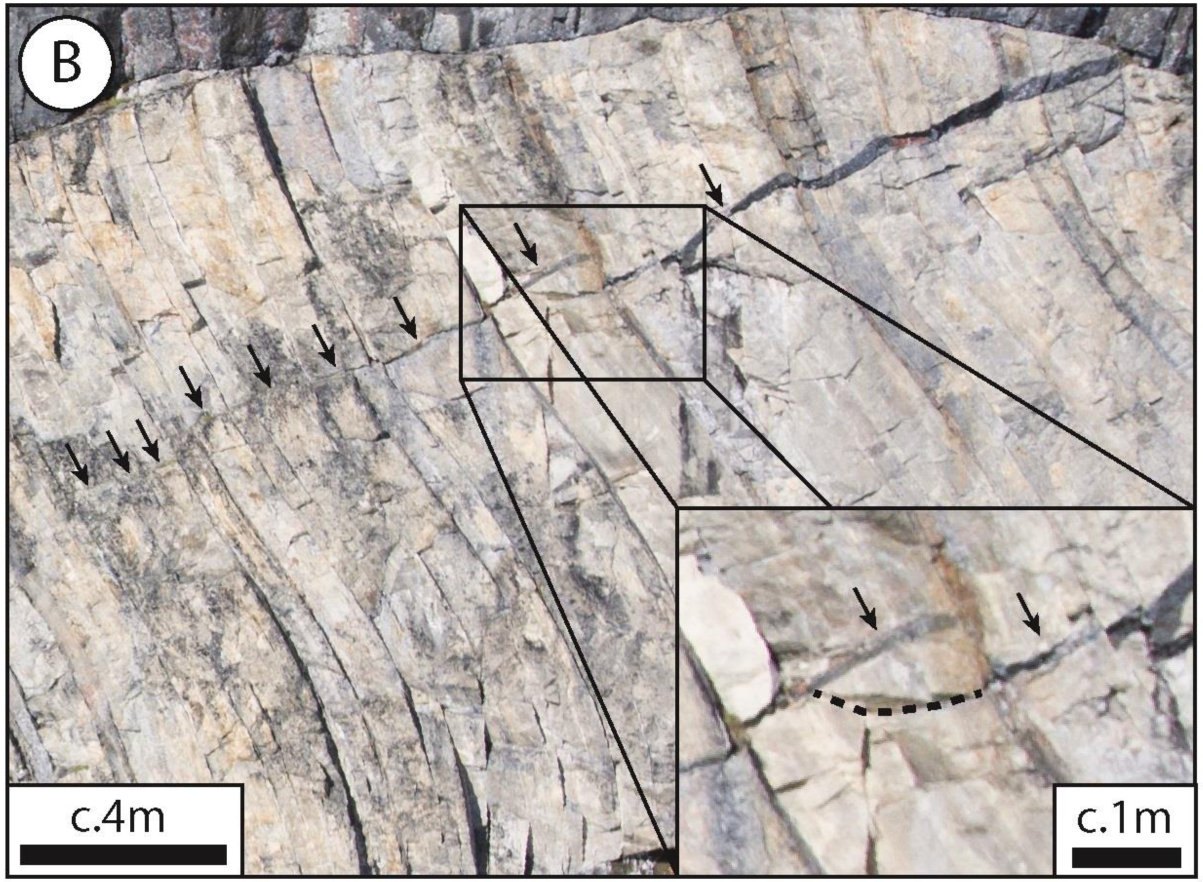
Two dyke orientations highlighted green and orange.
<u>The orientations are</u>:

- **Mutually cross-cutting**
- **Not strictly vertical** when bedding is restored to horizontal

Brittle structures - Sarek



‘Bent’ dykes, change from green orientation to orange orientation very rapidly. Note also broken bridge above the bend.



Very narrow and sharp dyke tip, propagating straight into the well bedded arkosic sandstone with some en-echelon segments.

Typical brittle structures, but the **dykes are not always straight**

Brittle structures - Sarek

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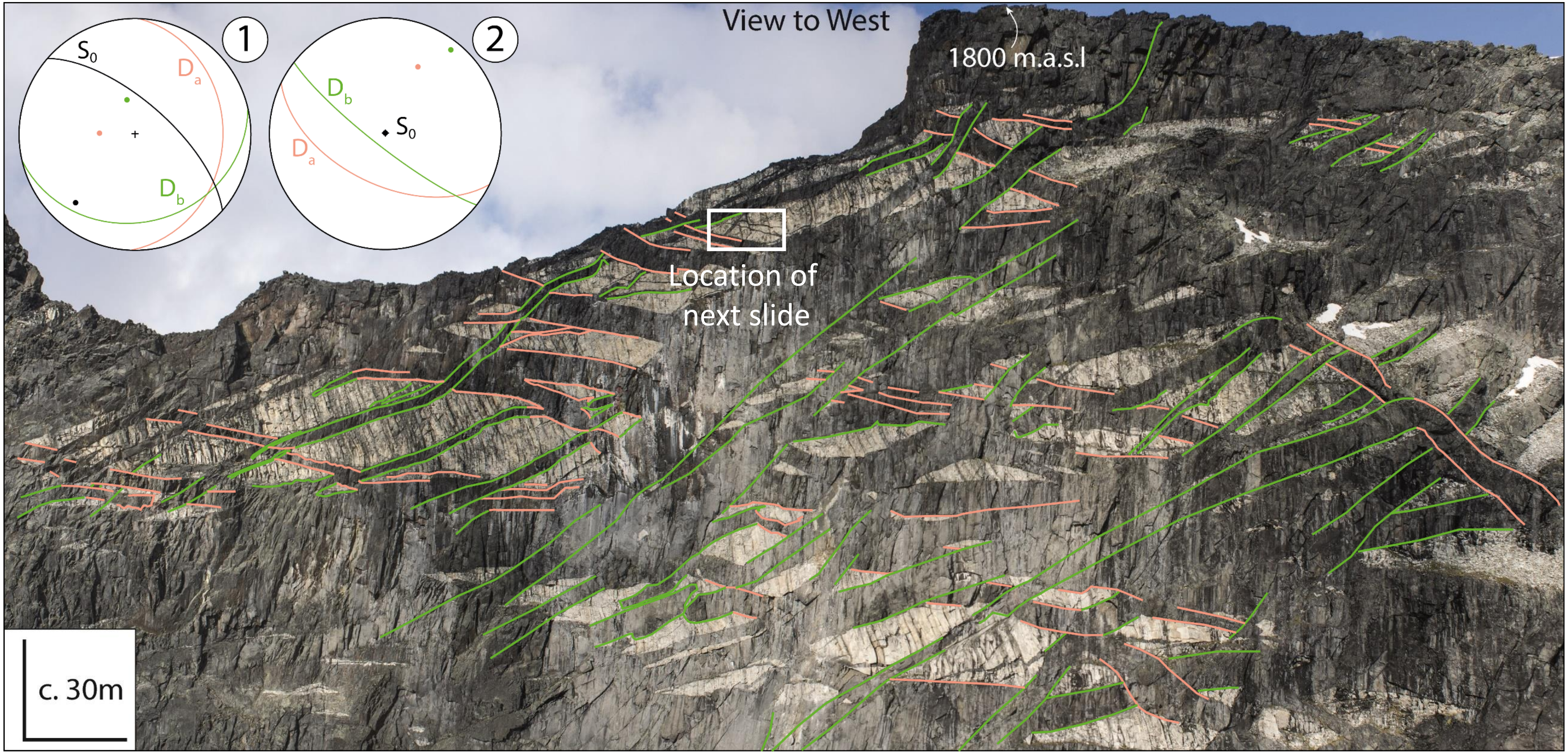

