Welcome to Verbania for the sixth Granulites and Granulites (G&G) conference. Anticipate an engaging week of discussions centred on high-temperature processes in the middle and lower crust. Our agenda includes topics such as migmatite and granulite formation, crustal anatexis, melt extraction and transfer, structure and composition of the lower crust, and crust-mantle interactions.

We are thrilled to gather over 130 delegates from various countries on the picturesque shores of Lago Maggiore in the Southern Alps. Located just a few kilometres away is the Ivrea-Verbano zone, featuring some of the Earth’s best-studied granulites, making it a fitting venue for this conference. The event boasts a comprehensive four-day schedule comprising talks and poster presentations featuring a curated selection of internationally renowned keynote and invited speakers.

On behalf of the convenors and organisers, we hope you enjoy G&G 2024.

Organising committee:

Alberto Zanetti  
Istituto di Geoscienze e Georisorse, CNR, Italy

Daniela Rubatto (committee chair)  
Institute of Geological Sciences, Universität Bern, Switzerland

Othmar Müntener  
Institute of Earth Sciences, Universität de Lausanne, Switzerland

Antonio Langone  
Department of Earth and Environmental Sciences, Universität di Pavia, Italy

Pierre Lanari  
Institute of Geological Sciences, Universität Bern and SFMC, Switzerland

Jörg Hermann  
Institute of Geological Sciences, Universität Bern, Switzerland

Jacob Forshaw  
Institute of Geological Sciences, Universität Bern, Switzerland

Patrizia Fiannacca  
Department of Biological, Geological and Environmental Sciences, Universität di Catania, Italy

Christian Chopin  
Ecole Normale Supérieure de Paris (ENS), CNRS, and SFMC, France

Bernardo Cesare  
Dipartimento di Geoscienze, Universität di Padova, Italy

Previous Granulites & Granulites meetings

G&G was born out of a major symposium of the same name that ran at a GAC/MAC/CGU Meeting in Ottawa, Canada, in 1986. Five meetings have been held in its current form:

<table>
<thead>
<tr>
<th>#</th>
<th>Place</th>
<th>Date</th>
<th>Convenor team</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>University of Brasilia, Brazil</td>
<td>July 2006</td>
<td>Joint US–Brazilian team led by Mike Brown and Renato Moraes</td>
</tr>
<tr>
<td>2</td>
<td>Hrubá Skála Chateau, Czech Republic</td>
<td>July 2009</td>
<td>Diverse international team led by Karel Schulmann</td>
</tr>
<tr>
<td>3</td>
<td>National Geophysical Research Institute, Hyderabad, India</td>
<td>January 2013</td>
<td>Joint Indian–Australian team led by Ian Fitzsimons</td>
</tr>
<tr>
<td>4</td>
<td>Windhoek, Namibia</td>
<td>July 2015</td>
<td>Johann Diener and Dick White</td>
</tr>
<tr>
<td>5</td>
<td>Ullapool, Scotland</td>
<td>July 2018</td>
<td>Joint British–Australian team led by Tim Johnson</td>
</tr>
</tbody>
</table>
# Programme contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sponsors</td>
<td>4</td>
</tr>
<tr>
<td>Supporting Institutions</td>
<td>4</td>
</tr>
<tr>
<td>Conference and excursion programme</td>
<td>5</td>
</tr>
<tr>
<td>Scientific programme at a glance</td>
<td>6</td>
</tr>
<tr>
<td>Full scientific programme</td>
<td>10</td>
</tr>
<tr>
<td>Abstracts</td>
<td>17</td>
</tr>
</tbody>
</table>
Sponsors

Supporting Institutions
### Conference and excursion programme

#### Information about the excursions

- **Pre-conference excursion Ivrea**: Departure from and return to Verbania for both days. Lunch and accommodation not provided.
- **Mid-conference activities**: You can choose between 3 half-day excursions and a scientific workshop (included in the conference fee).
- **Post-conference excursion Southern Calabria**: Departure from and return to Lamezia Terme International Airport. Lunch (x4), dinner (x3), accommodation (4 nights) included in excursion fees.
- **Post-conference excursion Finero-Central Alps**: Departure from Verbania and return to Bellinzona. Lunch (x2), dinner and accommodation (2 nights) included in excursion fees.

**Excursion not included in conference fee**
### Scientific programme at a glance

**Monday 2**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>19:00 - 22:00</td>
<td>Icebreaker <strong>Social activity</strong></td>
</tr>
</tbody>
</table>

**Tuesday 3**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30 - 12:15</td>
<td>Session &quot;Petrochronology &amp; Tectonics&quot; – Part 1</td>
</tr>
<tr>
<td></td>
<td>Invited speaker: Jean-François Moyen 08:45</td>
</tr>
<tr>
<td></td>
<td>Keynote: Barbara Kunz 09:45</td>
</tr>
<tr>
<td>13:30 - 16:30</td>
<td>Session &quot;Petrochronology &amp; Tectonics&quot; – Part 2</td>
</tr>
<tr>
<td></td>
<td>Keynote: Chris Yakymchuk 14:30</td>
</tr>
<tr>
<td>16:30 - 18:30</td>
<td>Poster session <strong>Excursion</strong></td>
</tr>
</tbody>
</table>

**Wednesday 4**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30 - 12:15</td>
<td>Session &quot;Ivrea-Verbano Zone&quot;</td>
</tr>
<tr>
<td></td>
<td>Invited speakers: Bruna B. Carvalho 08:30</td>
</tr>
<tr>
<td></td>
<td>György Hetényi 11:45</td>
</tr>
<tr>
<td></td>
<td>Keynote: Olivier Vanderhaeghe 09:45</td>
</tr>
<tr>
<td>14:00 - 17:00</td>
<td>Mid-conference activities <strong>Excursion</strong></td>
</tr>
<tr>
<td></td>
<td>A walk across the Moho</td>
</tr>
<tr>
<td></td>
<td>A geo-heritage marble</td>
</tr>
<tr>
<td></td>
<td>Visit to the picturesque botanical gardens of Villa Taranto</td>
</tr>
<tr>
<td></td>
<td>Workshop: Phase Equilibrium Modelling with MAVEN</td>
</tr>
</tbody>
</table>

**Thursday 5**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30 - 12:15</td>
<td>Session &quot;Petrology &amp; Geochemistry&quot;</td>
</tr>
<tr>
<td></td>
<td>Invited speaker: Emilie Bruand 08:30</td>
</tr>
<tr>
<td></td>
<td>Keynote: Andy Smye 11:30</td>
</tr>
<tr>
<td>13:30 - 16:00</td>
<td>Session &quot;Thermodynamic modelling&quot;</td>
</tr>
<tr>
<td>16:00 - 17:00</td>
<td>Session &quot;Timescales of HT metamorphism&quot; – Part 1</td>
</tr>
<tr>
<td></td>
<td>Keynote: Nathan Daciko 16:00</td>
</tr>
<tr>
<td>17:00 - 19:00</td>
<td>Poster session <strong>Social activity</strong></td>
</tr>
<tr>
<td>19:30 - 23:00</td>
<td>Conference dinner <strong>Social activity</strong></td>
</tr>
</tbody>
</table>

**Friday 6**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30 - 10:15</td>
<td>Session &quot;Timescales of HT metamorphism&quot; – Part 2</td>
</tr>
<tr>
<td></td>
<td>Keynote: Shujuan Jiao 09:45</td>
</tr>
<tr>
<td>10:45 - 12:30</td>
<td>Session &quot;Lithospheric processes&quot; – Part 2</td>
</tr>
<tr>
<td></td>
<td>Invited speaker: Luca Menegon 12:15</td>
</tr>
<tr>
<td>12:30 - 13:00</td>
<td>Closing Ceremony and Student Awards</td>
</tr>
</tbody>
</table>
Your sample is in 3D. Why isn’t your analysis?

Automated Mineralogy with ZEISS Mineralogic 3D
A game-changer for your petrology research, ZEISS Mineralogic 3D applies X-ray microscopy techniques and deep learning algorithms to deliver automated mineralogy analyses in 3D for mineral identification, textural classification, and data outputs including modal mineralogy, grain size, and morphology.

- Complete sample analysis with minimal sample preparation
- Gain more information with fewer samples from 3D analysis
- Non-destructive to allow for precious samples or correlative workflows

Scan for whitepapers and more
zeiss.ly/GG24
At the forefront of high precision analytical technology for over 25 years

Vitesse
Time-of-Flight ICP-MS

Astrum
Glow Discharge Mass Spectrometry

Sapphire
Dual Path MC-ICP-MS with Collision/Reaction Cell

Noblesse HR
Noble Gas Mass Spectrometry

TIMS
Thermal Ionisation Mass Spectrometry

Plasma 3
Multi-Collector ICP-MS

Attom ES
High Resolution ICP-MS

Horizon 2
IRMS

Perspective
SIRMS

Full range of instruments available through www.assing.it
Introducing
JEOL Soft X-Ray Emission Spectrometer
A Novel Approach to Light Element Detection

Featuring
• Excellent light element detection (suitable for Li)
• Extreme high energy resolution - 0.3eV guaranteed
• Superb sensitivity - few tens of ppm B in steel
• Parallel detection for several X-ray spectra

JEOL Germany GmbH - Gute Änger 30 - D-85356 Freising
http://www.jeol.de
info@jeol.de

Solutions for Innovation
# Full scientific programme

Schedule of talks, posters, and other activities for the week.

## Tuesday 3rd September, 2024

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30-08.45</td>
<td>Daniela Rubatto</td>
<td>Introduction</td>
</tr>
<tr>
<td><strong>Session 1: PETROCHRONOLOGY and TECTONICS (Part 1)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08.45-09.00</td>
<td>Jean-François Moyen (invited talk)</td>
<td>Long term melt-generation in the Archaean crust: a case study from the Northern Kaapvaal craton, South Africa</td>
</tr>
<tr>
<td>09.00-09.15</td>
<td>Robyn MacRoberts</td>
<td>Sustained HT metamorphism during polyphase deformation in the Central Zone of the Damara Belt</td>
</tr>
<tr>
<td>09.15-09.30</td>
<td>Dan Wang</td>
<td>Exhumation of an Archean Granulite Terrane by Paleoproterozoic Orogenesis: Evidence from the North China Craton</td>
</tr>
<tr>
<td>09.30-09.45</td>
<td>Meiyun Huang</td>
<td>High-pressure to ultrahigh-temperature metamorphism in Assynt terrane, NW Scotland</td>
</tr>
<tr>
<td>09.45-10.15</td>
<td>Barbara Kunz (keynote)</td>
<td>High-temperature trace element mobility – a curse and a blessing</td>
</tr>
<tr>
<td>10.15-10.45</td>
<td>BREAK</td>
<td></td>
</tr>
<tr>
<td>10.45-11.00</td>
<td>Robert M Holder</td>
<td>Tracking partial melting with the LREE content of monazite</td>
</tr>
<tr>
<td>11.00-11.15</td>
<td>Laura Morrissey</td>
<td>Pressure–temperature–time constraints on metamorphism in the southeastern Talton Domain, Saskatchewan, Canada</td>
</tr>
<tr>
<td>11.15-11.30</td>
<td>Jenny Andersson</td>
<td>Spatial and temporal relationships between granulite facies metamorphism, partial melting, and magmatism in the west central Svecokarelian orogen, Sweden</td>
</tr>
<tr>
<td>11.30-11.45</td>
<td>Jon Pownall</td>
<td>The Lapland Granulite Belt, Finland: a new look at its metamorphic and tectonic history</td>
</tr>
<tr>
<td>11.45-12.00</td>
<td>Anfisa Skoblenko</td>
<td>Palaeoproterozoic 2.0-1.97 Ga stage of high-temperature metamorphism recorded by Mg-Al pelitic granulites in the Volgo-Uralia (East European Craton)</td>
</tr>
<tr>
<td>12.00-12.15</td>
<td>Sponsor Talk</td>
<td>Zeiss</td>
</tr>
<tr>
<td>12.15-13.30</td>
<td>LUNCH</td>
<td></td>
</tr>
<tr>
<td><strong>Session 1: PETROCHRONOLOGY and TECTONICS (Part 2)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.30-13.45</td>
<td>Aphrodite Indares</td>
<td>Granulites and granites in the Grenville Province – a Mesoproterozoic puzzle</td>
</tr>
<tr>
<td>13.45-14.00</td>
<td>Arlin B Fonseca Martinez</td>
<td>Low-P to Mid-P granulites in the Central Grenville Province: a new finding</td>
</tr>
<tr>
<td>14.00-14.15</td>
<td>Fumiko Higashino</td>
<td>Timing of ultrahigh-temperature metamorphism in Balchenfjella, Sør Rondane Mountains, East Antarctica</td>
</tr>
</tbody>
</table>
### Session 2: IVREA-VERBANO ZONE (Special session)

<table>
<thead>
<tr>
<th>Time</th>
<th>Presenter</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30-08.45</td>
<td>Bruna B. Carvalho (invited talk)</td>
<td>Multiple facets of carbon in graphitic metapelites of the lower crust: implications for our current understanding of carbon mobility during anatexis</td>
</tr>
<tr>
<td>08.45-09.00</td>
<td>Sarah Degen</td>
<td>Drilling deep carbon (Ossola Valley, project DIVE)</td>
</tr>
<tr>
<td>09.00-09.15</td>
<td>Jörg Hermann</td>
<td>Geochemistry of ultramylonites in granulites (Ossola Valley, Ivrea Zone)</td>
</tr>
<tr>
<td>09.15-09.30</td>
<td>Mattia Bonazzi</td>
<td>Reconstruction of Amphibolite Protolith and Metamorphic Changes of the primary signature Using Trace Elements and Isotopic Characterization of Bulk Rock</td>
</tr>
<tr>
<td>09.30-09.45</td>
<td>Davide Mariani</td>
<td>Melt-rock reaction control on magmatic underplating: evidence from the Ivrea Mafic Complex (Italian Alps)</td>
</tr>
<tr>
<td>09.45-10.15</td>
<td>Olivier Vanderhaeghe (keynote)</td>
<td>Dynamics of long-lived partially molten crustal continental roots and crustal differentiation</td>
</tr>
<tr>
<td>10.15-10.45</td>
<td>BREAK</td>
<td></td>
</tr>
<tr>
<td>10.45-11.00</td>
<td>Luca Pacchiega</td>
<td>The fate of accessory minerals during melting, Ivrea Verbano Zone</td>
</tr>
<tr>
<td>11.00-11.15</td>
<td>Omar Bartoli</td>
<td>Boosting the ultimate petrochronometer: the age of granulite-facies metamorphism in the Ivrea-Verbano Zone (NW Italy) determined through in-situ U-Pb dating of garnet</td>
</tr>
<tr>
<td>11.15-11.30</td>
<td>Ankam Bhatnacharya</td>
<td>Trace element systematics in HT-UHT garnet - a case study from the Ivrea Verbano Zone, Italy</td>
</tr>
<tr>
<td>11.30-11.45</td>
<td>Antonio Langone</td>
<td>Emplacement and cooling history of the Anzola gabbroic sill - insights from U-Pb geochronology and thermal modelling (Val d'Ossola, Ivrea-Verbano Zone)</td>
</tr>
</tbody>
</table>
### Thursday 5th September, 2024

#### Session 3: PETROLGY and GEOCHEMISTRY

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30-08.45</td>
<td>Emilie Bruand</td>
<td>How does the crust differentiate and magmas hybridize in a collisional/post-collisional environment? A view from the Serre crustal section (Calabria, Southern Italy).</td>
</tr>
<tr>
<td>08.45-09.00</td>
<td>Wiledio Marc-Emile Bonzi</td>
<td>Petrographic characterization of partial melting of quartz-feldspathic to mafic protoliths in the middle-lower crust during Eburnean orogeny (Paleoproterozoic, West-African Craton)</td>
</tr>
<tr>
<td>09.00-09.15</td>
<td>Vojtěch Janoušek</td>
<td>Mass balance during deep subduction and relamination of the felsic metaigneous crust (Variscan orogenic root, Bohemian Massif)</td>
</tr>
<tr>
<td>09.15-09.30</td>
<td>Elisa Oliveira Da Costa</td>
<td>Controls on the mobilisation of Li, Be, Sn, Cs, Ta and W during the melting of metapelites</td>
</tr>
<tr>
<td>09.30-09.45</td>
<td>Aleksandr Stepanov</td>
<td>Quantification of melt loss from restites by mass balance: problems and solutions</td>
</tr>
<tr>
<td>09.45-10.00</td>
<td>Edinson Yesid Bonilla Celis</td>
<td>Understanding the partial melting of Fe-rich granites: Using an example of the Southern Brasilia Orogen, Brazil</td>
</tr>
<tr>
<td>10.00-10.30</td>
<td>Jacob Forshaw</td>
<td>The petrochemistry of metabasic granulites</td>
</tr>
<tr>
<td>10.30-10.45</td>
<td>Bernardo Cesare</td>
<td>Melting the mafic underplates of arc roots: an example from the arclogite xenoliths at Mercaderes, Colombia</td>
</tr>
<tr>
<td>11.00-11.15</td>
<td>Leo Kriegsman</td>
<td>Migmatites and migmatites - crustal melting levels from pelitic solidus to UHT</td>
</tr>
<tr>
<td>11.15-11.30</td>
<td>Tu Cong</td>
<td>The volatiles recycling in continental subduction revealed by melt/fluid inclusions in the Himalayan orogen.</td>
</tr>
<tr>
<td>11.30-12.00</td>
<td>Andy Smye (keynote)</td>
<td>Differentiation of continental crust by ultrahigh temperature metamorphism</td>
</tr>
<tr>
<td>12.00-12.15</td>
<td>Sponsor Talk</td>
<td>JEOL</td>
</tr>
<tr>
<td>12.15-13.30</td>
<td>LUNCH</td>
<td></td>
</tr>
</tbody>
</table>

#### Session 4: THERMODYNAMIC MODELLING

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.30-13.45</td>
<td>Juergen Reinhardt</td>
<td>Granulate-facies migmatites recording extensive in situ anatexis of metapelites (Namaqua Metamorphic Province, South Africa):</td>
</tr>
</tbody>
</table>
geochemical-mineralogical characterization of leucosome and melanosome fractions, and modelling of melt generation

13.45-14.00 Sandro Chatterjee Post-peak temperature loading of ultrahigh temperature granulites of the Eastern Ghats Province, India – evidence from microstructures and phase equilibria models

14.00-14.15 Richard White Controls on the spatial focusing of melt formation in migmatites

14.15-14.30 Chunjing Wei Phase equilibria and P-T estimation in basic granulites

14.30-14.45 Renato Moraes After UHT, extreme greenschist facies retrometamorphism in Anápolis-Itauçu Complex, Brazil

14.45-15.00 Hannah Schroeder Analysis of tectonic activity from modern thermobarometry during the late Archean in the English River Subprovince, Ontario Canada

15.00-15.30 BREAK

15.30-15.45 Félix Gervais Transitional Proterozoic metamorphic regime and the generation of anorthosites

15.45-16.00 Kevin Mahan Hydration of lower continental crust and impacts on Colorado Plateau elevations: Insights from xenolith studies from the Navajo Volcanic Field (Colorado, Utah, Arizona, New Mexico) and the Henry Mountains, Utah, USA

Session 5: TIMESCALES of HIGH-T METAMORPHISM (Part 1)

16.00-16.30 Nathan Daczko (keynote) Zircon coupled dissolution-precipitation replacement in granulites: nature and experiments

16.30-16.45 Leonid Shumlyanskyy Past granulite facies metamorphic events revealed by U-Pb and Hf isotope systematics of zircon

16.45-17.00 Stacia Gordon Partial Melting of Metasedimentary Rocks in the Deep Levels of Continental Arcs: Insight from the Late Cretaceous,AlEocene North Cascades Arc, Washington, USA

17.00-18.30 POSTER SESSION (see list below)

Followed by the social dinner.