Brittle structures - Sarek

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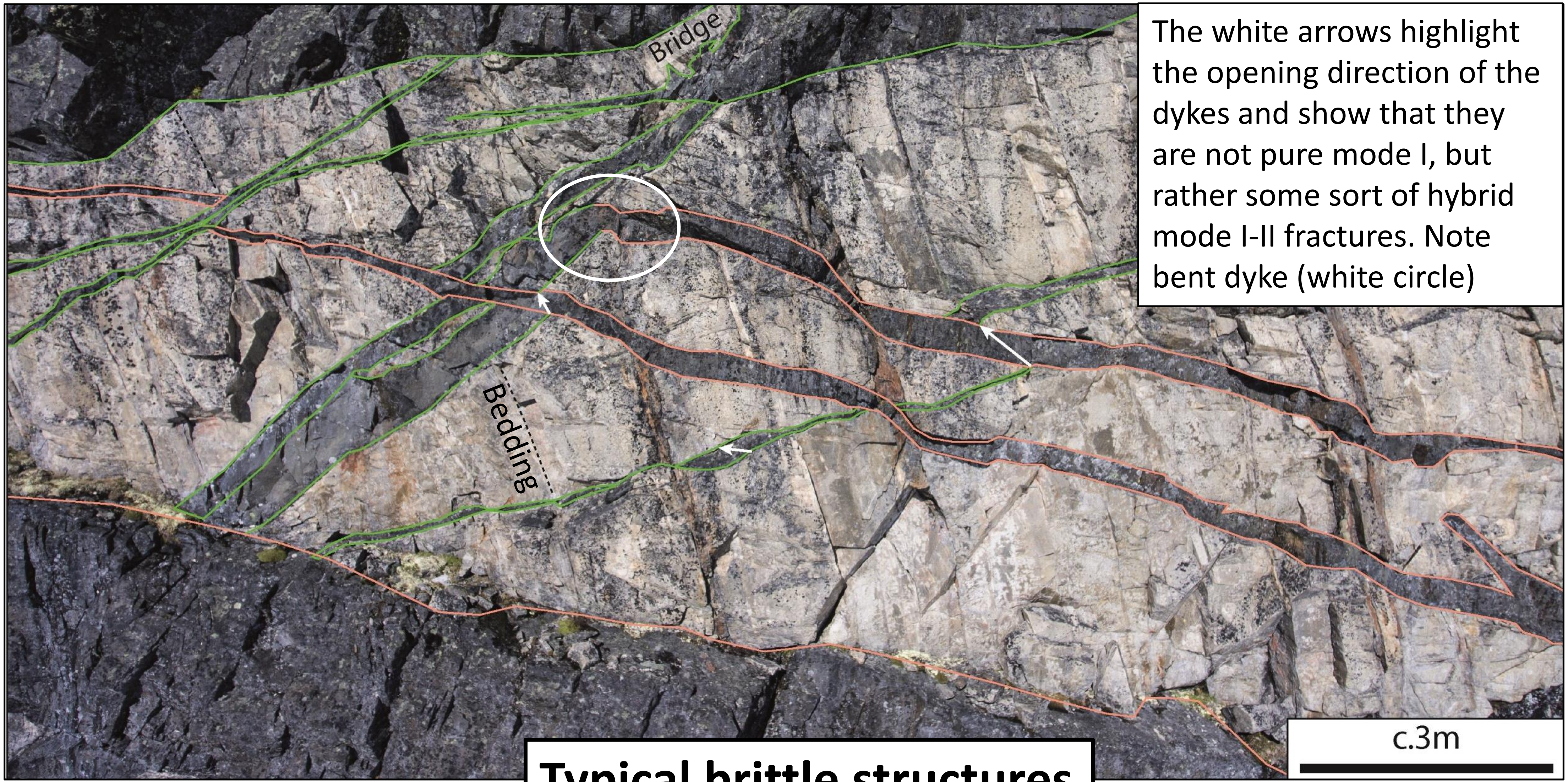
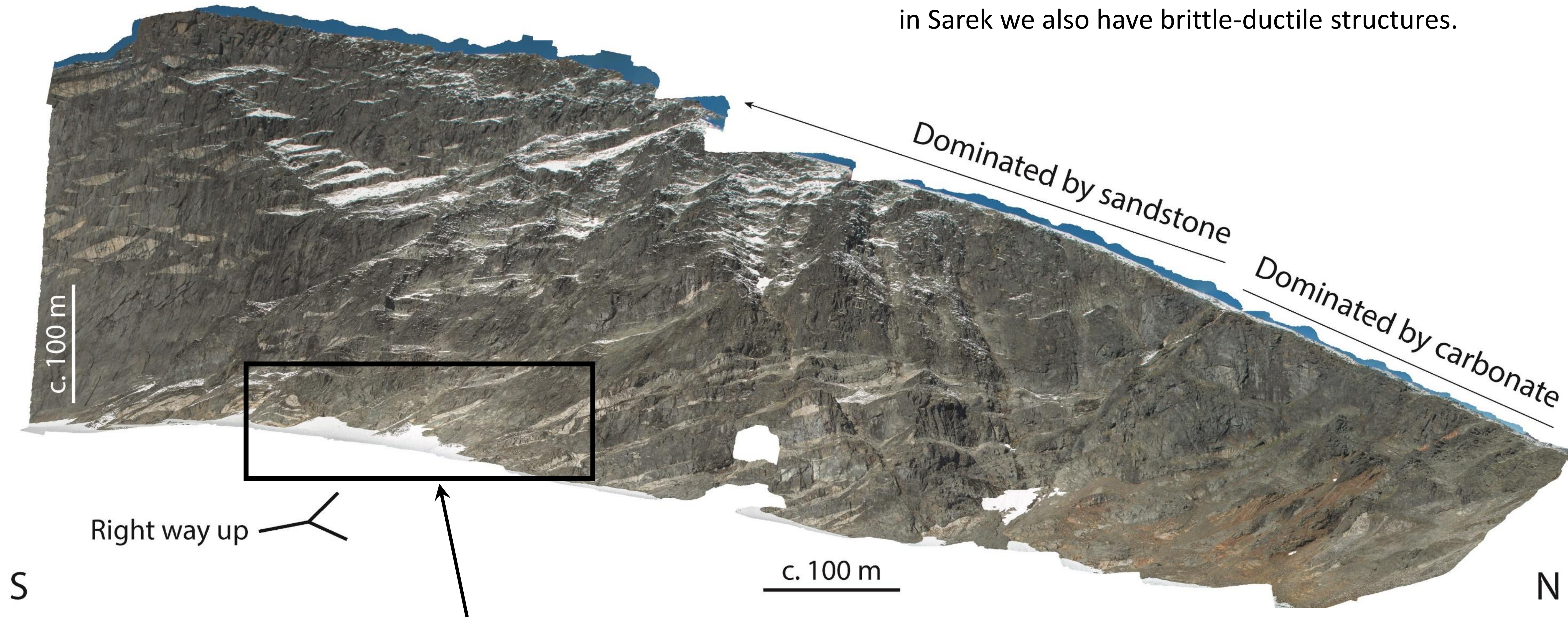


The white arrows highlight the opening direction of the dykes and show that they are not pure mode I, but rather some sort of hybrid mode I-II fractures. Note bent dyke (white circle)

Typical brittle structures

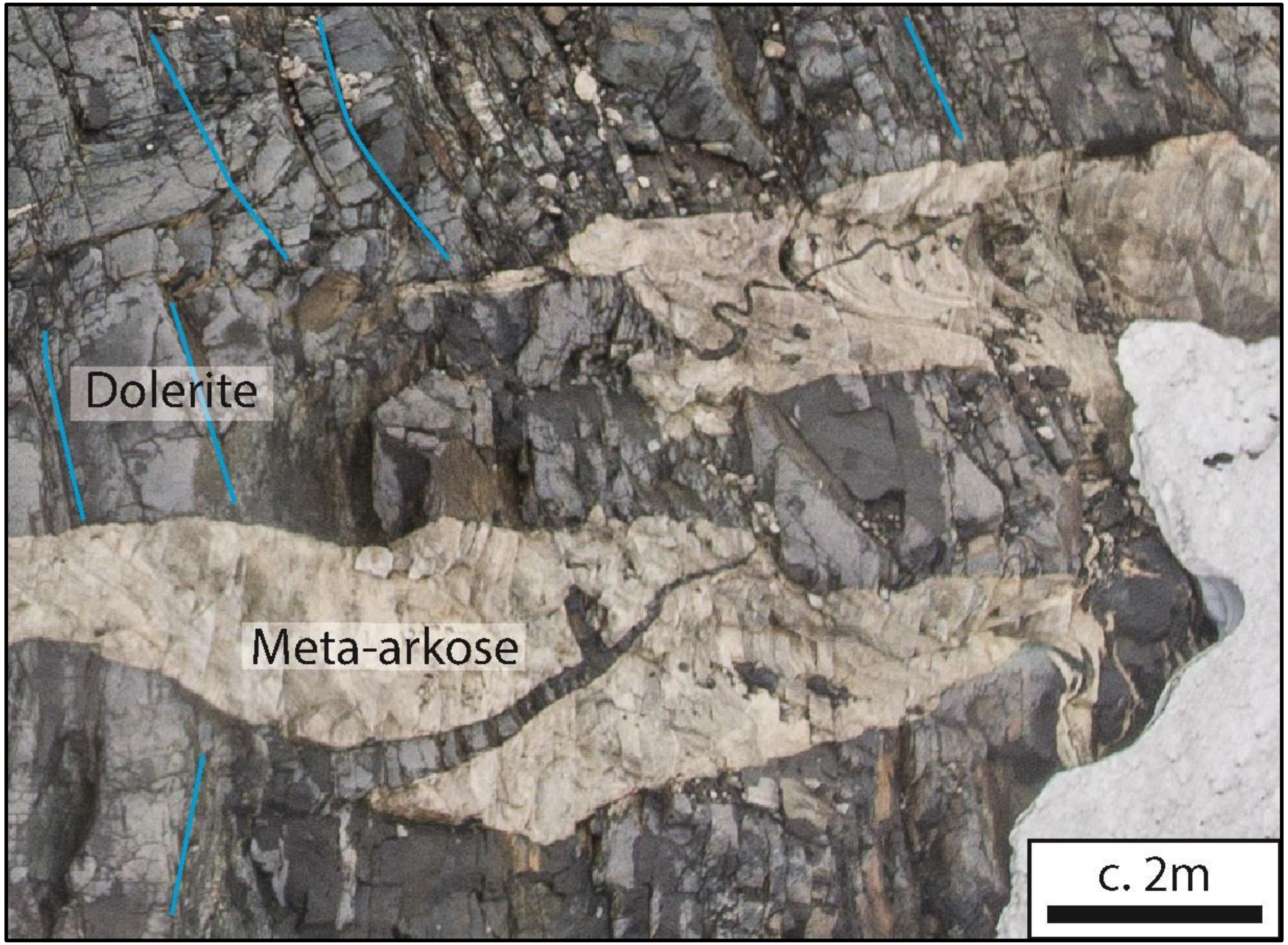
Brittle-ductile structures - Sarek

So far we've been looking at brittle structures, but in Sarek we also have brittle-ductile structures.



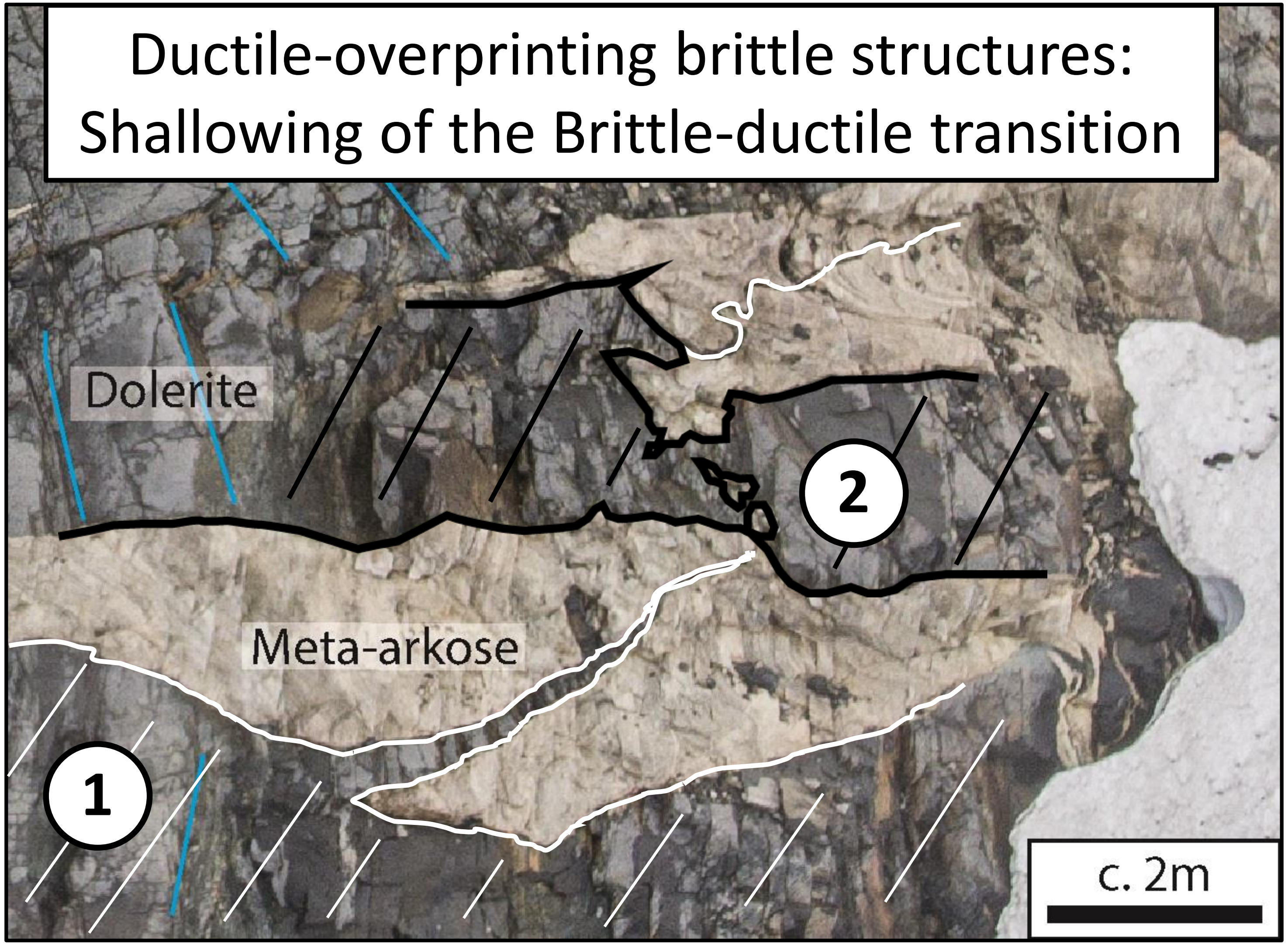
No we are going to look at this area here and what's important to note here is that we are still at a similar stratigraphic level as before, perhaps c. 200 m lower in the stratigraphy than what we looked at earlier

Brittle-ductile structures - Sarek



What has happened here?

Brittle-ductile structures - Sarek



What has happened here?