Friday 6th September, 2024

Session 5: TIMESCALES of HIGH-T METAMORPHISM (Part 2)

08.30-08.45 Antoine Godet Granulites on granulites: In-situ petrochronology helps disentangling Archean-Grenvillian polymetamorphism in the Grenville Front Tectonic Zone, Canada

08.45-09.00 Horst Marschall Garnet U–Pb dating as a robust petrochronometer for granulites

09.00-09.15 David Murphy In-situ Lu-Hf dating of garnet: a novel new tool for granulite geochronology

09.15-09.30 Naomi Tucker Garnet Lu–Hf speed-dating reveals complexities in the metamorphic history of the Narryer Terrane, Western Australia

09.30-09.45 Jiahui Liu Ultra-fast metamorphic reaction during regional metamorphism
### 09.45-10.15
Shujuan Jiao (keynote)
Mechanism to generate hot crust in Earth’s Middle Age

### 10.15-10.45
BREAK

### Session 6: LITHOSPHERIC PROCESSES

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.45-11.00</td>
<td>Michael Brown</td>
<td>Why are the global peaks in mantle T and granulite T/P not coeval?</td>
</tr>
<tr>
<td>11.00-11.15</td>
<td>Balz Kamber</td>
<td>Granulites as products and filters of basalt passage through continental crust</td>
</tr>
<tr>
<td>11.15-11.30</td>
<td>Ane K. Engvik</td>
<td>Proterozoic deep carbon - Characterisation, origin, petrophysical properties and the role of fluids during high-grade metamorphism of graphite (Lofoten-Vesterålen Complex, Norway)</td>
</tr>
<tr>
<td>11.30-11.45</td>
<td>Xiao-Feng Gu</td>
<td>Behavior of barium isotope fractionation during crustal anatexis</td>
</tr>
<tr>
<td>11.45-12.00</td>
<td>Tamás Spránitz</td>
<td>Lithosphere-scale fluid transfer in the central Pannonian Basin: carbon and noble gas isotope composition of deep fluid inclusions and groundwaters</td>
</tr>
<tr>
<td>12.00-12.15</td>
<td>Stephen Paul Michalchuk</td>
<td>Earthquake induced instantaneous garnet growth and deformation preserved in lower-crustal pseudotachylytes</td>
</tr>
<tr>
<td>12.15-12.30</td>
<td>Luca Menegon (invited talk)</td>
<td>Earthquake induced fluid flow and rheological transitions in granulites</td>
</tr>
<tr>
<td>12.30-13.00</td>
<td>Closing Ceremony and Student Awards</td>
<td></td>
</tr>
<tr>
<td>13.00-14.00</td>
<td>LUNCH</td>
<td></td>
</tr>
</tbody>
</table>

### List of Posters:

### Poster session 1: PETROLOGY AND GEOCHEMISTRY

<table>
<thead>
<tr>
<th>Poster</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Anthony Ramirez-Salazar</td>
<td>Garnet coronitic structures on the interface of felsic-mafic/restitic lithologies: possible evidence of fluid and/or melt movement during the ultra-high temperature metamorphism of the Oaxacan Complex, Southern Mexico</td>
</tr>
<tr>
<td>2</td>
<td>Emond W.F. de Roever</td>
<td>UHT garnet in the Bakhuis Granulite Belt, Suriname, South America</td>
</tr>
<tr>
<td>3</td>
<td>Pierre Lanari</td>
<td>Deciphering elemental behaviour during high-grade metamorphism using multi-phase quantitative compositional mapping by LA-ICPMS</td>
</tr>
<tr>
<td>4</td>
<td>Fernanda Torres Garcia</td>
<td>Constraints on the origin of Archean hornblendites: an example from the Lewisian Gneiss Complex, NW Scotland</td>
</tr>
<tr>
<td>5</td>
<td>Cindy Urueña</td>
<td>Tracking a polymetamorphic history: garnet trace element mapping in a Sveconorwegian granulate</td>
</tr>
<tr>
<td>6</td>
<td>Miisa Hakkinen</td>
<td>Two-stage metamorphism of the Sulkava granulite area, Southern Finland</td>
</tr>
<tr>
<td>7</td>
<td>Francois Guillot</td>
<td>Pre-Variscan granulite under Alpine high-P: the Ruitor Massif, W-Alps</td>
</tr>
<tr>
<td>8</td>
<td>Mona Lueder</td>
<td>Granulite facies rutile: Exploring trace element zoning and homogenization</td>
</tr>
<tr>
<td></td>
<td>Name</td>
<td>Title</td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>9</td>
<td>Caliméria Passos do Carmo</td>
<td>Zircon as a window on magmatic interaction between mantle-derived magmas and granulitic lower crust exposed in Ivrea-Verbano zone, northern Italy</td>
</tr>
<tr>
<td>10</td>
<td>Samikshya Mohanty</td>
<td>Granulites- Energy source for future: Case study from beach placers of eastern coast of India and Sri Lanka</td>
</tr>
<tr>
<td>11</td>
<td>Anuj Ghosh</td>
<td>Unravelling contrasting post-metamorphic peak tectonic evolutionary histories from a single high grade terrane: a case study</td>
</tr>
<tr>
<td>12</td>
<td>Emma Jordan Conway</td>
<td>Re-visiting Lower Crustal Xenoliths from Northeastern Australia</td>
</tr>
</tbody>
</table>

**Poster session 2: PARTIAL MELTING AND NANOGRANITOIDS**

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Guibin Zhang</td>
<td>Partial melting of eclogite in Central Himalaya and its contribution to Miocene climate change</td>
</tr>
<tr>
<td>14</td>
<td>Luojuan Wang</td>
<td>Entrainment of peritectic garnet in granite petrogenesis: evidence from metapelitic enclaves in S-type garnet granitoids</td>
</tr>
<tr>
<td>15</td>
<td>Mikaela Krona</td>
<td>Experimental investigation of H2O and CO2 solubility in graphite- and fluid-saturated anatexic melt</td>
</tr>
<tr>
<td>16</td>
<td>Guangyu Huang</td>
<td>Partial melting mechanisms of peraluminous felsic magmatism in a collisional orogen: an example from the Khondalite Belt, North China Craton</td>
</tr>
<tr>
<td>17</td>
<td>Silvio Ferrero</td>
<td>Pfaffenbergite &amp; “phase 430”, new mineral phases from melt crystallization in nanorocks</td>
</tr>
<tr>
<td>18</td>
<td>Mahyra Tedeschi</td>
<td>Nanorocks in zircon from a garnet-free granulite: insights from petrography and major and trace elements compositions</td>
</tr>
<tr>
<td>19</td>
<td>Jessie Shields</td>
<td>Experimental Melting of Eclogite Hosted Polycrystalline Melt Inclusions</td>
</tr>
</tbody>
</table>

**Poster session 3: THERMODYNAMIC MODELLING**

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Noralinde de Leijer</td>
<td>The sub- to supersolidus transition in the central Pyrenees, Lys-Caillaouas and Gavarnie-Héas</td>
</tr>
<tr>
<td>21</td>
<td>Volker Schenk</td>
<td>A re-appraisal of metamorphic conditions in the lower crustal section of the Serre, Calabria</td>
</tr>
<tr>
<td>22</td>
<td>Suvankar Samantaray</td>
<td>Tectono-metamorphic evolution from ultrahigh temperature granulite to amphibolite facies metamorphism in the Central Domain of Assam-Meghalaya Gneissic Complex: NE India</td>
</tr>
<tr>
<td>23</td>
<td>DingDing Zhang</td>
<td>Metamorphism of Chicheng HP and UHT granulites, northern Trans-North China Orogen and its implication for the initiation of the modern plate tectonics</td>
</tr>
<tr>
<td>24</td>
<td>Juraj Butek</td>
<td>A PHREEQC model for the transformation of gabbro into rodingite</td>
</tr>
<tr>
<td>25</td>
<td>Xia Teng</td>
<td>Metamorphic history of garnet pyroxenites from western Qaidam Block: Insights into the root of Andean-type arcs</td>
</tr>
</tbody>
</table>

**Poster session 4: PETROCHRONOLOGY**

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Fydji Sastrohardjo</td>
<td>U-Pb age constraints of migmatites in the Marowijne greenstone belt through textural analysis of zircons; NE Suriname, Paleoproterozoic Guiana Shield</td>
</tr>
<tr>
<td>27</td>
<td>Lucas Ramos Tesser</td>
<td>Assembly of the Riacho do Pontal orogenic wedge, NE Brazil: constraints from monazite petrochronology and phase equilibrium modeling</td>
</tr>
<tr>
<td>28</td>
<td>Sampriti Basak</td>
<td>Tracing the evolution of granulites and associated rocks at 2.9 Ga Fiskensæset Anorthosite Complex, SW Greenland</td>
</tr>
<tr>
<td>Page</td>
<td>Authors</td>
<td>Title</td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>29</td>
<td>Alberto Zanetti</td>
<td>Geochemical Characterization of Quartz-Dioritic Leucosome Reveals Evidence of Amphibolite Partial Melting from Val Sabbiola, Central Ivrea-Verbano Zone (Alps): Insights from Mineral Chemistry, Zircon Geochronology, and Zircon Isotopes</td>
</tr>
<tr>
<td>30</td>
<td>Stefano Piccin</td>
<td>New constraints on the high temperature metamorphism of the Oetztal-Stüibai Complex (Eastern Alps)</td>
</tr>
<tr>
<td>31</td>
<td>Marco Filippi</td>
<td>Timing and Metamorphic Evolution of the Deep Crust of Adria in the Valpelline Series</td>
</tr>
<tr>
<td>32</td>
<td>Yaron Katzir</td>
<td>Granulite xenoliths from the Arabian plate margin: Reworking of the East African lithosphere?</td>
</tr>
<tr>
<td>33</td>
<td>Cerine Bouadani</td>
<td>Reconstruction of the Variscan history of the Texenna basement (Lesser Kabylia, Algeria)</td>
</tr>
<tr>
<td>34</td>
<td>İnal Demirkaya</td>
<td>Unusual slow-cooling of amphibolite-facies rocks in an orogenic belt (Bolu Massif, NW Turkey)</td>
</tr>
<tr>
<td>35</td>
<td>Xiven Zhou</td>
<td>Metamorphism and formation age of pelitic granulite in the Jiapigou area, North China Craton</td>
</tr>
<tr>
<td>36</td>
<td>Ping-Hua Liu</td>
<td>Discovery and its tectonic significance of Paleoproterozoic high temperature pelitic granulites in Alxa Block, North China Craton</td>
</tr>
<tr>
<td>37</td>
<td>Juan Hu</td>
<td>Eclogite and medium-grade metamorphic rocks from northeastern Hainan Island, South China.</td>
</tr>
<tr>
<td>38</td>
<td>Jianxin Zhang</td>
<td>Late Ediacaran-Early Paleozoic HP/HT metamorphism in the northern Qilian block manifests a long-lived advancing accretionary orogeny along Northern Gondwana</td>
</tr>
<tr>
<td>39</td>
<td>Alex De Vries, Van Leeuwen</td>
<td>Identifying overprinting metamorphism in granulate-facies rocks via the application of LA–ICP–ToF–MS monazite U–Th–Pb age mapping</td>
</tr>
</tbody>
</table>

**Poster session 5: TIMESCALES and ISOTOPES**

<table>
<thead>
<tr>
<th>Page</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Yiruo Xu</td>
<td>Did Archean Metamorphic Terranes Cool Slower? Garnet Diffusion Study of the Quetico Subprovince, Canada</td>
</tr>
<tr>
<td>41</td>
<td>Sebastian &quot;Batzi&quot; Fischer</td>
<td>Variable Hf signatures in zircons of granitic bodies (can) already form by magma mixing in the source region</td>
</tr>
<tr>
<td>42</td>
<td>Hugo Dominguez</td>
<td>A multidisciplinary investigation of pluton formation and melt production in the deep crust: case study from the El Oro Complex, Ecuador</td>
</tr>
<tr>
<td>43</td>
<td>Miguel Angelo Stipp Basei</td>
<td>U-Pb ages and Hf isotopes in zircon from charnockites and mafic granulite enclaves of the Luis Alves Craton, Southern Brazil</td>
</tr>
<tr>
<td>44</td>
<td>Daniela Rubatto</td>
<td>Timescales of felsic lower continental crust formation: Insights from U-Pb geochronology of detrital zircon (Malenco Unit, eastern Central Alps)</td>
</tr>
<tr>
<td>45</td>
<td>Aratz Beranoaguirre</td>
<td>The effect of ultra-high temperature (UHT) and recrystallisation events on garnet U-Pb ages</td>
</tr>
<tr>
<td>46</td>
<td>Xiaofang He</td>
<td>Garnet ages, cooling rates and heat production in the Sri Lankan granulites</td>
</tr>
<tr>
<td>47</td>
<td>Martin Hand</td>
<td>Granulites record long-lived Meso-Neoarchaeon orogenic plateau</td>
</tr>
<tr>
<td>48</td>
<td>Min Ji</td>
<td>Anatectic rocks witness thermal evolution and fluid action in the Himalayan orogen</td>
</tr>
<tr>
<td>49</td>
<td>Shumpei Kudo</td>
<td>Development of U–Pb zircon dating using 2-4 μm spot size by LA-ICP-MS</td>
</tr>
</tbody>
</table>

**Poster session 6: DEFORMATION and STRUCTURE**

<table>
<thead>
<tr>
<th>Page</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Corey Flynn</td>
<td>Mechanisms of episodic brittle failure in deep continental crust; testing models in the Western Churchill Province, Canada</td>
</tr>
<tr>
<td>#</td>
<td>Author</td>
<td>Title</td>
</tr>
<tr>
<td>----</td>
<td>----------------</td>
<td>-------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>51</td>
<td>Christina Lipper</td>
<td>Reconstructing strain patterns in a deep crustal shear zone in the Canadian Shield: Evidence from kinematic vorticity analysis of host mylonite and sheared pseudotachylyte</td>
</tr>
<tr>
<td>52</td>
<td>Jonas Vanardois</td>
<td>Crucial role of water-present melting in metagranite: Implications for the instigation of crustal-scale shear zones</td>
</tr>
<tr>
<td>53</td>
<td>Fabiola Caso</td>
<td>Into the structure of the Permian deep continental crust: a multiscale approach to reconstruct migmatization in the Valpelline Series (Dent-Blanche Nappe, Western Italian Alps)</td>
</tr>
<tr>
<td>54</td>
<td>Stefania Corvo</td>
<td>Coupled monazite and titanite petrochronology to unravel the shear zones activity from mid- to low continental crust (Ivrea-Verbano Zone; Italy)</td>
</tr>
<tr>
<td>55</td>
<td>Maureen Gunia</td>
<td>The Chamrousse ophiolite, evidence of ductile deformation in amphibolitic facies during the pre-Variscan stage</td>
</tr>
<tr>
<td>56</td>
<td>Leonardo Casini</td>
<td>Seismic deformation and water-fluxed melting of the upper continental crust (N Sardinia, Italy)</td>
</tr>
</tbody>
</table>

**Abstracts**

Abstracts for all presentations are provided below. These are ordered chronologically in the same order as they are presented above; talks first, posters second.
On the northern edge of the Archaean Kaapvaal craton of South Africa, granulite-facies rocks are exposed. They contain abundant melt features in the form of leucosomes, in-source granites and small granite intrusions, as well as overprint not associated with clear petrological features and evidence of remelting of previously emplaced granites. At amphibolite facies conditions further South, large granite batholiths emplace during the same period.

U-Pb zircon (and occasionally monazite) dating of 36 samples (and compilation of data on 65 previously published ones) allows to build a comprehensive database of the age of melting in the Kaapvaal crust. The database reveals continuous melting from ca. 2950 to ca. 2650 Ma (culminating in the formation of spectacular anatectic metapelites at ca. 2710 Ma).

This peculiar pattern casts light on the evolution of the Archaean continental crust. The long duration of the melting period rules out one single cycle of heating and cooling, but the lack of clear peaks that may be related to distinct tectonic phases contrasts with modern orogenic systems. S-type granites at different stages, as well as deposition age of metasediments as young as 2750 Ma, show that burial was happening at multiple times during the period.

The general image that merges is that of an accretionary complex at the edge of a stable continent. Alternating phases of extension and compression allowed the formation of closure of sedimentary basins, and the burial and melting of all the lithologies in the region. In the generally hotter Archaean Earth, the system was both hotter, and cooled down more slowly, developing a “hot orogen” at the edge of the craton.

Fig. 1. Age distribution of all samples dated in this work, and from the literature.
Sustained HT metamorphism during polyphase deformation in the Central Zone of the Damara Belt
MacRoberts, R.J.1, Hasalová, P.2, Elburg, M.A.1, and Lehmann, J.1

1PPM Research Group, Department of Geology, University of Johannesburg, Auckland Park, 2006, Johannesburg, South Africa, robyno@uj.ac.za
2Czech Geological Survey, Klárov 3/131, Prague, 11821, Czech Republic

The Pan-African Damara Belt formed at 590–470 Ma, near-coevally with the adjacent and orthogonal Kaoko and Gariep belts during western Gondwana Supercontinent assembly (e.g., Miller, 2008). Up to three metamorphic phases are proposed for the HTLP (~825°C, ~4.9 kbar, Longridge et al., 2017) Central Zone (CZ), the polydeformed hinterland of the Damara Belt. However, the number, timing, duration, and geodynamic significance of these metamorphic phases are debated (e.g., Longridge et al., 2017; Goscombe et al., 2022). Contrasting views on polymetamorphism in the CZ render the relationships between metamorphism, anatexis, and polyphase deformation unclear. A pressure-temperature-time-deformation (P-T-t-d) investigation of the Namibfontein-Vergenoeg (NV) domes, two adjacent migmatite domes in the CZ, reveals that these rocks experienced sustained anatectic HTLP conditions during polydeformation. Monazite petrochronology of structurally controlled anatectic products constrains the timing of i) Kaoko Belt-related E-W shortening D1 between <558 Ma and ~535 Ma, ii) a tectonic switch to Damara Belt collision-related NNW-SSE shortening (D2 and D3) at ~535–532 Ma, and iii) enigmatic Damara Belt-parallel NE-SW shortening at ~523–494 Ma (Fig. 1). Pseudosection modelling of Damara Supergroup migmatite indicates that all deformation occurred at similar suprasolidus, HTLP conditions of ~750–780°C and ~5 kbar, defining a mostly temperature-controlled, hairpin P-T path (Fig. 1). Monazite U-Pb geochronology records at least ~50 m.y. (~540–494 Ma) of continual monazite crystallisation and recrystallisation during sustained anatexis at the NV domes. Three regional shortening events operating at similar suprasolidus P-T conditions are perplexing, pose the problem of reconciling these observations in a geodynamic model and question if heating and deformation are coupled for all deformation phases. Furthermore, could heat from contemporaneous and concurrent sources such as a radiogenic basement coupled with subduction- and crustal thickening-related heating, possibly from multiple, closely-timed orogenies (i.e., the Kaoko and Damara belts), have been responsible for sustained anatectic HTLP metamorphism in the CZ?

References:
Goscombe B et al. (2022) Gondwana Research, 109, 285-325
Longridge L et al. (2017) Lithos, 361-382

Figure 1: A summary of P-T-t-d data at the NV domes. Segments of the P-T path (bold solid line, the bold dashed line shows part of the inferred prograde path) are coloured to indicate the P-T conditions operating during each deformation phase. The timing of deformation is summarised in the colour-coded boxes to the far right, also showing when different monazite textures were likely to form. The topmost map inset (adapted from Barnes, 1981) shows the regional context of D1–D4 shortening (the black star indicates the position of the NV domes), while the bottom map shows rough trajectories of planar deformation fabrics at the NV domes.
Exhumation of an Archean Granulite Terrane by Paleooproterozoic Orogenesis: Evidence from the North China Craton
Wang, D.1, Mitchell, R.N.2,3, Guo, J.2,3 and Liu, F.1

1Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China. Corresponding author: Dan Wang, wangd221@gmail.com
2State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
3College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Granulites represent high-grade metamorphic rocks of the deep continental crust. The metamorphism and exhumation of granulites from Archean terranes provide insights into the crustal evolution of Archean cratons and shed light on the formation and reactivation of cratons. We present petrology, U–Pb geochronology (zircon, rutile, and titanite), and pressure-temperature (P–T) paths for metadiabase dikes in an Archean granulite terrane of the North China Craton. Garnet (Grt) coronae in the metadiabase dikes are developed between plagioclase (Pl) and clinopyroxene (Cpx) via the reaction Pligneous + Cpx → Pl1 + Grt ± quartz. The reaction proceeds inward within the plagioclase, progressively consuming Pligneous (XAn = 0.65–0.69) and leaving Ca-poor Pl1 (XAn = 0.46–0.53) as the residue. Geothermobarometry and P–T pseudosections suggest peak conditions for garnet formation at ~800 °C and 10–13 kbar. During retrograde metamorphism, Grt broke down to Ca-rich Pl2 (XAn = 0.73–0.74), and ilmenite replaced rutile. Geothermobarometry and Zr-in-titanite temperatures constrain the P–T conditions of retrograde metamorphism at 700–750 °C and 4.5–7.5 kbar. Zircon and titanite U–Pb geochronology shows that the protolith of the metadiabase dike was formed at 2.4 Ga and underwent granulite-facies metamorphism at 1.86 Ga. The intrusion of mafic dikes into the Archean granulite terrane indicates that the Archean basement was also heated and buried in the Paleooproterozoic. The metadiabase dikes and the hosting Archean basement underwent Paleooproterozoic granulite-facies metamorphism at a depth of ~40 km, followed by near-isothermal decompression and subsequent near-isobaric cooling (cooling rate of 1–3 °C Myr1) at depths of 15–25 km. Crustal shortening and thickening may have been caused by the underplating of the Khondalite series beneath the Archean basement during the amalgamation of supercontinent Columbia. The Paleooproterozoic orogeny induced a second generation of metamorphism of the Archean basement along the margin of the craton and drove the exhumation of the Archean granulite terranes to the middle crust (~15 km).
Partial melting mechanisms of peraluminous felsic magmatism in a collisional orogen: an example from the Khondalite Belt, North China Craton
Huang, G.¹, *, Liu, H.¹, ², *, Guo, J.¹, ², Palin, R.M.³, Zou, L.¹, ², and Cui, W.¹, ²

¹State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
²University of Chinese Academy of Sciences, Beijing 100049, China
³Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, United Kingdom

Sedimentary-derived (S-type) granites are an important product of metamorphism in a collisional orogen (Moyen et al., 2021), and a range of subtypes can be recognized by differences in field occurrence, mineralogy, and geochemistry. These subtypes can reflect variations of initial protolith composition, partial melting reactions, pressure and temperature of anatexis, or magmatic processes that occur during ascent through the crust (e.g. mineral fractional crystallization or crustal assimilation). Together, these diverse factors complicate geological interpretation of the history of peraluminous felsic melt fractions in orogenic settings. To assess the influence of these factors, we performed integrated field investigation, petrology, geochemistry, geochronology, and phase equilibrium modeling on a series of leucosomes within migmatite associated with different S-type granites within the Khondalite belt, North China Craton, which is an archetypal collisional orogeny (Zhao et al., 2005). Three types of leucosome are recognized in the east Khondalite belt: leucogranitic leucosome, K-feldspar (Kfs)-rich granitic leucosome, and garnet (Grt)-rich granitic leucosome. Phase equilibrium modeling of partial melting and fractional crystallization processes indicate that the leucogranitic leucosomes were mostly produced through fluid-present melting, Kfs-rich granitic leucosomes are produced through muscovite dehydration melting with 3 vol. % garnet fractional crystallization, and Grt-rich granitic leucosomes are produced through biotite dehydration melting with 20–40 vol. % K-feldspar fractional crystallization and up to 20 vol. % peritectic garnet entrainment. Mineral fractional crystallization and peritectic mineral entrainment occur in the source during melting, and play equally important roles in partial melting mechanisms in terms of affecting the geochemical compositions of granitic melts. Thus, we suggest that peraluminous felsic magmas preserved in collisional orogens are dominantly produced by fluid-absent melting in the middle to deep continental crust, although extraction of low-volume melt fractions from an anatectic source region at shallower depths during fluid-present melting can also generate small amounts of S-type granites that subsequently crystallize at high structural levels in the crust.