1. Emplacement of lower dyke, with tapered offshoot, *i.e.* brittle

2. Emplacement of second dyke, with irregular, rounded broken bridge.

-> **Emplacement of second dyke folds the pre-existing tapered dyke tip**

Ductile structures - Corrovarre

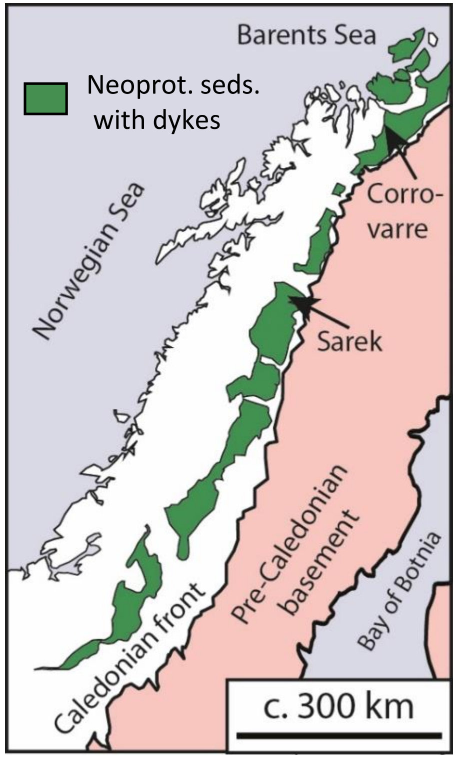
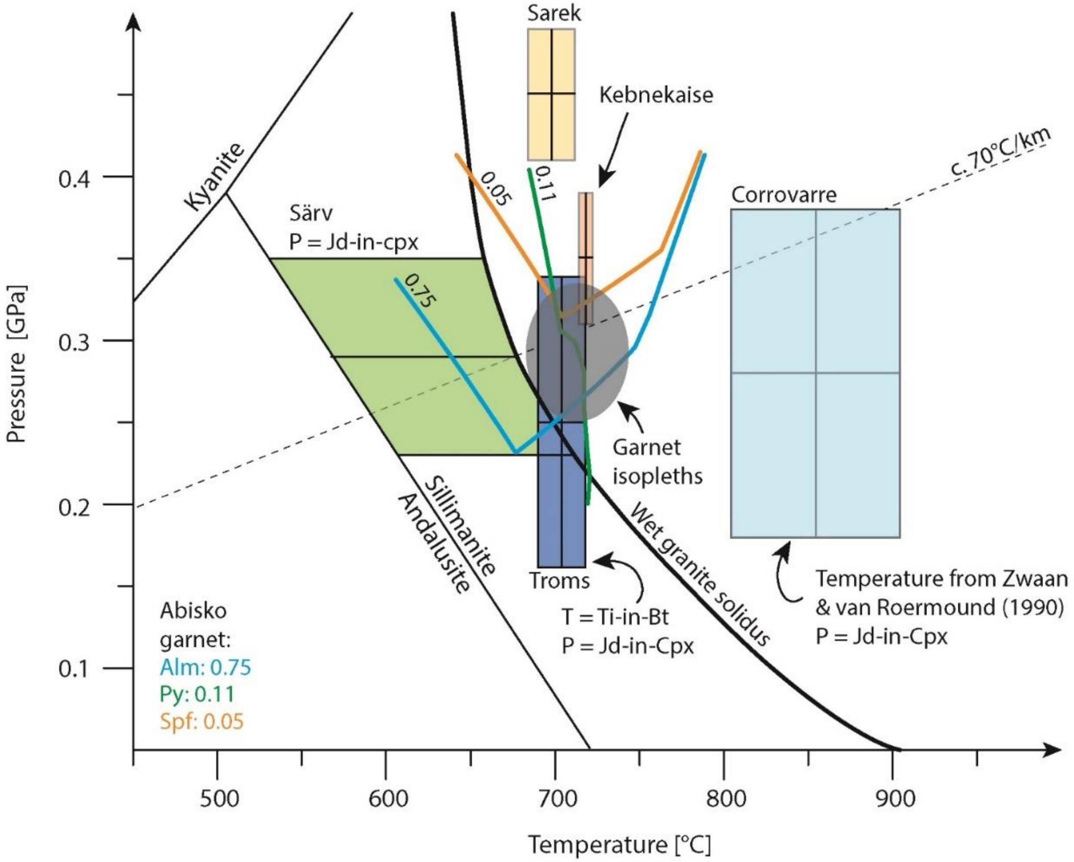
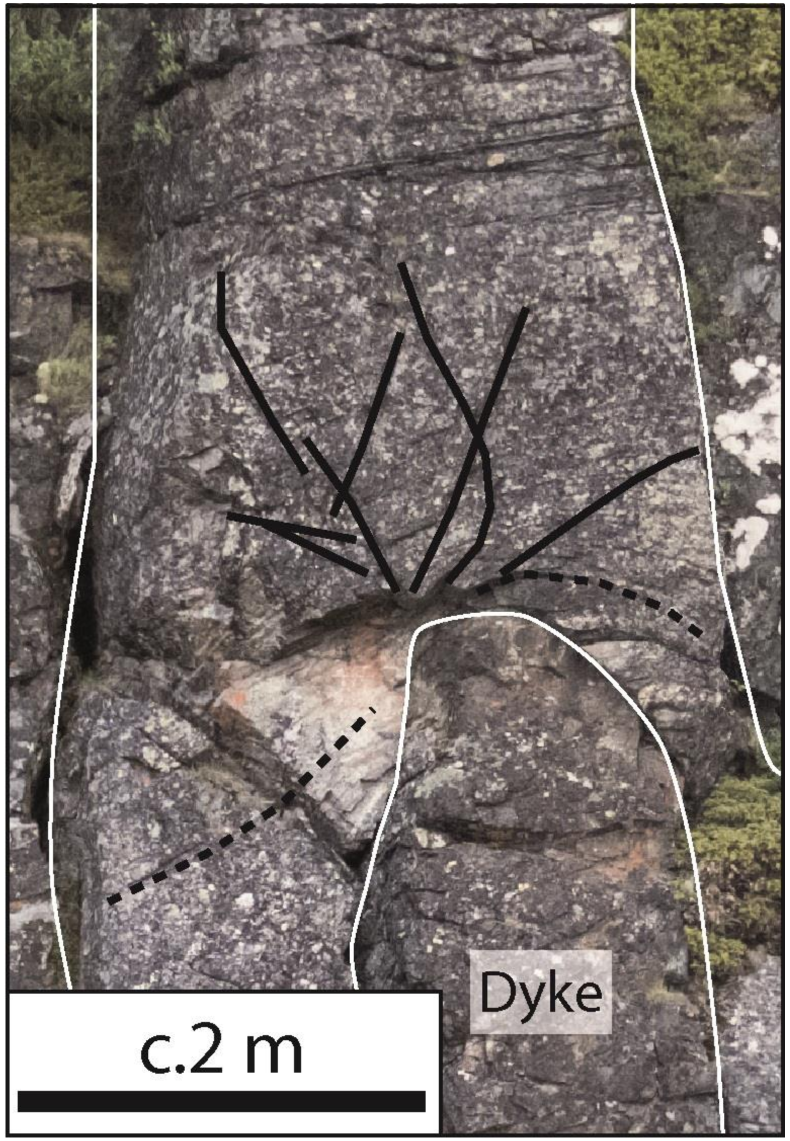


Figure from Kjøll et al., 2019b



Now we are moving further north to Corrovarre in northern Norway. Here the ambient temperatures were higher during dyke emplacement and the arkosic sandstones underwent partial melting while deforming by bedding parallel stretching. Temperatures has been estimated to be as high as 850°C during dyke emplacement by Zwaan and van Roermound (1990).