References:
High-temperature trace element mobility – a curse and a blessing
Kunz, B.E. 1, Oldman, C. 1, Warren, C. 1, Da Costa, E.O. 1, and Argles, T.W. 1

1School of Environment, Earth and Ecosystem Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK.
barbara.kunz@open.ac.uk

Geochemical signatures have become an integral part of the metamorphic petrologist’s toolbox to unlock metamorphic histories. Interweaving with petrography and geochronology, they allow us to trace processes through time and space, creating the discipline of petrochronology (e.g., Engi et al., 2017).

Over the last ten years many studies have demonstrated successful applications of petrochronology. One piece of research links crustal fragments, now exposed in the Western Alps and overprinted by high-pressure metamorphism, back to their pre-rifting crustal position in the Adriatic continental margin (Kunz et al., 2018a). Another example shows how matching geochemical signatures to petrographic and geochronological information allows us to unravel which melting reactions operated during collisional orogeny in migmatites from the Garhwal Himalayas (Oldman et al., submitted).

Other studies have shown that extended high-temperature metamorphism can be detrimental to petrochronological investigation, erasing records of past events, which makes reconstruction of P-T-t paths flawed or impossible. Improvements in analytical spatial resolution, accuracy and precision have not only allowed researchers to identify such problematic cases, but also sometimes unravel the underlying cause. In other cases, the mechanism for the breakdown of the petrochronological record isn’t fully understood. Research on granulite facies zircon from the Ivrea Zone has shown that the relationship between geochemical signatures and geochronological record can break down at temperatures above 850°C (Kunz et al., 2018b).

On the other hand, trace element mobility during high-temperature metamorphism and specifically partial melting is critical for transporting elements from the lower crust to the upper crust during crustal differentiation. This cycling of elements is of particular importance in light of the current interest in green energy and technology, which drives the demand for critical elements and sharpens the research focus on their sources. Studies on metamorphic systems (e.g., Da Costa et al. (under review); Kunz et al., 2022; Wolf et al., 2018) have shown that critical element release to melts is controlled by complex interplays between the consumption and crystallization of different minerals under the various melting reactions and conditions. Therefore, melting reactions and mineral stability may either help or hinder the enrichment of critical elements in the melt, with consequences for later mineralisation potential.

References:
Engi M et al. (2017) RIMG 83
Da Costa E.O. (under review) Geology
Kunz BE et al. (2018a) IJES 107, 203-229
Kunz BE et al. (2018b) CMP 173, 1-23
Oldman C et al. (submitted) CMP
Monazite U/Th–Pb dating is an ideal tool for constraining the timing and rates of metamorphic and magmatic processes. Monazite (re)crystallizes over a wide range of pressure–temperature conditions such that an individual thin section may preserve monazite with U/Th–Pb dates spanning millions of years (even greater than 100 million years). Such datasets create both challenge and opportunity. To a first order, it is useful to simply know that metamorphism lasted many 10’s of millions of years or that a pluton was aggregated by incremental injection over several million years. However, one might also want to know how a metamorphic or igneous environment changed with time. Additional information is needed to contextualize monazite U/Th–Pb dates to provide more precise interpretation of geological process and assessment of geological rates. Most work has focused on the Y+HREE (heavy rare-earth elements: Gd through Lu) concentrations and Eu anomaly in monazite as proxies for garnet and feldspar growth, respectively. This work presents quantitative modeling of changes in monazite LREE (light rare-earth elements: La through Sm) in migmatites. It is hypothesized that, just as one can use HREE ratios (e.g., Gd/Lu) as proxies for garnet growth/breakdown, one can use LREE ratios (e.g., La/Sm) as proxies for the timing and duration of partial melting.
Pressure–temperature–time constraints on metamorphism in the southeastern Taltson Domain, Saskatchewan, Canada

Morrissey, L.J.¹, Card, C.D.² and Reid, A.J.³

¹Future Industries Institute, University of South Australia, Mawson Lakes 5095, laura.morrissey@unisa.edu.au
²Saskatchewan Geological Survey, Saskatchewan Ministry of the Economy, 200-2101 Scarth Street, Regina, SK S4P 2H9, Canada
³Geological Survey of South Australia, Department of Energy and Mining, Adelaide, SA 5000, Australia

The southeastern Taltson Domain comprises a region of granulite facies orthogneiss and rare metasedimentary rocks located to the southwest of the Athabasca Basin in northern Saskatchewan, Canada. The southeastern Taltson Domain occupies a tectonically important position at the interface between the southern margin of the Rae Craton and two major orogenic belts, the 2.0–1.9 Ga Thelon–Taltson Orogen and the 1.9 Ga Snowbird Tectonic Zone. Despite its potential to provide important constraints on the metamorphic history of these orogenic belts, there has been relatively little metamorphic data collected from the southeastern Taltson Domain.

In situ LA-ICP-MS U–Pb monazite and zircon ages from rare metasedimentary rocks from the southeastern Taltson Domain reveal a polymetamorphic history, potentially spanning c. 2.19–1.9 Ga. Rare monazite ages of c. 2.19–2.01 Ga preserved in c. 1.9 Ga orthopyroxene–garnet gneiss from within the Snowbird Tectonic Zone suggest an early phase of metamorphism prior to c. 2.0 Ga. Another phase of metamorphism at high thermal gradients is recorded in a cordierite–sillimanite–spinel migmatite at 1988 ± 21 Ma, reaching P–T conditions of 4–6.4 kbar and > 900 °C. This event was coeval with emplacement of voluminous magmas at c. 2.01–1.97 Ga in the southeastern Taltson Domain. The cordierite–sillimanite–spinel assemblage overprints an earlier biotite–sillimanite-bearing assemblage that formed at 2075 ± 31 Ma. The significance of this event in the southeastern Taltson Domain is uncertain, but it is coeval with metamorphism in the southern Rae Craton.

The main metamorphic event to have affected the southeastern Taltson Domain occurred at c. 1.94–1.90 Ga. Phase equilibria modelling suggests peak P–T conditions were 8.3–11.2 kbar and 800–930 °C. Monazite with high HREE contents yields weighted mean ages of 1926–1918 Ma, interpreted to reflect prograde metamorphism prior to significant garnet growth. Zircon from an extremely garnet and zircon rich sample (now silicified and chloritized as a result of younger alteration) formed at c. 1918 Ma. REE compositions of the zircon indicate that it formed in equilibrium with garnet at temperatures of ~ 830 °C, suggesting peak metamorphism occurred around c. 1.92 Ga. HREE-poor monazite with weighted mean ages of c. 1910–1895 Ma formed after the majority of garnet growth and either reflect the timing of melt crystallisation or recrystallisation during retrogression and fluid flow along major shear zones in the region. The P–T conditions and c. 1.93–1.90 Ga ages from the southeastern Taltson Domain are very similar to other rocks in the Dodge–Snowbird Domain of the Rae Craton, and demonstrate that the footprint of mid-P granulite facies metamorphism extends south and west into the southeastern Taltson Domain.
Spatial and temporal relationships between granulite facies metamorphism, partial melting, and magmatism in the west central Svecoferralian orogen, Sweden.

Andersson, J.1, Klonowska, I.2, Nysten, P.3, Göransson, M.3, Evins, P.4, and Buczko, D.2

1Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden. jenny.andersson@nrm.se
2Department of Earth Sciences, Uppsala University, Sweden
3Geological Survey of Sweden, Uppsala, Sweden
4WSP, Stockholm, Sweden

Local enrichment of arsenic (As, 0.01-0.90 wt.%) in the Bergslagen lithotectonic unit of the Svecoferralian orogen has become a major concern in construction-intensive areas of Stockholm, Sweden. This issue has prompted detailed investigations of the bedrock focusing on field relations, petrography, geochemistry and geochronological work in two metamorphic sub-domains hosting As-rich rocks: a northern domain characterized by deformation and metamorphism at amphibolite facies conditions (the Arlanda domain; P=0.45-0.55 GPa, Ts550-600 °C), and a southern high-grade domain characterized by metamorphism and deformation at upper amphibolite to granulite facies conditions, including penetrative partial melting (the Nykvarn domain; P=0.50-0.55 GPa, T=780-800 °C, preliminary data, this study). The metamorphic basement in both domains is composed of sedimentary rock protoliths intercalated with volcanic deposits and intruded by 1910-1870 Ma granitoids and mafic rocks; the main metamorphic reworking is constrained at 1860 Ma and 1840-1800 Ma and late kinematic granite magmatism at 1870-1840 Ma and 1820-1750 Ma (Stephens and Jansson, 2020). In this study, detailed mapping of field relations, geochemistry, petrography and U-Pb zircon chronology confirm significant differences in the timing and character of igneous and metamorphic events between the northern and the southern domains but challenge current models for the extent and timing of anatexis, mafic magmatism and late kinematic granite-pegmatite magmatism. In the northern area, dykes and sills of andesite-dacite and gabbro in sedimentary deposits are dated between 1908±5 Ma and 1899±6 Ma. Although layers and lenses of mafic intrusions are common in the metasedimentary complex, there is no evidence for a spatial connection between metamorphism and mafic magmatism. Weakly deformed, structurally young granites were dated at 1846±4 Ma and 1845±4 Ma, identical to well-constrained ages for late-kinematic granite-pegmatite intrusions in adjacent low-grade areas to the north and northeast (cf. Johansson & Stephens, 2017). These dates set the lower age limit for the penetrative amphibolite facies deformation. With the exception for older imprecise U-Pb zircon and columbite age data, there is no support for voluminous late kinematic granite magmatism in the northern domain after 1850 Ma, that significantly postdates the main 1860 Ma metamorphic event. In contrast, the bedrock in the southern domain is dominated by metatexitic to diatexitic cordierite+garnet+sillimanite paragenesis with abundant disrupted dykes and lenses of metamafic rocks and late kinematic granitoids. Metamorphic zircon in leucosome-free metagabbro (orthopyroxene+amphibole+plagioclase) is dated at 1792±8 Ma. Anatectic zircon in veined mafic granulite (orthopyroxene+clinopyroxene+plagioclase+amphibole+quartz) with orthopyroxene megacrysts in the leucosome is dated at 1793±3 Ma. Identical zircon ages were obtained from weakly foliated late kinematic granite and undeformed pegmatitic granite (1793±3 Ma and 1792±5 Ma). Field relations indicate that the mafic intrusions injected the supracrustal complex while it was in a partially molten state. This supports models suggesting mafic underplating as the primary cause of the high-T/low-P metamorphism (cf. Stephens and Jansson 2020). In addition, however, this study directly demonstrates the spatial and temporal link between mafic magmatism, granulite facies metamorphism, crustal anatexis and granite magmatism at the present erosional level.

Arsenopyrite is the dominant As-mineral in both metamorphic domains. Arsenide (Löllingite) is also common and occurs in both metaigneous and metasedimentary rocks. In the northern domain, strong As enrichment (>200 ppm) occurs in different lithologies in a ca 1 kilometer wide zone. In the southern domain, such As enrichment has so far only been detected in the mafic granulites.

References:
The Lapland Granulite Belt, Finland: a new look at its metamorphic and tectonic history

Pownall, J.M., Cutts, K.A., Hiltunen, K., Yliknuussi, V. and Glorie, S.

1Department of Geosciences and Geography, University of Helsinki, Gustaf Hällströmin katu 2, Helsinki, Finland
2Geological Survey of Finland (GTK), Vuorimiehentie 5, Espoo, Finland
3Department of Earth Sciences, University of Adelaide, Adelaide, SA 5005, Australia

The Lapland Granulite Belt is a Paleoproterozoic (c. 1910–1880 Ma) granulite-facies metamorphic complex crossing arctic Finland, Norway, and the Kola Peninsula of Russia (Fig. 1). Studied in detail by Eskola (1952), the Finnish exposures of these rocks were pivotal in defining granulites as a distinct metamorphic facies. The Lapland granulites comprises pelitic grt + crd + sill migmatites hosting centimetre-to-kilometre-thick enderbitic (qtz + pl + opx ± cpx) and noritic (pl + opx ± hbl) sheets that were emplaced as mafic intrusions (Tuisku et al., 2006). Along part of the granulite belt’s southwest margin is a large anorthosite body, the Angeli Anorthosite. The Lapland granulites form a broad arc shape, the ‘Inari Orocline’ (Lahtinen & Huhma, 2019), concave along its northeastern margin (Fig. 1). This arc is sandwiched to its southwest by the Archean–Paleoproterozoic Karelian Craton and to its northeast by the Archean Inari Craton. Convergence between these cratons at 1930–1910 Ma (Daly et al., 2006; Lahtinen & Huhma, 2019) is thought to have driven dominantly collisional orogenesis of the intervening supracrustal rocks, causing long-duration high-temperature regional metamorphism and melting (at ~850°C, ~7 kbar) during a single, slow (c. 60 Myr) tectonic cycle (Tuisku et al., 2006).

Previous investigations into the metamorphic history of the Lapland Granulite Belt have focused on its broad-scale characterisation (e.g., Hölttä & Heilimo, 2017); but, crucially, sample-specific phase equilibria modelling, trace-element thermometry, and elemental mapping techniques have yet to be applied to metamorphic rocks from this region. Here, we present new field observations, Electron Probe Micro Analyser (EPMA) maps, P–T modelling, and in situ Lu-Hf garnet ages for a suite of garnet-bearing granulites and mafic enderbrites from the Lapland Granulite Belt (focussed on the Inari, Ivalo, and Kárášjohka regions) and adjacent Inari Terrane (including the bordering Kaamanen Complex). In situ Lu-Hf garnet geochronology (method of Simpson et al., 2021) reveals identical-within-uncertainty ages for both Lapland Granulite Belt granulites (1919 ± 10 Ma) and Kaamanen Complex gneisses (1919 ± 16 Ma) sampled either side of the terrane boundary, consistent with previously-published Lapland granulite U-Pb zircon ages (1919 ± 3 Ma; Tuisku & Huhma, 2006).

Fig. 1 – The Lapland Granulite Belt location within northern Fennoscandia (from Lahtinen & Huhma, 2019)

References:

Daly JS et al. (2006) in: Gee DG and Stephenson RA (Eds.) European Lithosphere Dynamics, Geol Soc London
Hölttä P & Heilimo E (2017) Geol Surv Finland Spec Paper 60, 77-128
Simpson A et al. (2021) Chem Geol 577, 120299
Palaeoproterozoic 2.0-1.97 Ga stage of high-temperature metamorphism recorded by Mg-Al pelitic granulites in the Volgo-Uralia (East European Craton)

Skoblenko, A.V.¹, Erofeeva, K.G.², and Samsonov, A.V.²

¹Geological Institute of Russian Academy of Sciences, Pyzhevsky lane 7/1, Moscow, Russia
²Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of Russian Academy of Sciences, Staramonetnaya lane, 35, Moscow, Russia

The Volgo-Uralia is one of the major segments of the East European Craton, which is completely overlain by sedimentary cover up to 10 km thick. Prospecting drillholes at depths up to 4.5-5 km allowed sampling of the basement to decipher the Early Precambrian crustal evolution of the segment. The Volgo-Uralia is majorly constituted of pelitic paragneisses of the Bolshoy Cheremshan Group aged 3.8-2.6 Ga with unevenly associated charnockitoids of the Kolyvan complex of 3.14 Ga in age (Bogdanova et al., 2021). Basic magmatism of various ages is recorded from the northern (ca. 2.6 Ga), central and southern (ca. 2.02 Ga) parts of the segment. From the south-west crustal blocks of the Volgo-Uralia are framed by Palaeoproterozoic metasedimentary flyschoid lithologies of the Volga-Don orogen intruded by granitoids aged ca. 1.95 Ga (Bogdanova et al., 2016).

Within the joint zone of the Volgo-Uralia segment and Volga-Don orogen high-grade metamorphic rocks have been recognized from the well Prigranichnaya. Mg-Fe-rich garnet-sillimanite-cordierite-spinel-K-feldspar-plagioclase-quartz granulites are considered to be the least retrograded varieties, which demonstrate detrital zircon core age distributions of mainly 2.2-2.05 Ga, with single grains of ca. 2.85 Ga. In turn, the zircons are overgrown by rims with inhomogeneous structure of 2.0-1.97 Ga in age, which is interpreted as the timing of granulite metamorphism occurrence. Garnets of the granulites do not show any features of zonation and correspond to almandine with notable contents of pyrope (X₁₇₀ 0.61 and X₁₇₀ 0.36). Spinels are unevenly distributed in the matrix as chains, or form inclusions in garnets. The spinels are of hercynite-spinel type; however, these demonstrate notable concentrations of Cr₂O₃ (0.8-1.1 wt.%) and ZnO (4.7-5.9 wt.%). Spinels constituting the inclusions in the garnet’s rims possess higher contents of gahnite and spinel components (X₁₇₀ 0.13 and X₁₇₀ 0.36), compared to those from the matrix with X₁₇₀ 0.10 and X₁₇₀ 0.27. Direct boundaries between spinel and quartz are not observed, alternatively cordierite associates with spinel replaced by Cr-bearing corundum (~1.4 wt.% of Cr₂O₃). The bulk content of zinc in the granulite is as low as 171 ppm, and no remnants of the pre-existing Zn-enriched phases are observed; zinc partitioning might therefore reflect re-distribution through metamorphic reactions. Biotite or staurolite breakdown could give rise to zinc-enriched spinel at the prograde stages, whereas an assemblage of garnet with the most zinc-rich spinel and cordierite correspond to the near-peak parameters of P ~8 kbar; T ~850°C. A decrease in Zn contents in spinel moves its stability towards the higher temperature/lower pressure field (Tajčmanova et al., 2009), while following breakdown of cordierite and growth of biotite with sillimanite mark the P-T shift to lower P of ~5-6 kbar; T <800°C. Voluminous felsic gneisses and granitoids sampled from the adjacent wells of the Volgo-Uralia segment show similar age clusters delineating the timing of the high-temperature metamorphic episode at 2.0-1.97 Ga. However, mineral assemblages of these varieties host rare sillimanite with cordierite and do not contain spinel; yet garnet, biotite, feldspars and quartz prevail.

The Mg-Al pelitic granulites of the Volgo-Uralia apparently followed subduction-collisional evolution reflected by the protolith accumulation at accretionary stage of ca. 2.2-2.05 Ga, subsequent burial or underthrusting at ca. 2.05-2.0 Ga to form the near-peak assemblages at collisional stage, and post-collisional extension with exhumation of the metamorphic complexes induced by underplating (basic magmatism of 2.02 Ga).

References:
Granulites and granites in the Grenville Province – a Mesoproterozoic puzzle

Indares, A.

Department of Earth Sciences, Memorial University of Newfoundland, Canada, aindares@mun.ca

The Grenville Province, in eastern Canada and US, holds a record of the closure of the SE Laurentian active margin during the ca. 1.09–0.98 Ga Grenvillian orogeny and assembly of Rodinia. It is classified as a large hot orogen with pervasive granulite-facies metamorphism especially in the orogenic core (hinterland), but whose age, duration and spatial distribution is far from uniform. The exposed orogenic crust is made of segments exhumed from different depths and records diachronous granulite-facies conditions: at ~1.08–1.06 Ga (early in the 1.09–1.02 Ga Ottawan orogenic phase) in the middle (mid-P) crust; to ~1.03–1.01 Ga (late-Ottawan) in deeper (high-P) crustal levels at the hinterland’s front in the central Grenville; and ~0.99–0.98 Ga (Rigolet phase) in the underlying top of the orogen’s NW margin (Parautochthonous Belt) in the same region. In addition, mid-P Ottawan metamorphism overprints earlier (1.09 Ga) eclogite-facies assemblages at the hinterland’s front in the west. Finally, shallower crust (low-P) structurally above the mid-P segments of the hinterland records late-Ottawan metamorphic gradients that locally reach granulite-facies conditions. The overall diachronicity is consistent with heating of: the footwall as the hot Ottawan orogen advanced to the NW over the Parautochthonous Belt; and the hanging wall, as shallower crust come in contact with the orogenic mid-crust during extension, inferred to have lasted from 1.06 to at least 1.02 Ga. Generally peak-T conditions were within the confines of biotite dehydration melting (max ~900°C) in aluminous rocks, with kyanite and sillimanite present in high- and mid-P segments respectively, and peak cordierite in the low-P segments. The hinterland has been inferred to represent remnants of a collapsed orogenic plateau, but evidence for this is limited to the western Grenville, and the high-P segments represent localized crustal thickening at the front of the Ottawan orogen rather than the exhumed base of an orogenic plateau.

Despite high-T metamorphism and widespread exposure of migmatites, S-type granites are inconspicuous, potentially due to limited presence of fertile protoliths in the precursor active margin on which the orogen was built. In contrast, high-T magmatism in the hinterland, manifested by locally abundant high-T granitoids with subordinate anorthosite and mafic rocks, covers the entire range of the Grenvillian orogeny pointing to enhanced mantle heat input in the orogenic crust in addition to heat produced by crustal thickening. The largest granitoid suites are spatially associated with a little older, 1.16–1.13 Ga large anorthosite suites in formerly pericratonic arc/backarc systems accreted to Laurentia before the Grenvillian orogeny, hinting to a potential connection between the ~1.16–1.13 Ga to Grenvillian-age high-T magmatism and lithospheric structures inherited from the Mesoproterozoic Laurentian margin. The metamorphic and igneous pattern reveal considerable lateral variations in the hinterland potentially linked to the earlier configuration of external Laurentia and is consistent with weak Mesoproterozoic lithosphere supporting a broad, hot, but not necessarily high-standing orogen for most of the Ottawan, in contrast to the Rigolet phase that marks the propagation of the orogen against the Archean lithosphere of internal Laurentia.

Figure: tectonometamorphic divisions of the Grenville Province and overall distribution of syn-orogenic plutonic rocks.
Low-P to Mid-P granulites in the Central Grenville Province: a new finding
Fonseca-Martinez, A.B.¹ and Indares, A.²

¹Earth Sciences, Memorial University of Newfoundland, Canada, abfonsecamar@mun.ca
²Earth Sciences, Memorial University of Newfoundland, Canada, aindares@mun.ca

The Grenville Province exposes crustal segments exhumed from different orogenic depths and with widespread granulite-facies metamorphism, recording deep to shallow high-T crustal processes during the continent-continent collision between Laurentia and presumably Amazonia in the Late Mesoproterozoic (1.09–0.98 Ga). This contribution focuses on the P–T signature of low-P to mid-P aluminous granulites from a recently recognized crustal domain, south of and structurally above the Mid-P segment of the Central Grenville Province (Quebec, Canada). P–T estimations were carried out through meticulous examination of textural relationships between minerals, mineral chemistry, and phase equilibria modeling, while LA–ICPMS monazite and zircon U–Pb dating is in progress.

Mineral assemblages are dominated by garnet, sillimanite, biotite, K-feldspar, plagioclase, quartz, and cordierite. Textures, such as films or fingers of inferred former melt (now plagioclase or quartz) enclosing garnet (Fig. 1a), K-feldspar, sillimanite, or plagioclase, overgrowths (symplectites) between biotite and plagioclase (Fig. 1a), and composite inclusions in garnet consisting of biotite and sillimanite in a pool of plagioclase (Fig. 1b), are evidence of melt production by dehydration melting of biotite during metamorphism. Textural relations suggest that cordierite is part of the peak mineral assemblage (Fig. 1c), in contrast to the Mid-P segment where cordierite is present only as a retrograde phase, formed during melt crystallization. Maximum P–T conditions for the aluminous granulites from the new crustal domain were inferred in the range of 6.0–8.0 kbar and 820–860°C. These conditions are in the same temperature range as those of the Mid-P segment to the north, but at consistently lower pressures, in agreement with other data that this is a distinct crustal segment. This area also contains voluminous 1.16-1.14 Ga anorthosite and Grenvillian-age high-T granitoid suites, and establishing their potential links to the metamorphism remains challenging. For instance, complex textures with two generation of garnet (Fig. 1d) in aluminous granulites close to high-T Grenvillian-age granitoid rocks may represent the imprint of successive thermal events.

Figure 1: Microphotographs of the aluminous granulites from the south part of the Central Grenville Province. a) Film of plagioclase surrounding garnet (cross-polarized light with the quartz plate inserted). b) Composite inclusion in garnet (cross-polarized light with the quartz plate inserted). c) Cordierite in the peak mineral assemblage (plane-polarized light). d) Two generations of garnet (plane-polarized light).
Timing of ultrahigh-temperature metamorphism in Balchenfjella, Sør Rondane Mountains, East Antarctica
Higashino, F.¹, Kawakami, T.¹, Kudo, S.¹, Nakano, M.¹, Kim, C.¹, Niki, S.², and Hirata, T.²

¹Department of Geology and Mineralogy, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo, Kyoto, 606-8502 Japan
Email: higashino.fumiko.2m@kyoto-u.ac.jp
²Geochemical Research Center, Graduate School of Science, The University of Tokyo, Tokyo, Japan

Ultrahigh-temperature (UHT) metamorphism is regarded as thermally extreme type of crustal metamorphism with temperatures over 900 °C at pressures of 0.5-1.8 GPa (Harley 2021). The UHT metamorphic rocks are commonly found in granulite terranes of early Paleozoic to Archean period, and their age distribution shows a temporal relationship to supercontinent assembly (Harley 2021). The Sør Rondane Mountains (SRM), East Antarctica are located at a key area of Gondwana supercontinent reconstruction, almost at the crossing point of the East African Orogen and the Kuunga Orogen (Satish-Kumar et al. 2013). Some previous studies had inferred an initial P-T conditions under UHT field in the SRM (Osanai et al. 2013; Grantham et al. 2013), and a UHT metamorphic rock was finally found from an outcrop (Higashino & Kawakami 2022). This study investigates the first UHT pelitic gneiss from an outcrop in the SRM and constrains the timing of UHT metamorphism from Balchenfjella, eastern SRM.

The studied sample is a sillimanite-garnet-biotite gneiss. The main matrix minerals are garnet, biotite, sillimanite, K-feldspar, plagioclase, mesoperthite and quartz. Coarse-grained mesoperthite-bearing polyphase inclusion that consists of mesoperthite + plagioclase + quartz is included in garnet. Nanogranitoid inclusions are also enclosed next to it. Ternary feldspar thermometry was applied to the matrix mesoperthite and mesoperthite inclusion in garnet. Their re-integrated compositions gave equilibrium temperatures of >900 °C at 0.8-1.0 GPa, using solvus of Fuhrman & Lindsley (1988), Kroll et al. (1993) and Benisek et al. (2004). Even taking the pressure dependence into consideration, this sample probably reached UHT condition of >900 °C. This suggests that the adjacent nanogranitoids are possibly entrapped under UHT metamorphism.

There are three types of zircon grains in this sample; zircon enclosed in UHT mesoperthite, zircon included in garnet and matrix zircon. The matrix zircon shows cathodoluminescence (CL)-dark core, CL-bright mantle and CL-dark rim, whereas zircon included in mesoperthite and garnet lacks CL-dark rim. In situ laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb zircon dating revealed that the CL-bright mantle of zircon included in mesoperthite gave a concordia ²⁰⁶Pb/²³⁸U date of ca. 594 Ma with high Th/U ratio of >0.3. This is likely the timing of UHT metamorphism, because the high Th/U ratio supports the zircon domain formed under UHT condition due to absence of monazite (Rubatto 2017; Yakymchuk et al. 2018). Rim of zircon in the matrix gave concordia dates of ca. 543-524 Ma, possibly following garnet formation. In addition, an equilibrium relationship between zircon and garnet using REE analyses will be discussed in order to understand a process to attain UHT and preserve its signature from petrochronological perspective.

References:
Benisek A et al. (2004) Am Min 89, 1496-1504
Fuhrman ML & Lindsley DH (1988) Am Min 73, 201-215
Kroll H et al. (1993) Contrib Miner Petrol 114, 510-518
Osanai Y et al. (2013) Precamb Res 234, 8-29
Satish-Kumar M et al. (2013) Precamb Res 234, 1-7
Yakymchuk C et al. (2018) J Metam Geol 36, 715-737
Long-lived metamorphism or polymetamorphism? A petrochronological study of granulite facies gneisses from Sør Rondane Mountains, East Antarctica

Kawakami, T.¹, Niki, S.², Suzuki, M.¹, Sakata, S.³, Adachi, T.⁴, Higashino, F.¹, Uno, M.⁵, and Hirata, T.²

¹Graduate School of Science, Kyoto University, Kyoto Japan. Email: t-kawakami@kueps.kyoto-u.ac.jp
²Geochemical Research Center, The University of Tokyo, Tokyo Japan
³Earthquake Research Institute, The University of Tokyo, Tokyo, Japan
⁴Advanced Asian Archaeological Research Center, Kyushu University, Fukuoka, Japan
⁵Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

The Sør Rondane Mountains (SRM) in East Antarctica is located at the crossing point of the East African Orogen (EAO) and the Kuunga Orogen (KO) and, therefore, is a paleo-geographically important area in understanding the formation and evolution of the Gondwana (Satish-Kumar et al. 2013). Detecting polymetamorphic events by EAO and KO from the SRM has been debated (Grantham et al. 2013; Higashino et al. 2023; Osanai et al. 2013; Satish-Kumar et al. 2013). In order to contribute in solving this problem, we studied two pelitic gneisses from the central SRM (Menipa). From a sillimanite-biotite-garnet (Sil-Bt-Grt) gneiss, a clockwise decompression P-T path starting from the peak metamorphic stage (~1.0 GPa/800 °C) to the retrograde re-equilibrium stages of ~0.38 GPa/610 °C and ~0.29 GPa/540 °C was constructed by geothermobarometric constraints. In situ laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb zircon dating revealed that metamorphic dates from ca. 615 Ma to 559 Ma are preserved both in the matrix zircon and zircon enclosed in the garnet rim. The ca. 560 Ma zircon is included in the outer rim of garnet together with sillimanite, and showed Yb$_n$/Gd$_n$~0.9, suggesting equilibrium growth with garnet. Since kyanite and sillimanite are both included in the inner rim of garnet, kyanite-grade metamorphism took place before ca. 560 Ma and sillimanite-grade metamorphism started at ca. 560 Ma. On the other hand, the ca. 601 Ma zircon domain showed Yb$_n$/Gd$_n$~1.2, implying equilibrium growth with garnet.

A V-bearing, grossular-rich green garnet surrounded by kelyphite occurs in a calcareous graphitic metapelitic gneiss in the same area (Osanai et al., 1990). This garnet was dated by in situ LA-ICP-MS U-Pb method. The rim of the green garnet yielded U-Pb garnet age of ca. 593 Ma and ca. 586 Ma. Titanite in the kelyphitic rim gave concordant U-Pb age ranging from ca. 550 to ca. 500 Ma from one sample and ca. 548 Ma from another sample. Outer zone of the kelyphite rim contains apatite, which gave U-Pb age of ca. 496 Ma. From these data, we consider that green garnet growth took place at ca. 590 Ma, followed by kelyphite formation starting from ca. 550 Ma. Coincidence of ca. 600 Ma metamorphic age obtained from the Sil-Bt-Grt gneiss with ca. 593-586 Ma green-garnet growth age suggests that the ca. 600-586 Ma was the timing of prograde metamorphism in Menipa. On the other hand, ca. 550 Ma U-Pb titanite age from kelyphite probably records the beginning of decompression. The age of the beginning of exhumation determined in this study is consistent with Grantham et al. (2013) who proposed that the SRM is a part of EAO terrane that thrusted over the Nampula terrane at ca. 580-540 Ma. On the other hand, since a few zircon domains from ca. 600 to ca. 560 Ma commonly show Yb$_n$/Gd$_n$~0.7-1.2, we may interpret that the garnet growth continued from ca. 600 Ma to ca. 560 Ma. Validity of this interpretation depends on whether we find any evidence of T and P increase in between ca. 600-586 Ma and ca. 560 Ma garnet growth stages. Tiny inclusions in the garnet core may be a key to solve the problem.

References:
Higashino F et al. (2023) Gondwana Res 119, 204-226.
Metamorphic Modelling – Applications and Limitations
Yakymchuk, C.

Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada, N2L 3G1

Metamorphic processes leave footprints that vary from micro to macro scales. Recent analytical advances allow us to collect large quantities of increasingly precise geochemical and geochronological data from metamorphic and igneous systems. These large datasets can be interrogated with sophisticated statistical techniques—including artificial intelligence approaches—that generate conceptual models of crustal processes and Earth’s long-term evolution. Testing these ensuing hypotheses requires linking geochemical datasets to underlying petrological processes. These processes have many controlling variables; the relative importance of each variable is not always clear. This results in a major gap between geochemical trends and understanding the dominant petrological controls. Metamorphic modelling is an exploratory tool that can test the wide variety of metamorphic and igneous controls that yield specific geochemical signatures (Johnson et al., 2021). Here, I present two case studies: (1) modelling trace element concentrations in accessory minerals and assessing their utility as proxies for pressure (i.e. depth) and temperature, and (2) a cautionary tale on the limits of an equilibrium approach to petrochronology in high-temperature metamorphic systems.

Anomalies in redox-sensitive rare earth elements (europium and cerium) in rocks and accessory minerals—mainly zircon—have been used as proxies for the P–T conditions of melting/crystallization (e.g. Tang et al., 2021). Europium anomalies in zircon are a complex function of temperature, pressure, residual mineral assemblage and—importantly—oxygen fugacity. Cerium anomalies in zircon reflect the complex interplay between oxygen fugacity and residual mineral assemblage; variations in P–T may only have a minor effect on cerium anomalies in zircon. Considering that the protoliths of metamorphic rocks and sources of igneous rocks are variably oxidized, it is unclear if temporal and spatial trends in europium and cerium anomalies in rocks and accessory minerals (e.g. zircon) represent changes in processes, source rocks, or both. A further complicating factor for zircon and other accessory minerals is understanding when in metamorphic cycles they grow/recrystallize to lock in europium and cerium anomalies.

An underlying assumption of phase equilibrium modelling and empirical studies that use petrochronology is the equilibrium of trace elements between accessory minerals (e.g. zircon, monazite, apatite), the residual mineral assemblage, and silicate melt. Here, I evaluate this assumption using a suite of ultra-high temperature granulites from southwest Peru. Rare earth element concentrations in zircon show no systematic trends with age, but are strongly dependent on whole-rock composition. Monazite of similar ages show variable trace element concentrations depending on microstructural setting (leucosome vs melanosome). Numerical modelling of trace element compositions in zircon and monazite does not reproduce measured values. An exception is Th in monazite; this is interpreted to record monazite growth from melt and can be approximated by an equilibrium-based model between these two phases. These results suggest that whole-rock equilibration of trace elements between residual minerals (including accessory minerals) and anatectic melt may be unlikely and that microstructural setting is a dominant control on trace element concentrations in accessory minerals (e.g. Weller et al., 2020) even during ultra-high temperature metamorphism. This raises significant doubts about the utility of equilibrium-based metamorphic modelling to accessory mineral behaviour in some natural systems, even in melt-bearing rocks at granulite-facies conditions.

References:
Johnson et al. (2021) Earth-Science Reviews 221, 103778
This presentation introduces how crustal thickening controls the growth of the Himalayan orogenic belt by summarizing the P-T-t evolution of the Himalayan Metamorphic Core. The Himalayan orogeny was divided into three stages. Stage 60–40 Ma: the Himalayan crust was thickened to ~40 km through Barrovian-type metamorphism (15–25 °C/km); the Himalaya rose from <0 meters to ~1000 meters. Stage 40–16 Ma: The crust was gradually thickened to 60–70 km, resulting in abundant high-grade metamorphism and anatexis (peak-P 15–25 °C/km, peak-T >30 °C/km); The three sub-sheets in the Himalayan Metamorphic Core were extruded southward sequentially through imbricate thrusts of the "Eo-Himalayan Thrust", "High Himalayan Thrust" and "Main Central Thrust"; The Himalayan mountains rose to ≥5000 meters. Stage <16 Ma: the mountain roots underwent localized delamination, causing asthenosphere upwelling and overprinting of the lower crust by ultra-high temperature metamorphism (900–970°C, 6–10 kbar); the upper crust underwent Buchan-type metamorphic overprinting (30–50 °C/km) through juxtaposition of the lower crust migmatites along orogen-scale syn-collision detachment fault; the Himalaya reached the present elevation of ~6000 meters. The growth and topographic rise of the Himalaya was dominated by underplating and imbricate thrusting, conforming to the Critical Taper Wedge model. Localized delamination of mountain roots facilitated further topographic rise. Future metamorphic studies in the Himalaya should pay attention to extreme metamorphism and major collisional events, contact metamorphism and skarn-type rare metal mineralization, and metamorphic decarbonation and the carbon cycle in collisional belts.

References:
Wang JM et al. (2024) Lithos 107428
Wang JM et al. (2023) Lithos 456-457, 107295
Wang JM et al. (2021) Earth Planet Sci Lett 558, 116760
Khanal GP et al. (2021) Tectonics 40(4): e2020TC006532
Wang JM et al. (2017) Contrib Mineral Petrol 172, 81
Wang JM et al. (2016) Tectonophysics 679, 41-60
Wang JM et al. (2013) J Metamorph Geol 31, 607-628
Augen to banded metagranite from the Snieznik dome have been modified locally to have stromatic, schlieren, nebulitic textures typical of migmatites. An increasing role of melt in the transformation towards nebulite is inferred from interstitial phases along grain boundaries in the dynamically recrystallized monomineralic feldspar and quartz aggregates, and from textures of fine-grained plagioclase and quartz replacing K-feldspar. These features are interpreted as the result of dissolution-reprecipitation due to melt migration along grain boundaries, being pervasive at the grain-scale, but localized at hand-specimen to outcrop scales. All the rock types have the same mineral assemblage of Grt−Ph−Bt−Ttn−Kfs−Pl−Qz±Rt±Ilm, with similar garnet, phengite and biotite composition and equilibrated at 15−17 kbar and 690−740 °C. Suprasolidus conditions in the model are achieved only if melt is added. Migmatite textures and modelling therefore suggest that an increasing degree of melt-rock interaction may be traced from the banded to the schlieren and nebulitic types during the fluid-fluxed grain-scale melt migration. In a large-scale context, the initiation of melt migration is related to gently dipping structures related to continental subduction at eclogite-facies conditions, while more pronounced melt migration is related to vertical fabrics, facilitating exhumation of the continental subduction wedge from eclogite-facies to mid-crustal conditions.

The effects of melt migration had impact on the partial recrystallization of zircon. Zircon in augen to banded types shows oscillatory zoning with a Cambro-Ordovician age of the protolith. In schlieren to nebulite types, domains of blurred oscillatory zoning to structure-less textures are located along grain boundaries, form embayments, straight or curved linear structures cutting through the oscillatory zoned domains, or are affecting the whole grains. The structure-less domains tend to give Carboniferous ages. The metamorphic domains are characterized by an overall decrease of HREE with large variation in zircon Yb/Gd ratio, either increase or decrease in LREE, increase in U, and decrease of Th and Th/U ratio. The overall decrease of HREE in zircon is interpreted as controlled by sequestration of HREE in garnet. However, large variation in zircon Yb/Gd ratio may be caused by variable distance from garnet, with flat slope in zircon HREE controlled by garnet in proximity. Increase in LREE and U in zircon due equilibration with melt is compatible with higher contents of solutes (LREE, U, Th) in melt compared to fluid. The observed overall loss of Th, and loss of LREE in some zircon is interpreted as due to presence or proximity of titanite, which competes for Th and M-LREE. The chemical changes in metamorphic zircon are therefore compatible with presence of melt, garnet and titanite. Zircon shows numerous apparent “inclusions” of phengite, K-feldspar, quartz, plagioclase, rare garnet, rutile, titanite and biotite. Because most of the “inclusions” are surrounded by metamorphic zircon domains, they are interpreted as secondary metamorphic inclusions. In places, where the inclusions are aligned, these structures are interpreted as former cracks, along which the metamorphic phases crystallized and passing melt facilitated zircon (re)crystallization. The garnet (Grs 0.35–0.39, Alm 0.50–0.55) and phengite (Si < 3.32) chemical compositions in the garnet–phengite-bearing inclusion assemblage are only slightly different from the matrix compositions, and indicate equilibration at ~15 kbar, 730°C. We interpret the Carboniferous zircon (re)crystallization as dating the eclogite-facies grain-scale melt migration process, which continued to amphibolite-facies on decompression.
Two generations of garnet and titanite in the anatectic eclogite from the South Altyn Tagh, western China

Cao, Y.T.1, Liu, L.2, Wang, C.2, Yang, W.Q.2, Kang, L.2 and Gai, Y.S.2

1Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, College of Geological Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China
2State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi’an 710069, China

Local partial melting of eclogite at the microscopic to field scales is observed in the Jianggalesayi area in the South Altyn Tagh (SAT). In the outcrop, felsic leucosomes are found in patch-like shapes distributed within the residual melanosome. In the melanosome, two generations of garnet (Grt1, Grt2) and titanite (Ttn1, Ttn2) are identified through a comprehensive study involving petrography as well as major and trace element profiles. Both Grt1 and Grt2, Ttn1 and Ttn2 exhibit distinct occurrences with varying chemical compositions. The Grt1 grain shows a homogeneous composition of Alm44.08–46.18Grs31.01–32.28Sp50.81–1.10Prp19.31–21.08, and displays a flat heavy rare earth element (HREE) pattern without any Eu anomaly; in contrast to Grt1, the granulated Grt2 surrounding the outer rim of the Grt1 demonstrates obviously higher Grs and Sp content, but lower Prp content, and noticeably lower light rare earth element (LREE), Cr and V contents. Additionally, Grt2 also displays a flat HREE pattern without any Eu anomaly. Ttn1 is observed as the coronas surrounding the outer rim of the relic rutile, while Ttn2 appears as coarse subhedral grains coexisting with garnet and amphibole. Ttn1 processes higher TiO2, SiO2, Nd and lower FeO, Al2O3, and Y content than Ttn2. Furthermore, Ttn1 exhibits an enrichment pattern in LREE with distinct positive Eu anomaly; Ttn2 has higher REE content and also shows LREE enrichment pattern but without any Eu anomaly. These results provide evidence supporting the differentiation between peritectic and anatectic garnet and titanite on the basis of BSE images, mineral assemblages and major and trace element compositions. Grt1 and Ttn1 originate from peritectic processes, formed through the reaction of Grt+Omp+Rt+Ep (eclogite facies) →Grt1+Cpx+Ttn1+melt (granulite facies); while Grt2 and Ttn2 are products of anatectic origin that crystallized from the melt.

The U-Pb dating of titanite yields a crystallization age of 470.9 ± 6.9 Ma for Ttn2, representing the timing of the melt crystallization. This age predates the retrograded granulite facies ages (462-450Ma) of HP/UHP rocks in SAT (Liu et al., 2012; Cao et al., 2019), suggesting that the partial melting occurred prior to granulite-facies metamorphism, most likely during the transformation from eclogite facies to granulite facies based on the petrological observation. Cao et al. (2019) has demonstrated that the Grt-bearing biotite gneiss from the same Jianggalesayi area underwent partial melting between 450 and 417 Ma, with melt crystallization occurring during the amphibolite facies stage of the exhumation. Consequently, two episodes of partial melting were identified during the exhumation of the subducted SAT slab, which significantly contribute to our understanding of the processes and mechanisms involved in partial melting during multiple metamorphic stages within deep subduction zones.

References:
Liu L et al. (2012) Lithos 136-139, 10-26
Exhumation of metamorphic rocks through time
Fitzsimons, I.C.W.\textsuperscript{1}, Johnson, T.E.\textsuperscript{1}, Chen, Q.\textsuperscript{1,2,3}, and Brown, M.\textsuperscript{4}

\textsuperscript{1}School of Earth & Planetary Sciences, Curtin University, GPOBox U1987, Perth WA6845, Australia I.Fitzsimons@curtin.edu.au
\textsuperscript{2}Centre of Deep-Sea Research, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
\textsuperscript{3}University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{4}Department of Geology, University of Maryland, College Park, MD 20742-4211, USA

Metamorphism occurs at depth, yet the direct study of metamorphic processes is almost entirely based on observation of rocks now exposed at the surface. These must represent only a fraction of Earth’s metamorphic record, with many more metamorphic rocks remaining buried or destroyed by weathering and erosion. An important question is where these surface rocks came from and whether they are truly representative of metamorphism on Earth, or if selective exhumation (e.g. from certain depths or certain tectonic settings) might create a bias in the surface record. A second question is whether any such bias might have varied with time, and if so whether this variation can be used to infer temporal changes in those factors likely to control exhumation in the Earth’s crust.