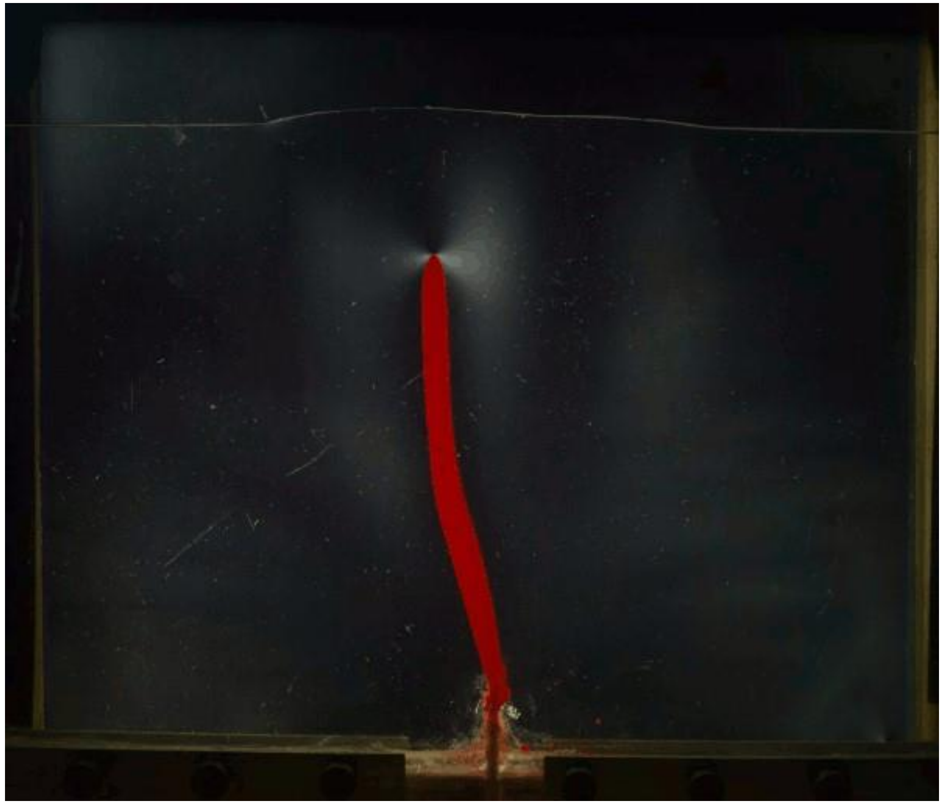
Ductile structures - Corrovarre



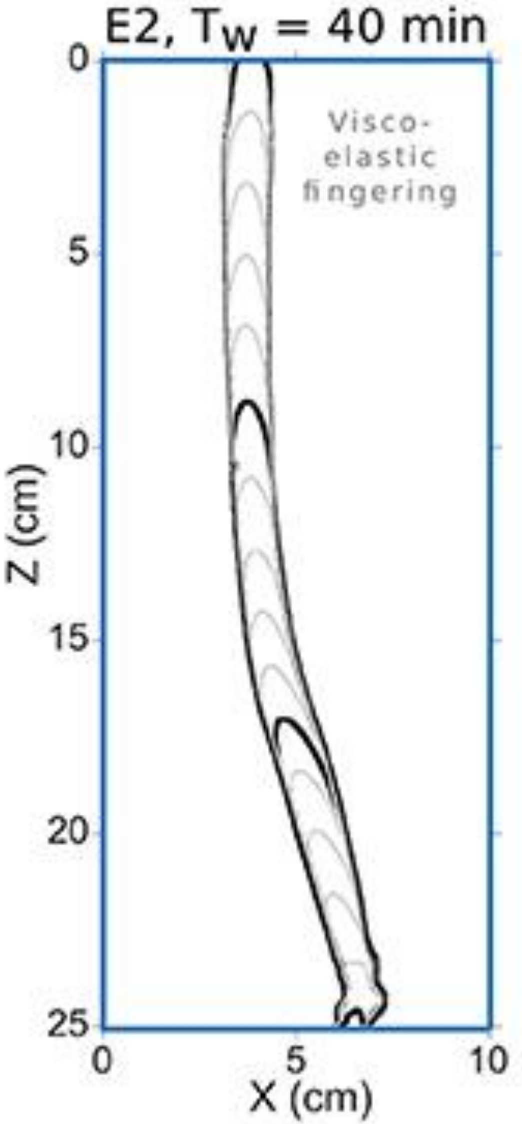
Some of the dykes in Corrovarre display rounded dyke tips with shear fractures propagating from the tip and into the host rock. Note also how the bedding of the arkosic meta-sandstone is wrapping around the tip of the dyke.

These observations suggest that the dykes did not passively fill in a void, but that the **dykes rather forced its way through the crust**.

Ductile structures - Corrovarre



Snapshot of the dyed oil intruding into cured laponite gel. Photographed through polarized light to enhance deformation in gel.



These dykes that were observed in Corrovarre resemble **visco-elastic fingers**, recently described from analogue models by Bertelsen et al. (2018). Where the dyke-analogue (dyed oil) intrude into weakly cured laponite gel resembling a weak host rock. The resulting dyke shape has a rounded dyke tip. Also note the ground deformation that occurs prior to eruption.

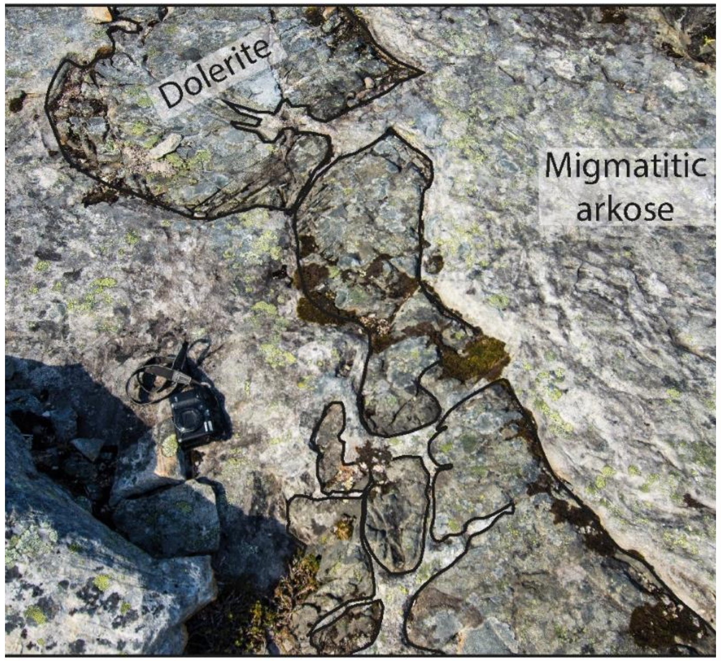
Bertelsen et al., 2018

Ductile structures - Corrovarre

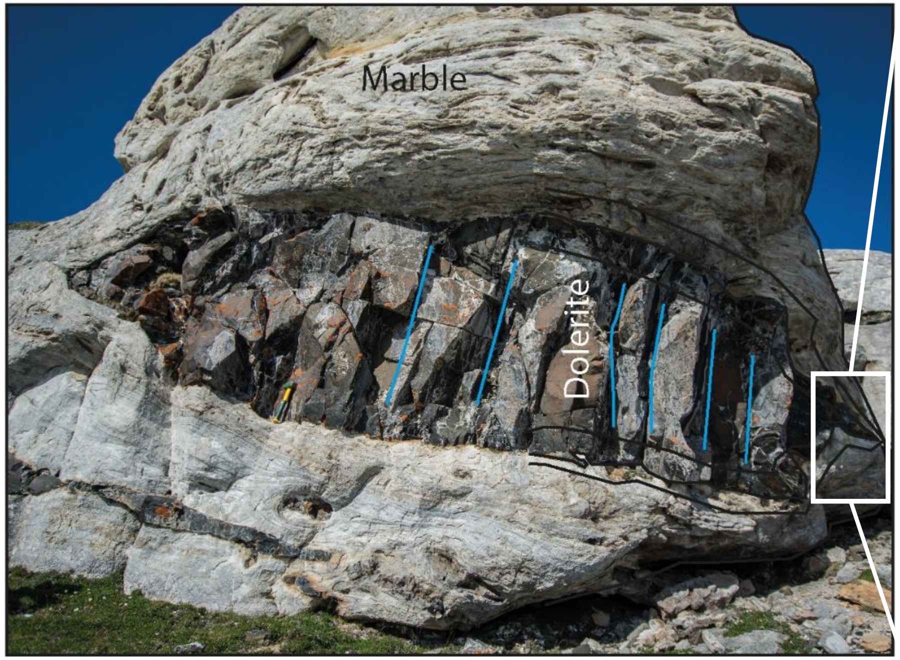
Purely ductile structures are also something that we can find in the Corrovarre area. This photograph shows a dyke that intruded a partially molten arkosic sandstone to create a dyke with highly complex shape, resembling pillows.

Where the dykes were emplaced into marble, the resulting structure resemble tectonic boudinage, but features such as columnar jointing (blue lines) and chilled margins can be seen surrounding the intrusion.