Here, we use quantitative pressure–age (P–t) information from equilibrated metamorphic rocks from orogenic belts worldwide to infer the depth of origin of Earth’s surface metamorphic record. We investigate the patterns in these data and other linked information including metamorphic temperature, cooling rate, and proximity to plate margins, and discuss their implications for exhumation mechanisms, surface elevation, sea level, and the orogenic and equilibrium thicknesses of continental crust. We highlight instances where this metamorphic depth record appears consistent with other methods used to constrain this fundamental geodynamic information, and instances where it does not.
Multiple facets of carbon in graphitic metapelites of the lower crust: implications for our current understanding of carbon mobility during anatexis

Carvalho, B.B.¹, Bartoli, O.¹, and Cesare, B¹

¹Dipartimento di Geoscienze, Università degli Studi di Padova, Via G. Gradenigo 6, Padova, 35131. bruna.borgescarvalho@unipd.it

Graphitic metapelites represent an important carbon reservoir in the roots of continents, therefore their behavior during high-grade metamorphism and anatexis may impact the geological carbon cycle globally. However, the mobility of carbon during anatexis remains largely unconstrained.

In this work, graphitic metapelites are investigated throughout the sequence of the Ivrea-Verbano Zone (NW Italy). Graphite is present in the matrix and as inclusions in garnet of metatexites and diatexites. Garnet contains abundant primary melt and fluid inclusions which in some samples, occur near rutile inclusions. Melt and fluid inclusions in garnet are investigated before and after high-temperature experiments with a piston cylinder. Melt inclusions are granitic in composition and store up to 2450 ppm CO₂ (Carvalho et al. 2019). Fluid inclusions in natural samples contain a residual C–O–H–N fluid together with siderite, calcite, pyrophyllite, and kaolinite. After the experiments, carbonates and OH-bearing phases are no longer present and the fluid contains considerable proportions of CO₂, CH₄, and N₂ but lower H₂O than predicted for graphitic systems at granulite facies (Carvalho et al. 2023). Phase equilibria predicts that garnet can grow up to near UHT conditions, in agreement with temperatures obtained using Zr-in-rutile thermometer. These results provide robust microstructural and thermometric constraints on the coexistence of graphite, CO₂-bearing anatetic melt and C–O–H fluids up to near ultrahigh temperature conditions, thus showing that the combined action of hydrous melt and C–O–H fluid is not able to dissolve and remove all the organic carbon in the metasedimentary lower crust.

The CO₂ contents of melt inclusions compared with the available experimental dataset on CO₂ solubility in felsic melts reveal important discrepancies. As most solubility experiments were conducted under carbonate-saturated (i.e. highly oxidizing) conditions which maximize the CO₂ content of melt, compared to graphitic (i.e. more reducing) protoliths, current CO₂ solubility in rhyolites cannot be used to interpret the volatile budget of anatetic melts.

Overall, data show that assuming only a limited extent of fluid-melt immiscibility in the deep crust contradicts the evidence from natural rocks and prompts to an incomplete view of actual carbon behavior and carbonic fluids. A sound evaluation of carbon budget and fluxes in suprasolidus graphitic metapelites should consider all the complex compositional relationships among fluid, melt and solids, as well as the possible respeciation in the fluid phases due to redox processes. To have a complete picture of carbon mobilization during crustal reworking, models must consider the persistence of C–O–H fluids in graphitic rocks (such as the ones in this study) up to near UHT conditions.

References:
Carvalho BB et al. (2023) Chem Geol 631C, 121503.
Drilling deep carbon (Ossola Valley, project DIVE)

Degen, S.¹, Secrétan, A.², Pacchiega, L.¹, Rubatto, D.¹, and Hermann, J.¹

¹Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, sarah.degen@unibe.ch
²Institut des Sciences de la Terre, University of Lausanne, CH-1015 Lausanne

The worldwide carbon budget of the deep crust is poorly quantified. Lower crustal rocks exposed in the Ivrea-Verbano Zone (northern Italy) consist of underplated mafic and metasedimentary rocks. In the metasedimentary rocks, substantial amounts of carbon in the form of residual carbonates and graphite can potentially be stored for millions to billions of years. This study aims to quantify the C budget of the lower crust and assess the mechanism of C mobilisation as well as to investigate the origin of the C in high grade rocks.

Drill cores obtained from the ICDP-funded DIVE-project (Drilling the Ivrea-Verbano Zone) have been studied for the distribution of C-bearing phases in the predominantly metasedimentary upper portion of the lower crust, represented by cores from drill hole DT-1B in Ornavasso. The drill core samples are mainly biotite-gneisses of the Kinzigite formation (75 vol-%, Qtz + Pl + Bt ± Grt ± Sil ± Kfs), amphibolites (20 vol-%, Amp + Pl ± Qtz ± Grt ± Cpx ± Bt) and calcisilicate rocks (2 vol-%, Cpx + Pl + Ttn ± Cc ± Grt ± Amp ± Qtz ± Scp) which were metamorphosed at upper amphibolite to lower granulite facies conditions (720-770 ± 50°C and 7.4 ± 1.5 kbar). Varying degrees of partial melting have been observed in all lithologies. Graphite occurs in the matrix of the biotite-gneisses and as inclusions in garnet. Moreover, calcite is present in calcisilicate rocks and occasionally in amphibolites.

C-N-S analyses revealed that the biotite-gneisses contain an average of 0.26 wt.-% C while the average values for the amphibolites and calcisilicate rocks are 0.07 and 0.73 wt.-%, respectively. For the 578.7m deep borehole, overall concentrations reach an average of 0.23 wt.-% C. The lower part of the lower crust (represented by cores from drill hole DT-1A in Megolo) is dominated by mafic rocks of magmatic origin with intercalated felsic, garnet-rich granulites (stronalites). Preliminary observations show much lower contents of carbonate and graphite in these rocks.

C mobilisation likely occurred in the calcisilicate rocks by means of garnet-forming decarbonation reactions (e.g., Zo + Hed + Cc → Qtz + Grs + H₂O + CO₂) as well as via melt, which is indicated by the presence of calcite in leucosomes. Fourier-transform infrared spectroscopy data of apatite indicate varying concentrations of CO₂ which reach >1500 ppm in case of the calcisilicate rocks. Furthermore, apatites hosted in leucosomes contain several hundred ppm of CO₂, suggesting the presence of C-bearing hydrous melts. Therefore, devolatilisation reactions as well as partial melting result in a moderate transfer of C from the deep crust to the upper crust. Our results indicate that metasedimentary rocks that reside at around 25 km depth at temperatures of ~750°C are an important reservoir for C, while mafic granulites derived from igneous protoliths and felsic granulites are poor in C.
A sequence of lower crustal felsic and mafic garnet granulites, metagabbros and pyroxenites crop out at Premosello, Ossola Valley, Ivrea Zone (N-Italy) representing the lowermost Permian continental crust. Peak metamorphic conditions of ~900°C and 1 GPa are consistent with a formation at about 35-40 km depth. All rock types display a granoblastic texture with a grain size of several mm, that is overprinted by a foliation which is locally crosscut by mylonites, ultramylonites and pseudotachylites.

Felsic granulites consist of garnet, K-feldspar, plagioclase, quartz and minor rutile/ilmenite. Two types of alternating ultramylonites have been observed inside this host. A light colored ultramylonite consists of plagioclase, quartz, K-feldspar and minor biotite with a grain size of 1-2 µm, while a dark colored ultramylonite with a similar grain size, also contains µm-sized ilmenites. Garnet and minor ilmenite form rounded porphyroclasts in both types of ultramylonites. Mafic garnet granulites have only trace amounts of K-feldspar but are otherwise similar to the felsic granulites. Metagabbros contain mainly clinopyroxene, orthopyroxene and plagioclase with minor garnet and ilmenite. Locally, the metagabbro is overprinted by dark and light colored ultramylonites that consist of 2-5 µm sized clinopyroxene, orthopyroxene and plagioclase (light) and additionally with µm-sized ilmenite (dark). All rock types are crosscut by pseudotachylites, which show a devitrified, glassy texture.

For all rock types bulk rock compositions were acquired from 0.5-1 kg of samples that was compared with microbulk analyses of ultramylonites and pseudotachylites, obtained by LA-ICP-MS analyses with a 100 µm spot size avoiding porphyroclasts. Major and trace element contents of pseudotachylites are very similar to the bulk rock composition, indicating that no element fractionation takes place during the frictional melting. In contrast, the light colored ultramylonites are depleted in FeO, MgO, TiO$_2$, HREE, Nb and Zr in comparison to their host, indicating that porphyroclastic ilmenite, garnet and zircon were not included in the deformation process. In contrast, the dark colored ultramylonites have the same TiO$_2$, Nb and Ta contents as the bulk rock, indicating that ilmenite has been dismembered as well during the deformation. FeO-, MgO- and HREE-concentrations in the dark colored ultramylonite are higher than in the light colored ultramylonite but lower than in the bulk rock, showing partial abrasion of the garnet porphyroclasts.

The mineralogy of the ultramylonites indicates fluid-poor conditions at upper amphibolite facies during deformation. We propose that the formation of ultramylonites and pseudotachylities are related to different strain rates of deformation. Deformation during earthquakes leads to frictional melting and pseudotachylites formation without element fractionation. The very fine grain size of the ultramylonites suggests a viscous granular flow deformation process. The most intriguing feature is the alternating sequence of light and dark ultramylonites that display different compositions. The light ultramylonites show the highest fractionation of elements with garnet and ilmenite as residual porphyroclastic phases and is interpreted to have formed at lower total strain and affecting mostly the felsic minerals. The dark colored ultramylonites abraded also ilmenite and partly garnet, interpreted to represent events of higher strain. The alternation of ultramylonites thus represent multiple relative fast viscous deformation events in the lower crust. Structural relationships indicate that all the described tectonites formed in the same regime, which indicate fast deformation (seismic) alternating with fast viscous deformation (slow slip events?) formed during initial exhumation of the rocks from lower crustal levels, likely during Triassic and/or Jurassic extension.
In terms of volume, the metasedimentary sequences of the Ivrea-Verbano Zone (IVZ) constitute the largest amount of lithologies in the continental crustal section. This metamorphic sequence consists mainly of metapelites/metapsammites and metabasites, with numerous lenses of metacarbonate rocks. The metamorphic grade of the crustal section increases progressively in P-T conditions, from amphibolite to granulite facies, with increasing crustal paleo-depth. Lithologies involved in this high-temperature metamorphism have been subjected to different equilibration processes that modified them to the extent of losing their original sedimentary or magmatic features. Although this effect poses problems in determining their origin, it is particularly difficult for metabasites (Leake, 1964). The metabasites that occur in amphibolite facies consist of numerous layers intercalated between siliciclastic metasediments; the paragenesis of these amphibolites is variable, sometimes showing several Al-rich minerals such as garnet and biotite as indicators of interaction with surrounding metasediments. According to several studies, the amphibolites also interacted with carbonate, forming calc-silicate rocks. Despite this heterogeneity, pioneering studies identified a possible MORB signature from geochemistry (Sills and Tarney, 1984; Mazzucchelli and Siena, 1980).

In this contribution, we report new constraints on the geochemical affinity of the protoliths for all amphibolitic paragenesis using trace elements and isotopes of the bulk rocks. To understand the primary signature of amphibolite and the metamorphic changes in these lithologies, we collected amphibolites from borehole 1B-Ornavasso of the DIVE project (Pistone et al. 2017). We selected 13 samples representative of amphibolite sequences following the different mineralogical parageneses, and one representative of siliciclastic metasediments (metapelites used as an end member). The selected samples of amphibolite are divided into four groups by mineralogy: (i) amphibolite in sensu stricto (Amph+Cpx+Pl±Qtz), (ii) garnet-bearing amphibolite, (iii) biotite-bearing amphibolite, and (iv) carbonate-rich amphibolite.

The results obtained from the characterization of bulk trace elements provided information on the geochemical affinity of the sequence, identifying that the sequence derived from two different protoliths with N-MORB to E-MORB affinity, respectively. Moreover, chemical information allowed us to trace back to the initial protolith, also highlighting how the initial geochemical signatures have been contaminated by various high-temperature metamorphic events that affected the amphibolite sequence. The Nd isotopes strongly indicated a mantle-derived source for the parental melt that formed the amphibolite. In contrast, Sr and Pb precisely tracked the interaction with other crustal lithologies, showing the overprinting of crustal signatures that occurred during the collisional and post-collisional metamorphism.

References:
Pistone et al. (2017) Sci Dril, 23, 47-56
Sills & Tarney DD (1991) Tectonophysics 107, 187-206
Melt-rock reaction control on magmatic underplating: evidence from the Ivrea
Mafic Complex (Italian Alps)
Mariani, D.1,2, Tribuzio, T.1,2,3, Liu, T.4, Renna, M.R.5, Wu F.-Y.4, and Zanetti, A.3

1National Institute of Oceanography and Applied Geophysics, Trieste (Italy). Corresponding author: dmariani@ogs.it
2Department of Earth and Environmental Sciences, University of Pavia (Italy)
3Institute of Geosciences and Earth Resources, National Research Council, Pavia (Italy)
4Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing (China)
5Department of Mathematics and Computer Sciences, Physical Sciences and Earth Sciences, Messina (Italy)

The processes leading to the building of the continental crust through magmatic underplating are fundamentally unknown, mainly because of the rare accessibility to deep level sections of the continental crust. The Ivrea-Verbano Zone from Italian Alps exposes the Permian Mafic Complex, an 8 km-thick gabbronorite-diorite batholith that intruded the lower continental crust during the post-Variscan transtensional tectonics. The Mafic Complex encloses several ultramafic bodies of magmatic origin, thereby enabling to provide new insights into the magmatic processes driven by emplacement of mantle magmas in deep crustal continental areas. Here, we present a petrological and geochemical characterization of the major cumulus ultramafic bodies exposed near the Balmuccia peridotite massif, within gabbronorites, and at the deepest levels of the Mafic Complex, within amphibole gabbros.

The largest cumulus ultramafic bodies from the Mafic Complex typically consist of a peridotite core, mostly dunitic in composition, and a websterite ring (e.g., Tribuzio et al., 2023; Mariani et al., 2024). The peridotite core generally includes websterite and/or gabbroic veins, and record a process of pervasive reactive melt percolation through an olivine-rich and spinel-bearing matrix, a pre-existing dunite or a melt-poor crystal mush. The growth of the websterite ring is attributed to a replacive mechanism, in response to a reactive melt percolation process associated with a high melt/solid ratio. The local occurrence of olivine-bearing websterite veins within the peridotite core document a process of focused reactive melt migration through the olivine-rich matrix. The formation of olivine-free websterite veins and gabbroic veins is related to melt penetration through narrow fractures.

Within a single cumulus ultramafic body, the peridotites, the websterites and the dykes provide a wide range of Nd-Sr-O isotopic signatures. We propose that the melts interacting with the olivine-rich matrix had previously undergone a magmatic evolution that at least locally implied assimilation of crustal material. The overall data provide evidence for involvement of primary mantle magmas with different compositions for the building of the Mafic Complex. This primary variability reflects a heterogeneous mantle source, which was likely related to a preceding mantle metasomatism event occurred during the Variscan orogenic cycle.

References:
Tribuzio R et al. (2023) Chemical Geology 619, 121315
The continental crust has a granodioritic average composition and its layering, marked by a felsic upper crust, an intermediate middle crust and a mafic lower crust, has been attributed to crustal differentiation. This differentiation results from liquid/solid segregation associated with partial melting and/or fractional crystallization, but its timing-duration and relationship with geodynamics are debated. In this contribution, I explore the geological record of Archean to Phanerozoic mid- to lower crustal sections to assess the duration of partial melting and the role of gravitational instabilities in the redistribution of material leading to crustal differentiation.

The protracted tectonic and magmatic record of cratons over the Archaean Eon has been classically interpreted in terms of long-lived shallow-dipping subduction or repeated mantle plumes. As an alternative, thermal modelling considering the secular decay of radioactive isotopes ($^{238}$U, $^{235}$U, $^{232}$Th, and $^{40}$K), responsible for heat production in the crust, shows that a generic 45 km thick Archaean crust might have had a Moho temperature above 900 °C before 3.5 Ga and that it might have remained partially molten for about one billion years. For the post-Archean period, convergent plate boundaries are invoked as the main sites of growth and differentiation of the continental crust. In the Mesoproterozoic Grenville Province, magmatic monazite and apatite in leucosome of migmatitic paragneiss that is part of the Allochthonous Belt yield dates ranging from 1080 to 1020 Ma and of 960 °C. The Allochthonous Belt with a shallow-dipping foliation is interpreted as the root of a past orogenic plateau exhumed by lateral flow and extrusion along its front and these petrochronological data indicate that the presence of melt lasted for about 60 My and was followed by cooling below 450 °C at a rate of 2 to 6 °C/My. In the Paleozoic the root of the Variscan orogenic crust exposed in the Ivrea Zone, U-Pb geochronology of monazite and zircon document a minimum duration for high-temperature metamorphism and partial melting of 30 Ma and possibly up to 70 Ma from at least 310 to 280 Ma. The decrease of U-Pb ages in metamorphic zircon and monazite from amphibolite to granulite facies (i.e. from the middle to the lower crust) is interpreted to record cooling and crystallisation of the Variscan orogenic root at the transition from orogenic collapse to opening of the Tethys Ocean. The Naxos crustal-scale migmatite dome, in the middle of the Aegean domain, exposes the former root of the Cenozoic Alpine orogenic belt and represents a key example to investigate the development of gravitational instabilities and their impact on crustal differentiation. Zircon grains from the migmatites record a succession of crystallization-dissolution cycles with a period of 1 to 3 My from 24 to 16 Ma. Granitic sills rooted in the migmatites and partially to totally transposed during dome formation are dated from 16 to 13 Ma, coeval with crustal extension and exhumation of the molten root of the Alpine orogenic belt. These features are attributed to convective and diapiric gravitational instabilities over about 10 My.

Thermal-mechanical models of the dynamics of a physically layered partially molten crustal root affected by basal heating shows a succession of gravitational instabilities. Gravitational instabilities initiate with local segregation of the buoyant versus heavier layers, followed by diapiric upwelling of buoyant pockets of aggregated less dense material. Convection starts when half of the crust has a viscosity lower than $10^{18}$ Pa.s, which is consistent with the viscosity of partially molten rocks. The size of the convection cells increases as the temperature rises in the crust. Some of the heterogeneous material is entrained in the convection cells with a revolution period of 1 to 3 My. However, most of the denser material accumulates in the lower crust, while the buoyant material segregates at the top of the convection cells and forms diapirs.

This synthesis shows that crustal roots might remain partially molten for several hundreds to several My and that grain to crustal-scale gravitational instabilities, triggered or coeval with tectonic processes or decoupled from it, might account for the redistribution of material leading to crustal differentiation.
The fate of accessory minerals during melting, Ivrea Verbano Zone
Pacchiega L.¹, Degen S.¹, and Rubatto D.¹,²

¹Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, luca.pacchiega@unibe.ch
²Institut des Sciences de la Terre, University of Lausanne, CH-1015 Lausanne

Accessory minerals, such as zircon and monazite, are key minerals for understanding lower crustal processes and for investigating the metamorphic history of high-grade terranes. Additionally, they are the main carriers of the heat producing elements (HPE) U and Th, therefore their spatial distribution has important implications for the thermal and physical evolution of the crust. Finally, the formation of these minerals in high-grade rocks is intimately linked with melting and melt migration.

We carried out a study of the accessory minerals in the Val d'Ossola metamorphic sequence, Ivrea Verbano Zone (IVZ). The rocks in Val d'Ossola represent a continuous lower crustal section from mid-amphibolite to granulite facies. The DIVE project (Drilling the Ivrea Verbano zone) has recently drilled two boreholes, DT-1A and DT-1B, which sample upper amphibolite facies (750° C, 7 kbar) and granulite facies (950° C, 11 kbar) metasediments and metamafics. A combination of field work, cored sample study and phase mapping of thin sections has been used to identify melting at different scales and metamorphic grades. Field mapping along the valley and the study of drilled samples show the presence of melting, melt accumulation and migration through dykes. SEM phase mapping of the distribution of zircon, monazite, apatite and allanite grains in melting domains in different rock types indicate that the HPE budget is primarily controlled by zircon and monazite at granulite facies, whereas allanite has a similar contribution to heat production as monazite in the amphibolite-facies samples.

U-Pb geochronology of zircon, monazite, allanite and titanite in different rock types and dykes along the metamorphic sequence show that gneisses and amphibolites have a relatively large spread of metamorphic ages between 280 and 260 Ma. The investigated leucosomes display narrower age distribution around 260 Ma. This demonstrates that high temperature metamorphism persisted for more than 20 Ma after the emplacement of the Mafic Complex (ca 285 Ma, Karakas et al. 2019). Allanite and titanite ages are in good agreement with zircon geochronology, demonstrating the robustness of these chronometers at upper amphibolite-facies conditions.

References:
Karakas O et al. (2019) Geology. 10.1130/G46020.1
Boosting the ultimate petrochronometer: the age of granulite-facies metamorphism in the Ivrea-Verbano Zone (NW Italy) determined through in-situ U-Pb dating of garnet

Bartoli, O.¹, Millonig, L.J.²,³, Carvalho, B.B. ¹, Marschall, H.R. ²,³, and Gerdes, A.²,³

¹Department of Geosciences, University of Padova, Via Gradenigo 6, 35131 Padua, Italy, omar.bartoli@unipd.it
²Department of Geosciences, Goethe-University Frankfurt, Altenhöferallee 1, 60438 Frankfurt am Main, Germany
³Frankfurt Isotope and Element Research Center (FIERCE), Goethe-University Frankfurt, Frankfurt am Main, Germany

Rates of melt production, extraction and crystallization, as well as scales of melt transfer and interaction with their residuum change continuously in migmatite and granulite, affecting the behavior of monazite and zircon as time capsules. Therefore, accessory mineral chronometers may be ambiguous and incomplete in providing an overview of the temperature–time evolution of high-grade metamorphic rocks.