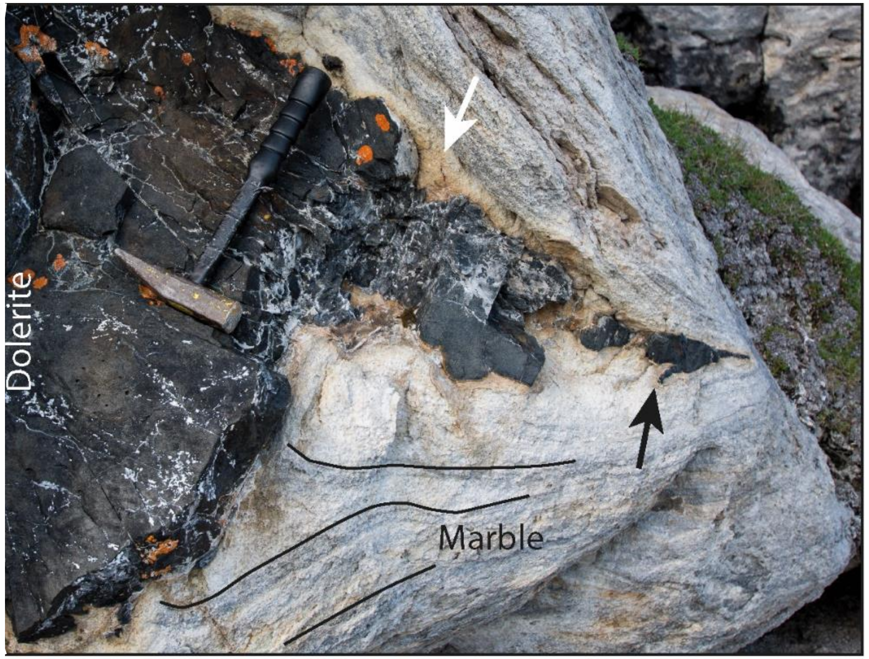
At the tip of the intrusion, a magmatic texture, vesicles and a complex geometry can be observed. Also, the 'dyke' cuts the foliation in the marble i.e. this is a magmatic intrusion!



Tectonic boudinage?

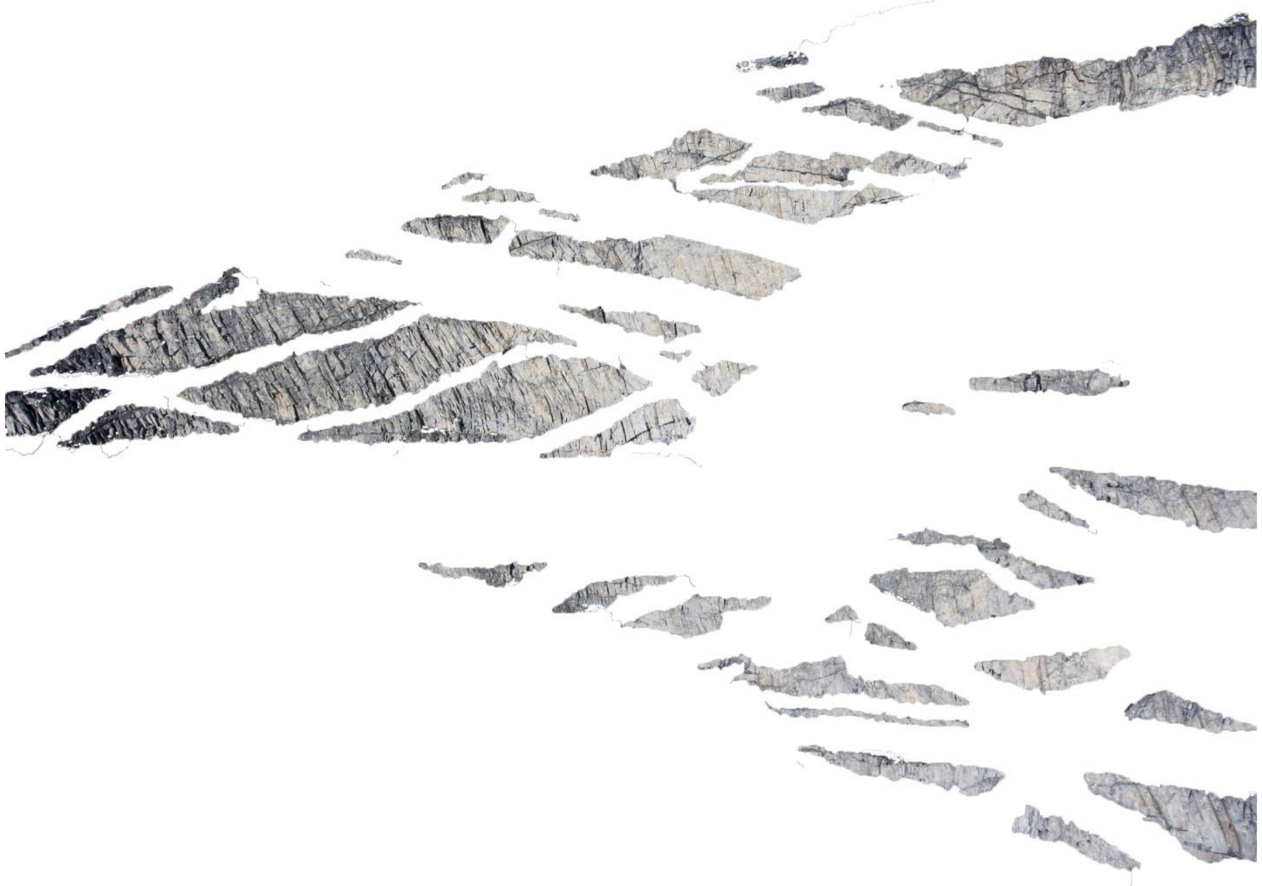


Magmatic 'boudinage'!



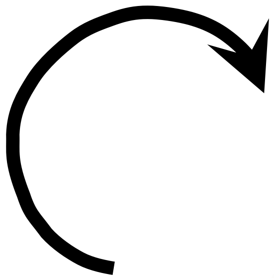
Quantification of deformation

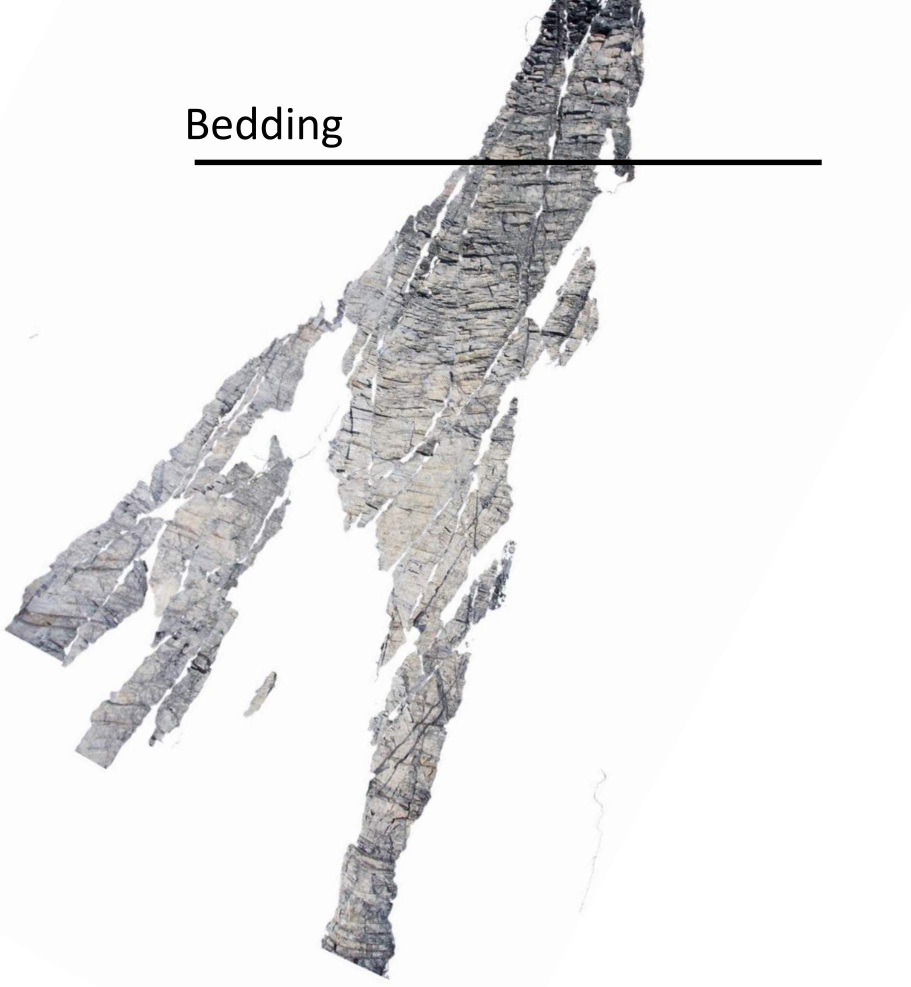
One of the questions arising when working with these dykes was can we quantify the deformation imposed by the dykes? So using adobe photoshop the dykes were removed.



Quantification of deformation

Then the sedimentary screens were moved back together using marker horizons in the sediments. Subsequently, we rotated the sequence back to what we infer could be the paleo-horizontal (see next slide for explanation), assumeing that the bedding was horizontal.

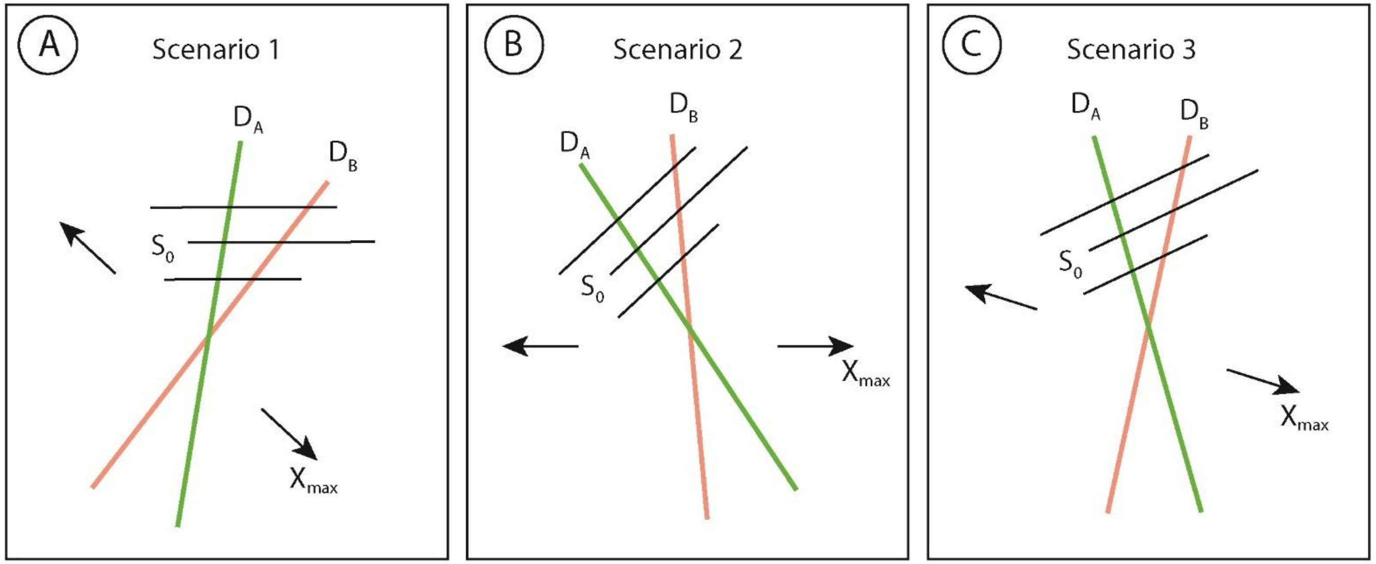


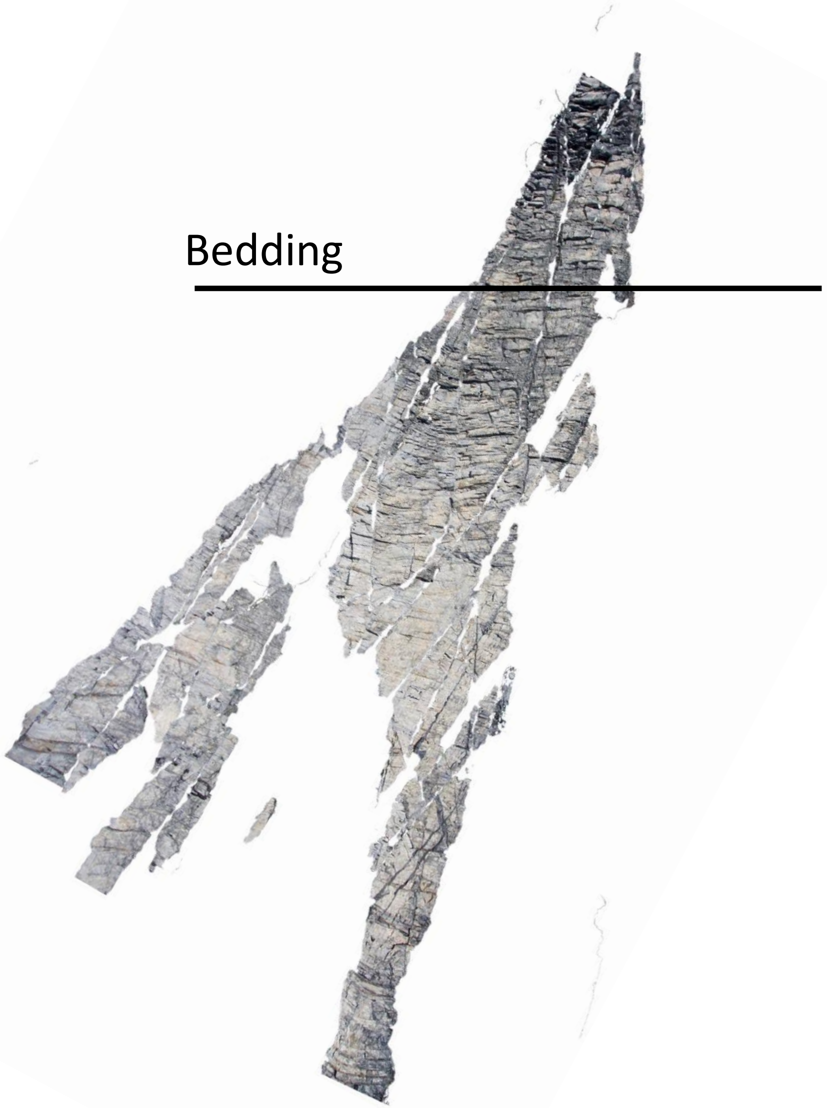


Quantification of deformation

We envisage three scenarios for choosing the paleo-horizontal:

A) The bedding is chosen as paleo horizontal
B) Direction of maximum stretching is chosen as paleo horizontal
C) Considering the two dyke orientations as conjugate sets, the bisector line of the obtuse angle between the dykes is chosen as the paleo horizontal