In this study, we applied the novel technique of in-situ U-Pb dating of garnet (Millonig et al. 2020) to the archetypal lower continental crust of the Ivrea-Verbano Zone (IVZ), NW Italy. In the IVZ, the temporal relationship between granulite-facies metamorphism and mafic underplating has long been debated, because of the interplay between tectonic, magmatic, metamorphic and metasomatic processes over a period of more than a hundred million years. Garnet from mafic and pelitic granulites yielded U-Pb ages between 287.4 ±4.9 Ma and 280.1 ±12.4 Ma, overlapping the timescales proposed for the emplacement of the Mafic Complex (286–282 Ma; Karakas et al 2019).

A closure temperature ($T_c$) in excess of 800 °C had already been proposed for the U-Pb system in garnet by Mezger et al. (1989), which was subsequently estimated to be ≥1010 °C by Dahl (1997). This very high $T_c$ has found support from the recent study of Shu et al. (2024), showing the preservation of garnet U-Pb ages during subsequent short-lived (5–10 Myr) UHT (1100 °C) metamorphism. The lack of a mix of old and young ages and the lack of any large scatter of datapoints away from the regression line in the Tera-Wasserburg plot, together with the P growth zoning, unequivocally rules out partial recrystallization as a widespread process affecting the IVZ granulitic garnets. Therefore, the garnet U-Pb dates obtained in this study are interpreted to reflect growth ages.

These results indicate that the thermal climax in IVZ granulites was caused by mafic underplating and concomitant asthenospheric upwelling, rather than being inherited from the post-Variscan Carboniferous evolution. This study demonstrates the strength of garnet petrochronology in resolving complex tectono-metamorphic histories of high-grade terrains.

References:
Dahl PS (1997) Earth Planet Sc Lett 150, 277-290
Karakas O et al. (2019) Geology 47(8), 719-723
Millonig LJ et al. (2020) Earth Planet Sc Lett 552, 116589
Shu Q et al. (2024) Contrib Mineral Petrol 179:49
Trace element systematics in HT-UHT garnet – a case study from the Ivrea-Verbano Zone, Italy
Bhattacharyya, A.¹, Rubatto, D.¹,², and Hermann, J.¹

¹Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012, Bern, Switzerland
²Institute of Earth Sciences, University of Lausanne, Géopolis, 1015, Lausanne, Switzerland
Email: ankan.bhattacharyya@unibe.ch

The slow diffusivities of trace elements (TE) in garnet provides a valuable tool for investigating high to ultra-high temperature (HT-UHT) metamorphic processes occurring in the mid- to lower-crust. The amphibolite- to granulite-facies lower crustal section of the Ivrea-Verbano Zone (IVZ) in NW Italy provides an ideal natural laboratory to study such processes. The IVZ consists of two main units: (i) the Kinzigite Formation, which shows a gradual increase in metamorphic grade from amphibolites to granulite facies (~850-900 °C), and (ii) the Mafic Complex, which is a gabbro-noritic intrusion into the felsic rocks of the Kinzigite Formation, causing local UHT contact metamorphism (~1000 - 1100 °C) (e.g. Barboza and Bergantz, 2000).

This study investigates the two-dimensional distribution of TE in garnet crystals from the IVZ and aims to understand the behavior and relative diffusivities of TE under different garnet growth conditions and bulk rock compositions with increasing metamorphic grade. Samples previously studied by Ewing et al. (2013, 2014) and providing credible Zr-in-rutile temperature estimates were selected and mapped using a LA-(Q)ICP-MS raster mapping method (Markmann et al. 2024). Garnet from both the mafic and felsic bulk, show no major element zoning at these elevated temperatures. However, in one metapelite, bell-shaped Ca-zoning is preserved despite having peak Zr-in-rutile temperature of 910 ± 25 °C. In both metapelites and leucosomes, garnet Y + HREE zoning shows patterns typical of prograde garnet growth with a progressive decrease in concentration from core to rim. The TE zoning shows evidence of diffusional relaxation to varying degrees depending on the metamorphic grade, from which cooling rates can be estimated. In the garnet bearing metagabbro, the Y + HREE show a pattern opposite to that of the metapelites, i.e. an increase toward the rim, which could be due to reaction with the melt. The other minor elements, including Zr, Cr, P, V and Ti, exhibit a variety of zoning patterns in both the metapelites and metagabbros that appear less systematic.

The factors responsible for the observed zoning patterns in different bulk could be attributed to a number of processes including Rayleigh fractionation, peritectic growth, backreaction with the melt, recrystallisation. Furthermore, all of these processes could later be affected by diffusional modification. This dataset allows exploring the dynamic interplay of processes that contribute to the redistribution of TE beside diffusion mechanisms, under high-temperature metamorphic conditions. Additionally, this approach offers the potential to estimate relative diffusivities for the TE and slow-diffusing major elements such as Ca.

References:
Barboza SA, Bergantz GW (2000) J Petrol 41(8), 1307-1327
Markmann T.A. et al. (2024) Chem. Geol. 646, 121895
Emplacement and cooling history of the Anzola gabbroic sill – insights from U–Pb geochronology and thermal modelling (Val d’Ossola, Ivrea-Verbano Zone)

Langone, A.1,2, Corvò, S.1,2, Maino M.1,2, Beranoaguirre A.3, Kylander-Clark, A.R.C.4, Casini L., Piazolo S.6, and Daczko N.7

1Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy; antonio.langone@unipv.it
2Institute of Geosciences and Earth Resources of Pavia, C.N.R., Pavia, Italy
3FIERCE Frankfurt Isotope & Element Research Center, Goethe University Frankfurt am Main, Germany
4Department of Earth Science, University of California, Santa Barbara, United States
5Department of Chemistry, Physics, Mathematics and Natural Sciences, University of Sassari, Italy
6School of Earth and Environment, University of Leeds, Leeds, United Kingdom
7School of Natural Sciences, Macquarie University, NSW, Australia

Underplating of mafic magmas at the base of the continental crust or at higher structural levels may exert a strong control on the thermal evolution and rheology of the lithosphere. Mafic intrusions tend to facilitate continental extension by thermal weakening, but enhance crustal strength soon after they have cooled (e.g., Liu & Furlong, 1994). Therefore, a detailed characterization of the temperature-time path of intrusive bodies is fundamental for reconstructing the tectono-metamorphic history of the middle and lower crust.

Mafic magmatism in the middle-lower section of the Ivrea-Verbano Zone (IVZ) ranges from late Carboniferous to Jurassic (e.g., Klötzli et al., 2016, Denyszyn et al., 2018). The underplating of voluminous mafic intrusions, collectively known as the Mafic Complex, occurred during the early Permian and was accompanied by mostly coeval felsic magmatism and volcanism (e.g., Karakas et al., 2019). Minor mafic bodies emplaced at different crustal levels predate or postdate the Mafic Complex, making the evolution of the regional geotherm more complex.

Here we present a preliminary geochronological dataset from the Anzola gabbroic sill (Val d’Ossola), emplaced at the boundary between migmatites, towards SE, and granulites, towards NW. It is made of gabbroic rocks consisting of clinopyroxene and plagioclase with rare orthopyroxene. Amphibole is common while garnet has been rarely observed. Felsic segregations with a thickness ranging from a few cm up to 40 cm are also common. Gabbroic rocks are zircon-free and contain abundant apatite, conversely zircon and titanite are abundant within the felsic portions. The intrusion age of the Anzola gabbroic sill is still unknown. Hornblende Ar–Ar age of 247±7 Ma was obtained by Brodie et al. (1989) and interpreted as the cooling age of the sill intruded during the early Permian, coevally with the widespread lower crustal intrusives of the IVZ. Recent geochronological data revealed that the gabbroic rocks are bounded towards SE by a Triassic-Jurassic shear zone deforming mostly migmatites and minor mafic layers related to the Anzola sill (Corvò et al., 2022, 2023). In order to constrain the T-t path of the gabbroic sill we performed in situ U–Pb dating of zircon, garnet and apatite by LA-ICP-(MC)-MS. Preliminary results suggest an emplacement of the sill during early Permian, mostly coeval or slightly younger than the Mafic Complex (e.g., Karakas et al., 2019). Jurassic lower intercept ages obtained from apatite are indicative of either very slow cooling, or can reflect re-heating due to the hyperextension of the lithosphere as already documented by U–Pb data of rutile (e.g., Ewing et al., 2015). The geochronological results have been validated by thermal modelling using a 2D Finite Difference approach (Casini & Maino, 2018). In the experiments we simulate the incremental growth of the Mafic Complex and the Anzola sill testing: i) different duration of the magmatic activity, ii) variable growth rate of magmatic systems, and iii) different initial, pre-magmatic, geotherm. The results of numerical modelling show that mafic underplating related to the growth of the Mafic Complex produced a persistent thermal anomaly enhancing the regional geothermal gradient. A relatively slow, bottom-up incremental growth of the Anzola sill is however required to explain the local record of different geochronometers.
The classical, large-scale seismology definition of the lower crust can be traced back to works by Andrija Mohorovičić and Victor Conrad. Over the decades, the sharpness of the lower crust’s boundaries as well its characteristic physical properties have been deduced by applying various geophysical surveys. Among others, seismic reflectivity was an intriguing observation, triggering various explanatory models. Based on decades of initially single-, and increasingly multi-method geophysical surveys, a series of physical, chemical, and joint physico-chemical models of the lower crust have been built. However, the level of uncertainty on a number of characteristic parameters remains relatively high. Moreover, the difference in perspectives between geophysical and petrological descriptions of the lower crust is still striking, which is only partly due to the different spatial scales of analyses.

The geologically famous lower continental crust to mantle transition zone in the Ivrea-Verbano zone was an attractive area for geophysical studies in the past and remains to be so in the current DIVE project (Drilling the Ivrea-Verbano zone) funded by ICDP (International Continental Scientific Drilling Program) under expedition ID 5071. This interdisciplinary program offers an extraordinary opportunity to better compare the geophysical and petrological perspectives, and to close some of the gaps, both in terminology and spatial scales. Two scientific boreholes have been drilled between Autumn 2022 and Spring 2024, which continuously sample the upper part of the lower crust over 578.5 metres (hole DT-1B), and the lowermost crust over 909.5 metres (hole DT-1A). The borehole logging data is directly compared with lithological and petrological analyses, and, despite 1D sampling, reveal a much higher level of spatial heterogeneity than expected. These observations, and the various surface surveys allow us to begin the upscaling exercise. Results achieved by the time of writing point towards the conclusion that the deepest drilled portion has started sampling the crust-to-mantle transition, as many geophysical parameters (namely density) cannot be considered crustal any more. However, the transition zone has not been crossed, and from a petrological point of view, no mantle rocks (e.g. peridotite) have been reached.

A third borehole is planned in a later phase of project DIVE, to fully cross both the geophysical and the petrological crust-mantle transition. That borehole will sample for the first time the thickness of the continental Moho, for which we hitherto had only indirect observations and estimates of several hundred metres.
How does the crust differentiate and magmas hybridize in a collisional/post-collisional environment? A view from the Serre crustal section (Calabria, Southern Italy).

Bruand, E.¹, Biget, T.¹ ², Langone, A.³ Boyet, M.², and Caggianelli, A.⁴

¹Laboratoire Geo-Ocean, CNRS, Université de Bretagne Occidentale, France
²Laboratoire Magmas et Volcans, Université Clermont Auvergne, France
³Dipartimento di Scienze della Terra e dell’Ambiente, Università di Pavia, Pavia, Italy
⁴Dipartimento di Scienze della Terra e Geoambientali, Università di F Bari, Italy

In most collisional/post-collisional environments, the “pure” crustal melting endmember (S-type granite) is not the only observed type of granitoid. Instead, crustal sections often present a wide variety of granitoids with a hybrid mantle/crustal signature. The mechanisms of hybridization, though critical to understanding the chemical signatures in these rocks, are poorly understood. Previous authors have proposed that magmas hybridize at the base of the continental crust in the so-called Melting-Assimilation-Storage-Homogenization zone (e.g. Hildreth & Moorbath, 1988). In this zone, felsic crustal and mafic mantle magmas would mix and the resulting products are injected and emplaced into the middle and upper crust, forming granitoid plutons. More recently, Schwindinger & Weinberg (2017) proposed that in some crustal sections, the main hybridization mechanism might be driven by multiple interactions between different felsic melts in a purely crustal environment along the pathways to plutons.

Few regions in the world offer the opportunity to study hybridization and lower crustal processes in the field. One rare example of crustal reworking processes is found in the 26 km thick crustal sections exposed in Calabria (Serre and Sila massifs, Italy; Schenk, 1980; Rottura et al., 1990). These localities contain a variety of granitoids (e.g. calc-alkaline and peraluminous) and partially melted lower and middle crust samples (granulite- and amphibolite-facies) are present. They mainly formed and emplaced during the late stage of the Variscan orogeny at ca. 305-290 Ma, contemporaneously with the metamorphic temperature peak affecting the lower crust (Fiannacca et al., 2015).

Direct partial melting of the lower crust has long been referred to as the main mechanism to explain (i) the enrichment of incompatible elements in the middle and upper crusts and (ii) the mechanism of recycling crustal rocks. However, other studies of lower crust sections suggest that this mechanism may not be efficient enough because accessory minerals, which are important incompatible elements carriers, could be retained in the residue (Wolfram et al., 2018; Schwindinger et al., 2019). As such, the Serre massif (Calabria, Italy) is an ideal natural laboratory to study such process. Here, we aim to quantify the contribution of partial melting of the lower crust involving biotite-breakdown (T>800°C) to the hybridization of granitoids. Trace elements and Nd isotopic results obtained on accessory phases and whole-rock from metamorphic and magmatic rocks of this crustal section allow us to (i) characterize the accessory minerals of lower crustal rocks and test the influence of P-T variations on their chemistry; (ii) compare their signatures with those from middle-crust granitoids; (iii) test if partial melting processes preserve isotopic equilibrium at the whole-rock and accessory minerals scales and (iv) see if incompatible elements are effectively redistributed across the crustal section. Altogether, this study provides a comprehensive dataset to better quantify the crustal component in a collisional/post-collisional setting.

References:
Fiannacca et al. (2015) Lithos, 123-140
Rottura et al. (1990) Lithos 24, 97-119
Schenk (1980), CMP, 23-38
Petrographic characterization of partial melting of quartzo-feldspathic to mafic protoliths in the middle-lower crust during the Eburnean orogeny (Paleoproterozoic, West African Craton)

Bonzi, W.M.-E.¹,², Sourgou, O.², Ilboudo, H.², and Borst, A.M.³,⁴

¹Université Daniel Ouezzin Coulibaly, BP 176 Dédiouf, Burkina Faso, wiledio.bonzi@gmail.com,
²Laboratoire Géosciences et Environnement (LAGE), Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso
³Katholieke Universiteit Leuven, Celestijnenlaan 200 E, Heverlee 3001, Belgium
⁴Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium

The Garango-Tenkodogo migmatitic complex (south-East of Burkina Faso) is part of a granitoid-gneiss domain within the Paleoproterozoic West African Craton, where such domains alternate with meta-volcanosedimentary belts (Birimian). Both the granitoid-gneiss formations and the greenstone belts underwent greenschist to amphibolite facies metamorphism during the Eburnean orogeny (2200-2100 Ma). Here we describe petrographic features of the Garango-Tenkodogo migmatitic complex and discuss their implications on anatexis in the middle-lower crust.

The Garango-Tenkodogo migmatites form several metatexite lenses oriented NE-SW, extending 20-30 km in length and up to 8 km in width, and surrounded by dioritic to granodioritic facies. They are deformed by ductile to brittle shearing (folding, S/C structures, faults), and intruded by pegmatites containing biotite, garnet, tourmaline and micro-inclusions of Ta-Nb-U oxides. Paleosomes can be categorized in mesocratic layers, which includes leucosomes, and mafic melanocratic layers.

Mesocratic layers are composed of fine-grained quartz-feldspar-muscovite/biotite assemblages, with accessory epidote, garnet and abundant opaque minerals. Centimetric to decametric potassic leucosomes, characterized by thin biotite-rich and epidote-bearing selvages, are aligned with the foliation inducing a layered-structure. A transition to a net-structure is driven by cross-cutting collection veins and melt-filled shears. We distinguish two types of mafic layers: (i) biotite-rich layers composed of biotite, garnet porphyroblasts and rare amphibole, with the latter two partially retrograded to biotite and chlorite; (ii) amphibole-rich mafic layers composed of fine-grained grano-nematoblastic hornblende-plagioclase, with anhedral titanite(1), accessory garnet and apatite.

Leucosomes in mesocratic and biotite-rich layers consist of quartz, plagioclase, relics of biotite/amphibole, rare garnet, and accessory zircon. In amphibole-rich layers, leucosomes always intersect the mineral foliation and contain poikilitic hornblende, euhedral to sub-euhedral titanite(2), and actinolite-quartz intergrowths. Leucosome networks are connected between mesocratic and mafic layers, and are also observed in textural continuity with pegmatite veins. Hornblende is present in veins emanating from mafic layers, indicating a directional transport and suggesting local equilibrium of anatetic melt with the mafic layers.

Thus, the Garango-Tenkodogo migmatites result from the initiation of melting of a hybrid quartz-feldspathic to mafic protolith under amphibolite facies metamorphic conditions. The solidus is crossed for the quartz-feldspar assemblages, leading to the generation and segregation of melt. However, the absence of a layered structure in mafic layers suggests that anatexis is not reached in these layers, or partial melting occurred to a very low extent. Nonetheless, the occurrence of amphibole in leucosomes indicates that the anatetic melt was in equilibrium with the surrounding mineralogical assemblage. Fluid-saturation might be investigated as an explanation of brittle deformation and abundant pegmatite formation.
Mass balance during deep subduction and relamination of the felsic metaigneous crust (Variscan orogenic root, Bohemian Massif)
Janoušek, V.¹, Franěk, J.¹, and Vrána, S.¹†

¹Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic, vojtech.janousek@geology.cz

The HP–UHT (garnet–kyanite) felsic granulites, enclosing variably-sized bodies of Grt/Spl peridotites and Grt pyroxenites, are an iconic rock type in the former root of the Variscan Orogen of Central Europe (Moldanubian Zone). These granulites were interpreted as felsic metaigneous material of Saxothuringian origin subducted to the mantle depths (Janoušek et al. 2004, Kotková et al. 2011; Nahodilová et al. 2020) that later ascended through the subduction channel (Schulmann et al. 2014) or in the form of trans-lithospheric diapirs (Maierová et al. 2021) and were relaminated to the base of the overriding Moldanubian plate (Maierová et al. 2016). Correct understanding to what extent were individual elements remobilized during these processes is crucial to reconstruct the compositional, thermal, and rheological evolution of the Variscan orogenic lithosphere.

We studied the mass balance during the transformation of the Saxothuringian felsic metaigneous crust under (U)HP–UHT conditions, as well as their subsequent P–T evolution. The protolith composition was exemplified by the Ordovician–Silurian orthogneisses of the Fichtelgebirge and Eger complexes in western Bohemian Massif (Siebel et al. 1997, Wiegand 1997, Závada et al. 2018); the felsic granulites came from Blanský les, southern Bohemia (Vrána et al. 2013). Wedge plots (Ague 1994) indicate that the typical felsic granulites conserved most of their major-element inventory. Only Ca is enriched, and P depleted, in some samples. Among trace elements, many behaved as conservative e.g., transitional metals (Cr, Ni, Sc), Sr, REE and Ga and, for majority of samples, Zr, Hf and Nb. The Nd isotopic composition also overlaps with that of the protolith. Characteristic is ubiquitous strong depletion in Cs, Th and U; less compromised were Pb, Sn, W and Be. Wedge plots register small, if any, loss of Rb and the Rb–Sr isotopic system in many samples preserves the Ordovician equilibria. Still some granulites show too high \(^{87}\text{Sr}/^{86}\text{Sr\text{eq}}\) ratios (up to ~0.76), which can be explained by the up to 80% decrease in the \(^{87}\text{Rb}/^{86}\text{Sr\text{eq}}\) ratios in course of the Variscan metamorphism or distinct, much more evolved source. Peculiar Si-rich peraluminous granulites show very low Zr, Hf, Nb and Ta contents. These rocks were interpreted as residual after extraction of restite-rich melts that crystallized to hyperpotassic Plešovice granulites characterized by a mineral assemblage ternary Fsp–Grt–Zrn–Ap (Janoušek et al. 2007). Of particular interest is the fate of the radioactive elements U and Th that were stripped of the (U)HP–HT granulites to the surrounding lithospheric mantle. These metasomatized mantle domains became, soon thereafter, a source of ultra-K magmas, crystallizing to highly radioactive melasyenitic–melagranitic plutons and lamprophyre dykes spatially and temporarily associated with the granulites (Becker et al. 1999, Janoušek & Holub 2007, Janoušek et al. 2022).

References:
Janoušek V et al. (2007) J Geosci 52, 73–112
Maierová P et al. (2016) Tectonics 35, 1760–1780
Maierová P et al. (2021) Commun Earth Environ 2, 56
Schulmann K et al. (2014) Geology 42, 275–278
Vrána S et al. (2013) J Geosci 58, 347–378
Controls on the mobilisation of Li, Be, Sn, Cs, Ta and W during the melting of metapelites

Costa, E.O.¹, Argles, T.W.¹, Alt, I.⁴, Hoogendoorn, S.¹, Kriegsman, L.M.²,³, Kunz, B.E.¹, and Warren, C.J.¹

¹School of Environment, Earth and Ecosystem Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom, email: elisa.oliveira-da-costa@open.ac.uk
²Department of Research & Education, Naturalis Biodiversity Center, Darwinweg 2, 2333 CR, Leiden, Netherlands
³Department of Earth Sciences, University of Utrecht, Princetonlaan 8A, 3584 CB, Utrecht, Netherlands
⁴Department of Earth Sciences, Faculty of Science, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV, Amsterdam, Netherlands

Elements such as Li, Be, Cs, Sn, Ta, and W are critical for transitioning to green energy supplies and are needed for modern technologies. These metals are commonly mined from peraluminous granitoids and pegmatites, which form from sedimentary protoliths through mica melting reactions (Linnen et al., 2012). While previous studies on the genesis of deposits of these elements have focused on igneous processes, increasing attention is being given to how metamorphic minerals and melting conditions affect the mobilisation of Li, Be, Cs, Sn, Ta, and W. For instance, recent studies have shown that (1) there is a preference of critical elements for either muscovite or biotite and that concentrations in these minerals are often temperature-dependent (Kunz et al., 2022); (2) W and Sn mobilisation at different temperatures is related to the stability fields of muscovite and biotite, respectively (Zhao et al., 2022); and (3) Li and Be concentrations are affected by the peritectic phase that forms during biotite dehydration melting (Ballouard et al., 2023; Costa et al., in review). However, further data and/or constraints are needed to explore numerous still unclear aspects, such as the behaviour of critical elements in different minerals and melting reactions.

In this study, we investigated critical element concentrations in various minerals from high-grade terranes across the Variscan orogen in Europe. Also, we coupled our data with existing global datasets, phase equilibria and trace element modelling to understand what controls Li, Be, Cs, Sn, Ta, and W mobilisation to melt during the partial melting of metapelites. Our preliminary data show that: (1) cordierite is the main host of Li and Be, ilmenite and rutile are the main hosts of Ta, Sn and W, and biotite is the main host of Cs, and a secondary host of Li, Sn, Ta, and W (no muscovite present); (2) inclusions and matrix Ti-oxides show variable trace element concentrations; (3) Li concentrations in cordierite are temperature-dependent; and (4) biotite has higher W concentrations in low-pressure samples.

In combination with existing literature data, our results have important implications for Li, Be, Cs, Sn, Ta, and W mobilisation during partial melting, particularly in the light of melting reaction sequences at different pressures. These findings underscore the importance of metamorphic minerals and melting conditions and also highlight uncertainties and open questions for future research.

References:
Kunz et al. (2022) Geology 50(11), 1219-1223
Zhao et al. (2022) Geology 50(1), 121-125
Ballouard et al. (2023) Cont to Min and Petr, 178(11), 75
Costa et al. (in review)

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 956125.
Quantification of melt loss from restites by mass balance: problems and solutions
Stepanov, A.S.¹

¹State Key Laboratory of Geological Processes and Mineral Resources, Collaborative Innovation Center for Exploration of Strategic Mineral Resources, School of Earth Resources, China University of Geosciences, Wuhan 430074, China

The amount of melt extracted from restitic rocks is a major parameter for quantitative models of crustal processes (Vigneresse and Burg 2000; Brown 2013), however, its quantification is obstructed by the heterogeneity of sediments and uncertainty in melting history and the amount of fluid present during melting.

One approach, known as melt-reintegration, is based on the calculation of thermodynamic pseudosections coupled with assumptions on water content and melt extraction history (Bartoli 2017). The melt-reintegration methods require assumptions on fluid content, and commonly free fluid at the solidus is assumed. The caveat is that an increase in melt productivity with the addition of an external fluid as in case of fluid-fluxed melting, and a decrease in melt productivity due to dehydration are difficult to demonstrate with this method.

Another approach is mass balance, which utilizes the law of conservation of matter and, with assumptions about original rock composition, allows quantification of the mass transfer in metamorphic and metasomatic rocks. For mass balance, the selection of the protolith is crucial and a major source of uncertainty.

I will present a method that utilizes the systematic variations in the composition of the turbiditic metasediments and the low variability of the anhydrous metasediment-derived granitic melts to obtain estimates of melt loss from the restitic rocks with quantified uncertainties of melt loss proportion and protolith composition. The application of this method to the restitic rocks could reveal the heterogeneity of melt generation in granulites with unprecedented detail and offer new perspectives on the fate and role of hydrous fluids during anatexis. The application of the technique to some well-studied metamorphic complexes shows that melt generation could be highly heterogeneous, ranging from negligible to 70 wt% melt loss. The heterogeneous melt productivity could be caused by the redistribution of fluids generated by muscovite decomposition during heating. The estimated high melt productivity of some granulites is remarkable and implies that large volumes of granitic melt could originate from the anatexis of relatively small crustal blocks.

References:
Understanding the partial melting of Fe-rich granites: Using an example of the Southern Brasília Orogen, Brazil
Celis, E.¹ and Moraes, R.¹

¹Instituto de Geociências, Universidade de São Paulo, Brazil. edinsons@usp.br

In the Southern Brasília Orogen, there are outcrops of amphibole-bearing stromatic diatexite, with a crystallization protolith age dating back to the Statherian and metamorphism occurring during the Ediacaran, the latter event being associated with the assembly of Gondwana. This migmatite comprises medium-grained biotite-rich residue interlayered with coarse-grained leucosome of granitic composition, both of which contain amphibole, as a peritectic mineral. Selvedge with millimeter-thick biotite is present, which occurs between leucosome and residue. Moreover, schlieren inside leucosome is observed, representing melt flow direction orientation.

Petrography, whole-rock geochemistry, mineral chemistry analyzed by EPMA and LA-ICP-MS, and thermobarometry by phase equilibria modelling, amphibole-plagioclase, Zr in titanite, and quartz c-axis fabrics opening angles were used with the purpose to understand the partial melting and crystallization conditions in this rock. The results suggest water influx partial melting, evidenced by the presence of hydrated mineral such as amphibole as a peritectic phase. The water was controlled by the a syn-anatetic Jacuí Shear Zone, what is supported by the observed increase degrees in deformation and partial melting towards the direction of this geological structure.

During the prograde path, the breakdown of plagioclase produced a negative Eu anomaly in titanite and amphibole, increased Sr, Al and Ca, and a depletion of Ba and Rb in the system. Additionally, the breakdown of ilmenite and biotite contributed Ti and F to the system, and along with Ca, facilitated the crystallization of aluminous titanite (X_{Al} ≈0.25). The metamorphic peak was reached at 670—680 °C and 7—7.4 kbar under reduced conditions, with low oxygen fugacity, close to ΔQFM buffer, and X_{Fe} =0.9 in whole-rock, amphibole and biotite. This peak is characterized by a mineral assemblage of amphibole (hastingsite) + quartz + plagioclase (ab_{0.92} an_{0.07} or_{0.01}) + K-feldspar (ab_{0.06} or_{0.94}) + biotite (annite) with titanite + allanite + zircon + apatite + magnetite as accessory minerals in leucosome, residue, and schlieren. Later, during the cooling path, plagioclase was formed, resulting in positive Eu anomaly in plagioclase, K feldspar, and biotite. Moreover, the crystallization of the melt liberated water, generating selvedge at the leucosome-residue contact with a mineral assemblage of biotite + quartz + plagioclase + titanite + fluorite + apatite + allanite.

Challenges during the phase diagrams modelling have been presented, associated with appropriate a-x models for Fe-rich amphibole, alkali melt, and the effect of fluorine on the stability of amphibole and titanite, resulting in uncertainties due to this Fe-rich bulk-rock composition.
Granulite-facies metabasites represent a critical source of information on the lower continental crust. Elucidating the metamorphism of these rocks provides insights into the processes occurring at depth throughout Earth’s history. However, despite a century of geochemical studies examining high-temperature metabasites in the rock record, several aspects of their phase equilibria remain enigmatic, complicating the development of reliable thermodynamic equations of state for key phases (Forshaw et al., 2019).

This problem exists in part because studies of natural rocks primarily aim to establish the pressure-temperature (P-T) conditions of their respective region. Whilst researchers typically examine the relationship between the geochemical composition of different phases in pursuit of these P-T estimates, observations are necessarily restricted to the bulk composition of their rock and the P-T conditions at which the minerals equilibrated. In contrast, when developing equations of state, a rigorous understanding of how mineral compositions vary for a wide range of pressures, temperatures, and bulk compositions is required (Green et al., 2016). This study lays the groundwork for such an understanding of metabasic phase equilibria by compiling a database of geochemical analyses from studies of natural samples worldwide.

Whole rock compositions, phase assemblages, modal abundances, and mineral compositions have been extracted from over 100 studies in the literature to construct a database containing >1000 samples. First, we determine the median value for and examine the range in the major- and minor-element whole rock composition of metabasites. These values are then compared to several average basalt compositions from the literature. Second, we examine the range and variability in the composition of individual minerals and the partitioning of elements between them. Third, using wet chemical analyses from the database, we test the ability of current ferric iron estimation techniques to reproduce that measured in garnet, orthopyroxene, clinopyroxene, and amphibole. Future work will use this database to test the capability of new thermodynamic equations of state and make it available as a community resource.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 850530).

References:
Forshaw JB et al. (2019) JMG 37, 153–179
Green ECR et al. (2016) JMG 34, 845–869
Melting the mafic underplates of arc roots: an example from the arclogite xenoliths at Mercaderes, Colombia
Cesare, B.¹, Gianola, O.¹, and Ferri, F.²

¹Department of Geosciences, University of Padova, Via G. Gradenigo 6, Padova, Italy. bernardo.cesare@unipd.it
²EIT RawMaterials CLC South S.r.l., Via Ostiense, 92, Rome, Italy

Volcanic arcs above subduction zones are thought to be the principal locations where juvenile magmatic crust forms by underplating of basaltic magmas and is refined to become continental crust with an andesitic composition. During this refinement mechanism, the formation of dense garnet pyroxenites (arclogites, Lee and Anderson, 2015), represented by high pressure cumulates and restites after partial melting, leads to the delamination of the lower arc crust.

The Mercaderes-Río Mayo area in southern Colombia is the only known locality in an active volcanic arc where arclogitic xenoliths have been recovered. These xenoliths are entrained in the Granatifera Tuff, a late Cenozoic volcanic vent, and they mainly consist of garnet, clinopyroxene, amphibole, plagioclase, rarely scapolite, and accessory mineral inclusions of rutile, apatite, zircon, and quartz.

The arclogites are also characterized by the presence of melt inclusions (MI), which are mainly found within garnet, but can be also observed in amphibole, plagioclase, clinopyroxene and scapolite. The glasses measured for the MI in garnet and scapolite typically have SiO₂-contents >57 wt.%, ranging from andesite to rhyolite in composition.

Petrographic and geochemical investigations (Gianola et al., 2023) allowed to discriminate between cumulitic and restitic arclogites. In the latter, the presence of primary melt inclusions, along with the occurrence of quartz exclusively as inclusions in garnet, indicate that garnet is a peritectic phase and that the rock contained quartz at the onset of partial melting. Therefore, some arclogite samples are probably the residue after partial melting of a precursor metabasite protolith. To produce a rhyolitic melt and a garnet-bearing residue (but not an omphacitic pyroxene), the degree of melting must have been low and pressure must have exceeded 1.0 GPa.

Pressure and temperature conditions for the studied arclogites were estimated by intracrystalline geothermometry, elastic geothermobarometry, phase equilibria modelling and classical Fe–Mg exchange between garnet and clinopyroxene. Results mainly fall within the range 960-1150°C and 1.6-1.9 GPa for most samples.

We suggest that the investigated arclogites derive from the root of the active Colombian volcanic arc, where differentiation processes from mantle-derived melts and lower crust anatexis occur in close association. This is one of the first and most straightforward examples of the reworking of the sub-arc crust by partial melting, with production of felsic melts and a highly residual and dense restitite.

References:
Gianola O et al. (2023) J Petrology 64, 1-24
Partial melting is the key factor in intracrustal differentiation and in the transfer of many critical elements from the deepest continental crust to shallower levels via granitoids. These processes are recorded in deeply exposed migmatite and granulite domains of former mountain belts. Migmatites (here: patch migmatites, metatexites and diatexites derived from pelitic to psammopelitic protoliths) are sites of melt production, but are also affected by melt influx from deeper levels. Additionally, the restitic units and crystallizing melts frequently react at microscale and outcrop scale, leaving a retrograde overprint on peak mineral assemblages. By contrast, most granulates are more melt-depleted and commonly show less restite-melt back reaction, although (i) some areas do show spectacular examples of that process; and (ii) migmatization may locally occur in mafic protoliths (e.g., Fischer et al. 2021), indicating incomplete melt loss in those lithologies.

This presentation combines observations from a number of well-exposed mid- to lower-crustal sections (Hercynian Pyrenees; Proterozoic Sweden and SW Finland; Neoproterozoic Sri Lanka) to highlight the interplay between pro- and retrograde processes, melt influx and outflux, and their effect on element transfers. The observations are summarized in a conceptual model for melt-mediated fluid transfer and recycling at the scale of samples, outcrops, and crustal sections. I propose to subdivide crustal sections structurally below the solidus (here: metapelitic melt-in isograd) into three migmatite zones, each with its own characteristics, and an underlying granulite domain, and to distinguish four retrogressive stages. The model serves as the foundation for quantifying element fluxes by a mass balance approach, including trace element redistribution. For example, in some samples, retrogression can be fully attributed to fluids released from in-situ melts, whereas others require an additional external fluid source. At a larger scale, the model can explain why some migmatite terrains are more enriched in incompatible elements than average crust. At crustal scale, it may help to improve balanced cross-sections by taking volume changes due to melt loss, transfer, or gain, into account.

This project is part of the FluidNET research and training network on fluid-rock interaction, funded by the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 956127.

References:
Fischer SL et al. (2021) Prec Res 355, 106074
The volatiles recycling in continental subduction revealed by melt/fluid inclusions in the Himalayan orogen. 
Cong, T.¹, Xiao-Ying, G.¹, ², Min, J.¹, and Yu-Xin, D.¹

¹CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China  
²CAS Center for Excellence in Comparative Planetology, University of Science and Technology of China, Hefei 230026, China

Continental subduction-zone is the main location of recycling of subducted continental crust materials. Melts and fluids produced by the dehydration and partial melting of subducted crust are important carriers of volatiles such as H₂O and CO₂. However, the main volatiles recycling mechanism in subduction-zone is poorly understood. Here, we investigate well-preserved primary nanogranitoids (NGs) and multiphase fluid inclusions (MFIs) in peritectic garnets from the Cona migmatite in eastern Himalaya, China. Microstructural features suggest that the coexisting NGs and MFIs are formed during the growth of peritectic garnet. NGs are mainly composed of muscovite, quartz and K-feldspar/potassium-rich melt. Melt composition obtained by in-situ experimental re-homogenization of NGs is consistent with the composition rationed by Raman 3D mapping. The peraluminous granitic melt shows a crustal contribution, probably due to incongruent melting of muscovite. According to Raman quantitative analysis of water content in glasses, these melts contain variable H₂O contents (1.08-7.78 wt.%) but almost no CO₂. However, MFIs are mainly composed of H₂O, CO₂ and CO₃²⁻ well constraining oxidation conditions of partial melting. These inclusions indicate that the deep subduction-zone is rich in volatiles as H₂O and CO₂. We propose that these volatiles are derived from subducted continental crust materials. They not only promote the partial melting of crustal rocks, but also improve the rheological properties of subduction-zone and promote exhumation. Our study makes a critical influence on recycling of crustal materials and dynamic evolution of subduction-zone.

References: 
Borghini A et al. (2023) Sci. Adv. 9, eabp9482.  
Stabilization of Earth’s most enduring tracts of continental crust over billion-year timescales requires that the crustal inventory of heat-producing elements (HPE), U, Th and K, are concentrated in the upper crust. Continental lower crust is depleted in U, Th and LREE relative to average continental crust and yet contains significant volumes of felsic metasedimentary rock whose protoliths are enriched in HPE, principally Th, as a result of weathering processes [1,2,3]. Major differences exist between the compositions of peraluminous metasediments that have been metamorphosed at ultrahigh temperatures (UHT), >900 °C, and those that attained lower peak temperatures [e.g., 4]. UHT metasediments exhibit strong depletions in U, Th, LREE, similar to average continental lower crust, whereas non-UHT compositions are more similar to upper continental crust. Removal of small weight fractions, <10 %, of ultrahigh temperature granitic melt from peraluminous metasediments can explain the observed depletions in U, Th and LREE in average lower crust as well as the excesses of U, Th observed in average upper crust. Effective crustal differentiation and ensuing mechanical stability of felsic continental crust requires UHT metamorphism. Such ‘UHT refining’ of felsic materials may operate in the lower crust of continental arcs and Himalayan-like continental collisions. Applied to the Neoarchean, the latter mechanism accounts for the formation of large tracts of strongly differentiated crust during this time period.

References:
Granulite-facies migmatites recording extensive in situ anatexis of metapelites (Namaqua Metamorphic Province, South Africa): geochemical-mineralogical characterization of leucosome and melanosome fractions, and modelling of melt generation

Reinhardt, J.1, Mayne, M.J.2, Leetz, A.1, Bailie, R.1, and Jöns, N.3

1Department of Earth Sciences, University of the Western Cape, Bellville, 7535, South Africa, jreinhardt@uwc.ac.za
2Department of Earth Sciences, Stellenbosch University, Matieland, 7602, South Africa
3Department of Geology, Mineralogy and Geophysics, Ruhr University Bochum, 44801 Bochum, Germany

Common pelitic rock compositions experience partial melting at upper amphibolite- to granulite-facies conditions. Hence, migmatites are a common feature in granulite-facies terrains. Due to the potential mobility of the melt at or near peak pressure-temperature conditions, the proportion of the leucosome fraction of a migmatite may or may not be representative of the original melt fraction or melt composition in relation to the associated residual material. Once a significant proportion of melt has been generated, it is generally assumed that the melt effectively separates and migrates away from the site of anatexis.

Field observations on an unusual migmatite in the granulite zone of the Bushmanland Domain in the Grenville-cycle Namaqua Metamorphic Province of southern Africa suggest that much of the anatectic melt has remained in place, forming a rock with tightly intermingled leucosome and melanosome at relatively constant proportions, at a scale of a decimetre and beyond. The leucosomes form S-L-aligned elongate patches, contained within a melanocratic matrix. Although the leucosome proportion is high (between 40 and 60 vol%), there is very little local interconnectivity between adjacent leucosome patches, with no clear evidence for either larger-scale melt accumulation, or for melt escape channels along or across the rocks’ structural anisotropy.

A geochemical-mineralogical study reveals leucosome compositions which are less siliceous and which have a higher maficity compared to the melanosomes. The melanosome is characterized by the abundance of cordierite, biotite and sillimanite, while the quartz-feldspar-rich leucosome contains a substantial amount of garnet. The presence of accessory hercynite with quartz in both fractions underlines the high grade of metamorphism (as well as low pressures). Bulk geochemical analyses of the migmatite point to a pre-anatectic metapelitic protolith composition. The leucosomes show no evidence for the involvement of externally-derived melts. Garnet plays a critical role for the major and trace element distribution between leucosome and melanosome, as it is concentrated in the former, lowering the Si content relative to the bulk rock while significantly increasing FeO, MnO, Sc and HREE.

Initial thermodynamic modelling of migmatite compositions using whole-rock data and mineral analyses, assuming that phases in the leucosome and melanosome represent the last equilibrium assemblage (garnet, cordierite, biotite, sillimanite, plagioclase, K-feldspar, quartz), give conditions of 3.8-5.2 kbar and 720-764°C. These temperatures are lower than previous literature estimates, and apparently also at variance with the observed hercynite-quartz assemblage. This discrepancy is presently investigated further. Otherwise, calculated garnet compositions and proportions match well with those of the analysed garnets, and the observed high proportion of melting of at least 40 % is also reproduced in the model. Thus, while melt segregation into leucosome and melanosome fractions was effective at the small scale, this did evidently not result in significant melt migration and corresponding melt loss from the system. Possible critical factors are the lack of interconnectivity between the leucosome patches and the high proportion of peritectic garnet lowering the density contrast between magma and the surrounding melanosome matrix.
Post-peak temperature loading of ultrahigh temperature granulites of the Eastern Ghats Province, India – evidence from microstructures and phase equilibria models
Chatterjee, S.¹*, Dey, S.¹, Ghosh, A.¹, and Gupta, S.¹

¹Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India
*Corresponding author. Email address: sandrochatterjee2@gmail.com

The complexity of rock microstructures, and their relationship with metamorphism in ultrahigh temperature (UHT) terranes is the key to a more fundamental understanding of the mechanical behaviour of UHT granulites. In the Eastern Ghats Province (EGP) of India, UHT metamorphism of crustal rocks, during which peak temperatures exceeded 900°C, are commonly assumed to be related to collisional tectonics associated with assembly of the supercontinent Rodinia (Das et al., 2017). However, the relationship between shortening structures and peak metamorphism in the UHT domains of this terrane are yet to be studied in detail. In this study, we combine field, microstructural and metamorphic information from the celebrated UHT locations around Araku and Anantagiri in the EGP, to reveal an undocumented aspect of the tectonic history of the terrane.

In the study area, an early gneissic foliation (S₁) related to deformation D₁, is refolded into regional- and micro-scale isoclinal recumbent folds during a second deformation event, D₂. Results from phase equilibria modelling of UHT rocks reveal that the peak assemblages sapphirine + quartz + spinel + cordierite + ilmenite + melt (garnet-free domain), and sapphirine + quartz + cordierite + ilmenite + melt (garnet-bearing domain) stabilized in the P-T range of 6.7-7.6 kbar and 1100-1250° C. The S₁ foliation is interpreted to comprise the assemblage sapphirine + quartz; coronae of sillimanite around sapphirine and layers of orthopyroxene subsequently separate the sapphirine from matrix quartz. This texture can be modelled by the reaction sapphirine + quartz = orthopyroxene + sillimanite, indicating an isobaric cooling, consistent with the long-lived UHT orogeny in the EGP. This episode of isobaric cooling was followed by the formation of garnet, biotite and rutile, which indicates an up-pressure, down-temperature post-UHT (counter clockwise; CCW) retrograde path following isobaric cooling from peak temperature conditions. Inclusions of sapphirine, coronal sillimanite and cordierite are prominent within garnet.

The sapphirine-bearing fabric preserves micro-scale isoclinal folds correlatable with the post-UHT shortening deformation, with coronal sillimanite being co-folded with sapphirine.