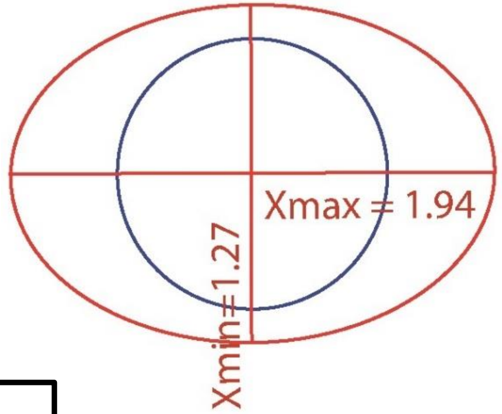


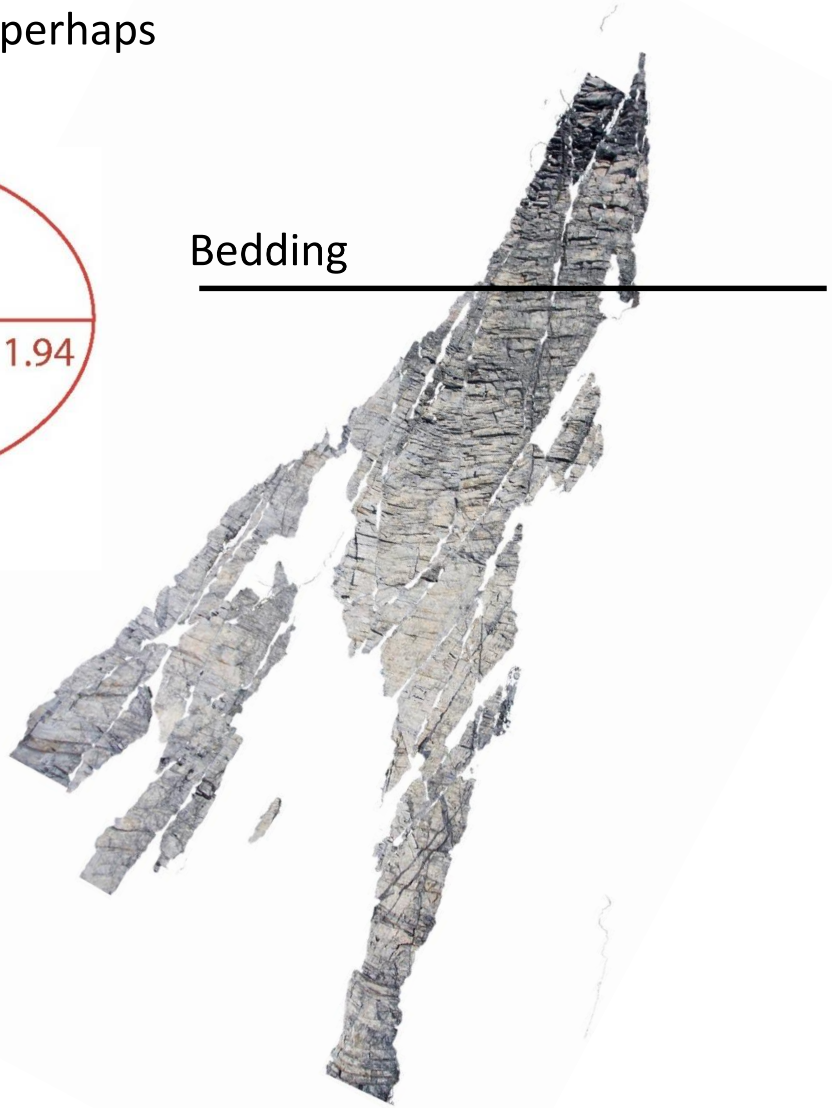
In all the scenarios, at least one dyke orientation will be oblique

Quantification of deformation

Then we used Matlab to calculate the amount of deformation imposed by the dykes. And as you can see, the dykes accounted for almost **100% horizontal stretching** but, and perhaps more counter-intuitively, they also accounted **for 27% vertical thickening**!

Implying that the magma input rate must have been significantly larger than the tectonic stretching rate!





94% bedding parallel stretching

27% vertical thickening

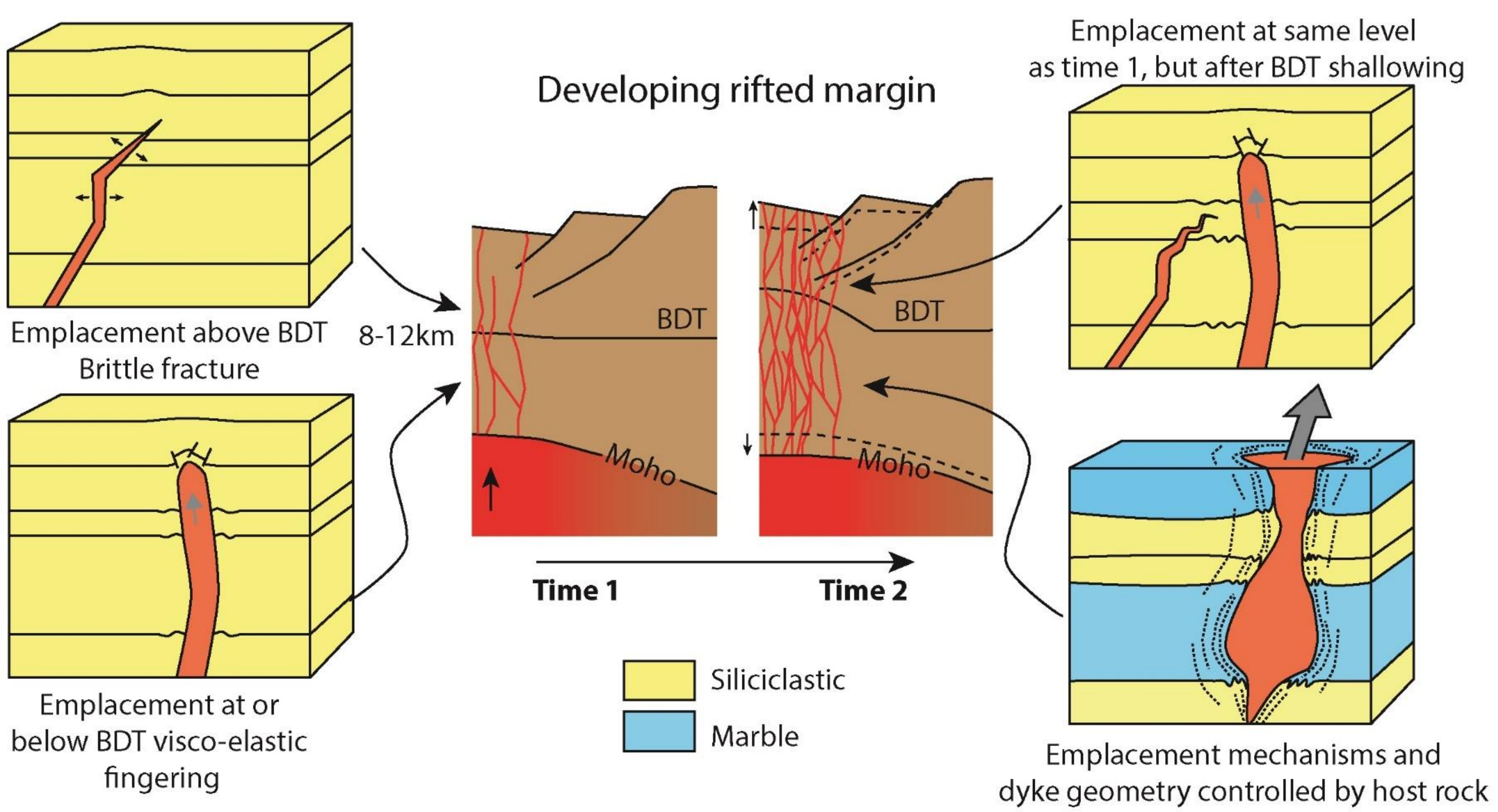
Magma input rate > tectonic stretching rate

Model

The emplacement of large amounts of mafic material into the crust led to a **shallowing of the brittle-ductile transition** (BDT).

The injection rate of magma into the crust was greater than the tectonic stretching rate and led to **shortening structures in the host rock** as well as **inclined dykes**, which again led to **vertical thickening** in the stretching crust.

Emplacement mechanisms as well as dyke geometries are strongly controlled by the host rock rheology as observed in Corrovarre where the dykes were emplaced in hot marbles.



If you would like to learn more, please see: **Emplacement mechanisms of a dyke swarm across the brittle-ductile transition and the geodynamic implications for magma-rich margins**, published in EPSL

References

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Kjøll, H. J., Galland, O., Labrousse, L., & Andersen, T. B. (2019a). Emplacement mechanisms of a dyke swarm across the brittle-ductile transition and the geodynamic implications for magma-rich margins. *Earth and Planetary Science Letters*, *518*, 223-235.

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