Microstructural studies using Electron Backscatter Diffraction (EBSD) analysis of the UHT fabric indicate that the crystallographic preferred orientation (CPO) patterns of sillimanites coronal to the micro-folded sapphirine domains are associated with the activation of intracrystalline slip systems in sillimanite, with [001] (010) as the dominant, and [001] (100) as the subordinate slip systems along with systematic CPO development in the folded sillimanites. This confirms that D₂ isoclinal folding post-dated the UHT metamorphic peak temperature. The CPO patterns of cordierite are also well developed and are associated with dominant [001] (010) slip. BC type CPO of orthopyroxene is also documented from these domains. The distribution of (001), (010) and (100) axes of cordierite in the UHT fabric indicate that this post-UHT D₂ deformation is correlatable with thrusting. CPO patterns of quartz are indicative of rhomb <a> slip during thrusting; CPO patterns of sapphirine are associated with [100] (010)/ [100] (001) slip systems and can also be correlated with post-UHT thrusting.

This study therefore documents the operation of a shortening event (D₂) that post-dates UHT metamorphism in the Araku and Anantagiri areas of the EGP. Since the terrane was cooling but experiencing increasing pressures concomitant with thrusting at high temperatures, collision-related shortening deformation must have post-dated UHT deformation. This tectonic sequence is not yet reported from UHT granulite terranes across the globe.

References:
Das E et al. (2017) Geol Soc Lond 457, 141-170
Controls on the spatial focusing of melt formation in migmatites
White, R.W.¹, Palin, R.M.², and Powell, R.³

¹School of Earth and Environmental Sciences, University of St Andrews, Scotland
²Department of Earth Sciences, University of Oxford, Oxford, UK
³School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Australia

The presence of porphyroblasts as reactants or their formation as products of metamorphic reactions imparts a spatial control on reaction progression where reaction may become focussed around the porphyroblast phase. Reaction progression then requires the diffusion of elements in and out of this site along gradients in chemical potential (White et al., 2008) and can result in a specific spatial distribution of phases. At high temperatures, reactions commonly produce silicate melt and can result in melt formation being spatially focused within a rock, producing in situ formation of melt pools and, as a consequence, leucosome. This process was investigated semi quantitatively in White et al., (2004), in which quantitative pseudosections were combined with qualitative chemical potential diagrams to constrain the diffusion directions of different elements and to explain the preserved leucosome structures around porphyroblasts. Development of quantitative techniques for producing chemical potential diagrams means that this process can now be investigated quantitatively. The formation of in situ leucosome spatially focused around porphyroblasts will be illustrated using an example from Mt Stafford in central Australia where the porphyroblastic phase is a reactant in the melting reaction, and an example from Round Hill in Broken Hill, NSW where the porphyroblastic phase is a product of the melting reaction.

References:
Phase equilibria and P-T estimation in basic granulites
Wei, C. Wang, B., and Dong, J.

School of Earth and Space Sciences, Peking University, Beijing, China

The Metamorphic evolution in basic granulites is dominated by amphibole dehydration melting (ADM). Experimental studies suggest that ADM in basic rocks may start from ~800 ºC and terminate to 1000–1100 ºC. However, phase modelling indicates that ADM in basic rocks should initiate from the wet basic solidus under high amphibolite-facies conditions. ADM in basic granulites is governed by the reactions Amp = Cpx + Opx + Pl + Ml (melt) in the garnet-absent domains generally below 10 kbar, and Amp + Pl = Grt + Cpx + Ml (melt) in the garnet-present domains generally above 10 kbar. There have been great challenges for retrieving the peak temperature conditions of basic granulites especially for the rocks that are subjected to UHT conditions. On the one hand, most basic granulites share the common mineral assemblages of Cpx + Opx + Pl ± Amp and Grt + Cpx + Pl ± Amp ± Qz under normal granulite and even UHT granulite-facies conditions from 800 ºC to even 1100 ºC. The diagnostic UHT indicators such as sapphirine cannot appear in them under an equilibrium state unless in local domains with the former presence of kyanite. On the other hand, the peak mineral assemblages in granulites are differently modified during the post-peak cooling evolution with the growth of amphibole by consuming retained melt and anhydrous minerals. This cooling evolution is terminated at a fluid-absent solidus with temperatures that depend on the amounts of retained melt. Moreover, most conventional Fe-Mg thermometers are proved to be unavailable for UHT granulites because they can only record the close temperature of the Fe-Mg exchange mostly at 800 ± 50 ºC even under subsolidus conditions.

Herein we summarize the following characters of basic granulites that are significant for constraining their peak conditions using pseudosection modelling.

(i) Basic granulites with minor amounts of amphibole tend to record elevated solidi with temperatures even great than 900 ºC, suggesting that the rocks represent residues dominated by anhydrous minerals after a great mass of melt loss. In contrast, basic granulites with large amounts of amphibole tend to record solidi with reduced temperatures, suggesting that the peak temperature is lower or a great mass of melt is retained.

(ii) UHT basic granulites may contain Ti-rich amphibole generally with Ti > 0.25 (pfu), and Ti-Amp is a good thermometer in the assemblages with Ti-oxides.

(iii) Clinopyroxene in UHT basic granulites is predicted to be a augitic with high AlT (tschermak component). The AlT in Cpx is a good temperature indicator in the assemblage Cpx + Opx + Pl + Amp, and both P-T dependent in the garnet-bearing assemblages. However, the AlT in Cpx is dependent in the bulk-Al2O3 in the assemblage Cpx + Opx + Pl after the disappearance of amphibole.

(iv) The anorthite content of plagioclase (XAn(Pl)) is a temperature indicator in the two-pyroxene assemblages, and mainly pressure-dependent in the high-pressure garnet-bearing assemblages. However, the XAn(Pl) is highly influenced by the water content that assumed for calculating P-T pseudosections.
After UHT, extreme greenschist facies retrometamorphism in Anápolis-Itauçu Complex, Brazil
Moraes, R.¹, Kawai, G.S.D.¹, and Campos Neto, M. C.¹

¹Instituto de Geociências, Universidade de São Paulo, Brazil. rmoraes@usp.br
²Instituto de Geociências, Universidade de Brasília, Brazil.

The Anápolis-Itauçu Complex is a Neoproterozoic, Gondwana related UHT granulite belt, where UHT rocks are reported. Occurrence of sapphirine + quartz, Al-rich orthopyroxene + sillimanite + quartz, quartz, + spinel + rutile + ternary feldspar, Al-rich orthopyroxene + Mg-rich garnet, wollastonite + scapolite (Moraes et al., 2002; 2007). These mineral assemblages occur only in a few places, but are geographically widespread, and this attest its regional character. Close to Petrolina de Goiás, in the eastern border of the complex, there is an outcrop where a migmatite looking rock crops out. It is composed of garnet-bearing leucosome and the residue layers are composed of porphyroblasts of pyrope-rich garnet (alm₃₃prp₄₃sps₁₃grs₃ and XMg of 0,45) with inclusions of spinel and Zr-rich rutile (2800 ppm) plus intensely retrogressed matrix. The rest of matrix is composed of kyanite, chloritoid, intergrowths of muscovite and chlorite, a typical greenschist facies mineral assemblage. Zr-in-rutile temperatures varies a lot, but maximum values are 860 °C, taken in a large inclusion grain, but that presents clear signs of retrogression. Thermodynamic modelling was made in two different chemical model systems KFMASH and NCKFMASTO, in two different P-T windows, 4 to 11 kbar and 450 a 650 °C and 5 to 13 kbar and 800 to 1000 °C. In the first set of modellings, the retrometamorphic conditions were the target and no field with kyanite + chloritoid was generated when NCKFMASTO is used, but in the simpler KFMASH, a small field is generated. P-T conditions of 5.5 and 480 °C are inferred using chloritoid composition. An exercise was made with thermodynamic modeling, in which, with the present bulk composition, a pseudosection was calculated for a high temperature window to check with any diagnostic UHT mineral assemblage would be produced. For temperatures higher than 840 °C, up to 1000 °C, in most pressure window, the dominant mineral assemblage is quartz + ternary feldspar + garnet + sillimanite + rutile + melt. Locally variations occur with ilmenite and spinel at lower pressures, replacing garnet and rutile. The mineral assemblage quartz, + spinel + rutile + ternary feldspar is the one that occurs in the largest area in the complex. This kind of retrometamorphism occurs in other places in the Anápolis-Itauçu Complex and it is related with late shearing and transport of the rock to upper levels of continental crust. Locally, rocks composed of staurolite and kyanite, instead of chloritoid are observed, indicating intermediary P-T conditions of this retrometamorphism.

References:
Moraes R et al. (2002) J. Pet. 43, 1673-1705
Moraes R et al. (2007) Rev. Bras. Geoc. 37, 11-17
Analysis of tectonic activity from modern thermobarometry during the late Archean in the English River Subprovince, Ontario Canada
Schroeder, H. and Holder, R.

University of Michigan, Earth Department, hyschroe@umich.edu

Earth is the only planet in our solar system with evidence of active plate tectonics. Determining when plate tectonics originated on Earth could provide insight into why Earth is the only planet in our solar system with plate tectonics, if other planets once had plate tectonics, and potentially how life began on Earth due to the interconnectedness of Earth’s systems. The late Archean is of particular interest for tectonic research, given the large changes that occurred at that time, such as emergence of the first true continents, compositional changes of igneous rocks, and deposition of the first modern-like passive-margin sediments. These changes have been interpreted as recording the onset of plate tectonics. However, the lack of evidence for Archean subduction and subduction-related rocks makes the hypothesis of modern-like Archean plate tectonics ambiguous. To address whether plate tectonics of any form occurred in the late Archean, I am studying the English River Subprovince (ERSP) which is a 1000 km linear metasedimentary belt in the Superior Province. The Superior Province is interpreted to have formed either by accretion of exotic arc systems in a modern-like plate tectonic system or by large-scale non-plate-tectonic rifting (extension) then reassembly (contraction) of a pre-existing continent above a gigantic mantle overturn. Modern thermobarometry of amphibolite to granulite facie metasedimentary units from the ERSP provide higher constraints on peak metamorphism than previously documented. East of Lac Suel pressure and temperature range from ~790-820°C and ~5.5-6.0 kbar in the north to ~810-860°C and ~4.6-7.0 kbar near the boundary with the Winnipeg River subprovince (WRSP), and in the area near Ear Falls conditions are ~790-860°C and ~3.9-6.0 kbar. Previous estimates from Fe-Mg exchange thermometry provided estimates of ~600°C in the north, and ~725°C at the contact between the ERSP and the WRSP and range of pressure from 3.5 to 6.0 kbar. The new estimates of peak metamorphism are more congruent with peak conditions of other subprovinces within the Superior Province, with the Pikwitonei domain ranging from 8.0-10.0 kbar, the Ashuanipi and Minto subprovinces ranging from 6.0-8.0 kbar, and the Quetico belt reaching 770°C and 6.0 kbar suggesting the Superior Province, as a whole, did not form through plate tectonics.

References:
Stern, R.J., 2005, Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time: Geology, v. 33, p. 557.
Anorthosites are a geological enigma, not only because they are constituted by vast areas of monomineralic feldspar, but because they were mostly emplaced during the Proterozoic. There are two main hypotheses for their formation: i) magmatic differentiation in moho-level intrusions; ii) extensive partial melting of basal crust after orogenic thickening. Trace element inversions applied to anorthositic massifs in the Grenville Province of eastern Canada (Bédard, 2009), imply the melt from which the plagioclase accumulated resulted from extensive melting of a depleted arc tholeiitic crust at high pressures, leaving behind a residue composed of pyroxene, rutile or ilmenite, abundant garnet, but no plagioclase. As these melts rise into the crust, they would intersect the plagioclase liquidus and form large masses of plagioclase with uniform compositions. Although appealing, this model does not elucidate why anorthosites are much more abundant in the Proterozoic.

In this study, we test whether metamorphic conditions in the Proterozoic, which were likely transitional between the high-temperature/low-pressures typical of the Archean and low-temperature/high-pressure regimes of the Phanerozoic, could explain the temporal distribution of anorthosites. Partial melting of mafic rocks of various compositions was simulated by phase equilibria modeling. Results demonstrate that representative Archean Style Oceanic Lithosphere (ASOL) composition could have melted to high degree (>30%) with abundant residual garnet and no residual plagioclase at pressure-temperature conditions slightly deeper and hotter than the high-pressure granulite conditions recorded in Grenvillian lower crustal exposure (1.5-2.0 GPa at 800-900 °C). In contrast, modern basalts stabilize residual plagioclase to higher pressures and do not generate as much melt nor garnet. The Proterozoic would thus have combined the conditions required for the subcreation of ASOL slabs below the base of the crust where the temperatures was high enough to generate the melts parental to anorthosites. Once all ASOL had been destroyed or consolidated into craton at the end of the Proterozoic, Earth was too cold and the conditions required for production of anorthosites had vanished.

References:
Hydration of lower continental crust and impacts on Colorado Plateau elevations: Insights from xenolith studies from the Navajo Volcanic Field (Colorado, Utah, Arizona, New Mexico) and the Henry Mountains, Utah, USA

Mahan, K.H.1, Sims, J.R.1, Gasnier, B.2, Litton, S.D.3, Lipper, C.1, Newell, D.L.3, Goncalves, P.2, and Farmer, L.1

1Geological Sciences, University of Colorado Boulder, 2200 Colorado Ave., Boulder, CO, 80309, USA, mahank@colorado.edu
2Laboratoire Chrono-Environnement, Université de Franche-Comté, 16 Route de Gray, 25030 Besançon, France
3Geosciences, Utah State University, 4505 Old Main Hill, Logan, UT, 84322, USA

Laramide-aged metasomatic effects on the composition and physical properties of western North America lithosphere are still poorly known. One proposed mechanism for producing some of the modern 2 km elevation of the Colorado Plateau is lithospheric hydration (Humphreys et al., 2003; Jones et al., 2015), where mantle and crustal density reduction induced isostatic elevation gain. This is an update on xenolith studies of these processes in central Colorado Plateau crust. Xenoliths from the Oligocene Navajo Volcanic Field (NVF) from the Four Corners region have a range of hydration textures but commonly retain enough unaltered portions to quantify both pre-hydration (M1) and syn-hydration (M2) P-T conditions and densities. M1 conditions (Proterozoic) range from 0.5 to 1.2 GPa and 650 to 1050 °C and those for M2 are 400-500 °C at similar pressures. This is consistent with a Proterozoic Moho T near 1000 °C and near 600 °C in the late Cretaceous, the latter being closer to modern estimates for the interior of the plateau derived from Pn velocities. Hydrogen isotope data from secondary phases (e.g., actinolite, zoisite, muscovite) in >20 samples, and the calculated composition of the water that was in equilibrium with these minerals (δ2H -50 to +5 ‰ vs. VSMOW), along with late Cretaceous Th-Pb dates from M2 monazite in one xenolith (Butcher et al., 2017), are consistent with a fluid source from a shallowly subducting Farallon slab. Our xenolith-based estimates of the hydration-induced surface elevation change suggest that felsic lithologies have minimal impact (less than +100 m if 20-25 km of hydrated lower crust were that composition) whereas intermediate and mafic lithologies would induce higher values of up to about +1000 m. The latter compositions are probably more important since published seismic studies and model crustal columns suggest relatively mafic plateau deep crust. These values of predicted surface elevation gain encompass the 300-1000 m range from prior studies that are based on model bulk crustal compositions and geophysical density models (Porter et al., 2017; Levandowski et al, 2018; Worthington et al., 2024). The Oligocene Henry Mountains laccolith complex is ~150 km NW of the NVF and provides a new opportunity to evaluate the spatial extent of crustal hydration across the plateau. The xenoliths are dominantly mafic and textures indicate that some have early pyroxene and/or garnet with amphibole reaction rims suggesting a history involving hydration prior to upper crustal emplacement.

References:
Butcher LA et al. (2017) Lithosphere 9, 561-578
Jones C et al. (2015) Geology 43, 355-358
Levandowski W et al. (2018) Geosphere 14, 1150-1164
Porter R et al. (2017) Tectonophysics 712-713, 221-231
Worthington JR et al. (2024) Journal of Metamorphic Geology, DOI: 10.1111/jmg.12772
Zircon coupled dissolution-precipitation replacement in granulites: nature and experiments
Daczko, N.R.\(^1\), Piazolo, S.\(^2\), Halpin, J.A.\(^3\), Asimus, J.L.\(^{1,3}\), Gazi, J-A.\(^1\), and Ezad, I.S.\(^1\)

\(^1\)School of Natural Sciences, Macquarie University, Sydney, Australia
\(^2\)School of Earth and Environment, University of Leeds, Leeds, United Kingdom
\(^3\)Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia

Zircon geochronology provides essential insights into the rates and durations of high-temperature geological processes. However, some zircon datasets exhibit a continuum of near concordant ages without distinct age populations, often interpreted as reflecting variable radiogenic Pb loss or protracted geological events. Coupled dissolution-precipitation replacement has been proposed as a mechanism to explain complex age datasets (e.g., Halpin et al., 2020; Varga et al., 2022; Wang et al., 2022; Spier et al., 2022, 2024).

We conducted melt-zircon reaction experiments to show that short-term exposure of zircon to natural intermediate and mafic melts (0.9 GPa, 1100–1180 °C) can alter zircon geochronology. Experiments with Mud Tank zircon fragments reveal that within 6 hours to 3.5 days, most fragments show microstructural and chemical modifications at boundaries, with U-Pb ages smearing over one hundred million years (c. 764–647 Ma). This indicates that coupled dissolution-precipitation replacement can obscure the true age and duration of geological events.

Complementary research on the Pembroke Granulite, New Zealand, and the Mawson Charnockite plutonic complex, East Antarctica, supports these findings. Zircon from high-strain zones and melt-reaction halos in the Pembroke Granulite shows dissolution modifications, micro-porosity, and disrupted zoning, resulting in smeared ages over tens of millions of years. Similarly, zircons from the Mawson Charnockite exhibit porosity and reaction interfaces linked to trace element and Pb mobility, producing apparent age arrays spanning hundreds of millions of years (c. 1000–500 Ma). These studies highlight that zircon modified by coupled dissolution-precipitation in granulite rocks may not reliably record geological histories, emphasizing the need for detailed microstructural analysis to interpret zircon geochronological datasets accurately.

References:
Halpin JA et al. (2020) Lithos 105363, 1-12
Spier AS et al. (2022) Gond Res 105, 262-289
Spier AS et al. (2024) Precam Res 404, 1-27
Varga J et al. (2020) Lithos 106872, 1-22
Wang W-(RZ) et al. (2022) J Pet 63, 1-30
Past granulite facies metamorphic events revealed by U-Pb and Hf isotope systematics of zircon

Shumlyanskyy, L.V. 1,2,3

1Institute of Geological Sciences of the Polish Academy of Sciences, Senacka 1, Krakow, Poland, Lshumlyanskyy@yahoo.com
2School of Earth and Planetary Sciences, Curtin University, Perth, Australia
3M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation, Palladina ave. 34, Kyiv, Ukraine

The Dniester-Bouh Domain of the Ukrainian Shield comprises granulite-facies granitoids intercalated with mafic-ultramafic granulites and various supracrustal rocks. This assemblage was formed during three episodes of juvenile crustal growth, at ca. 3.8, 3.0-2.7, and 2.1-1.9 Ga. The last granulite facies metamorphic event occurred at ca. 2.0 Ga and affected the SW part of the Shield, while the rest of the Shield experienced amphibolite-facies metamorphism. This event overprinted mineral assemblages and masked evidence of the previous geological history of the rocks. Its deciphering is not a trivial task since high-grade metamorphism has reset the isotope systematics of all minerals in the rocks.

We report the results of the U-Pb and Lu-Hf isotope study of zircon from the oldest (ca. 3.8 Ga) rocks (enderbites) in the Ukrainian Shield, which crop out in the Middle Bouh area (Claesson et al., 2015; Shumlyanskyy et al., 2021). Although the high-grade metamorphism has compromised the U-Pb isotope systematics of zircon, in combination with Hf isotopes it can be successfully used to decipher the pre-metamorphic history.

Zircon from the studied enderbites reveals complex internal structures. Three crystal growth events can be identified, including euhedral cores with fine oscillatory zonation, wide overgrowth, and thin outer rims that can be either bright or dark in CL images. Cores and so-called “granulite-type zircons” forming the football-shaped equant crystals belong to the 3.8 Ga and 2.8 Ga age populations, whereas most of the rims were dated at ca. 2.0 Ga. The available (insufficient) trace element data does not allow for distinguishing between the zircons belonging to different age groups. Neither zircon’s appearance can be unequivocally used to attribute the particular crystal to one of the age populations.

The distribution of the analytical results on the U-Pb concordia diagrams demonstrates that they generally form three linear patterns: between 3.8 Ga and 2.8 Ga; 3.8 Ga and 2.0 Ga; and 2.8 Ga and 2.0 Ga. We interpret those patterns as Pb-loss trajectories caused by two granulite-facies metamorphic events. Hf isotope data supports this interpretation. Around half of the results plot close to the Pb-loss line at the εHf vs. age diagram. They all have the same Hf isotope composition irrespective of their apparent U-Pb age, meaning that the Pb-loss is the sole reason for the age variations. Analytical spots are more or less evenly distributed on this line starting at ca. 3.8 Ga, and down to ca. 2.0 Ga. However, at 3.0-2.7 Ga and 2.0 Ga some results deviate from the Pb-loss line towards more radiogenic (higher εHf values) compositions. These deviations are caused by some input of either juvenile material or radiogenic Hf expelled from Lu-bearing minerals during metamorphic recrystallisation. Thus, these deviating zircons record significant metamorphic or metasomatic disturbance of the rock that caused its recrystallisation and redistribution of radiogenic isotopes and allow the identification of such events, even though other isotope systems have been partly or completely reset.

This research is part of Project No. 2021/43/P/ST10/02283, jointly funded by the National Science Center and the European Union's Horizon 2020 Framework Program for Research and Innovation under Marie Sklodowska-Curie Grant Agreement No. 945339.

References:
Shumlyanskyy L et al. (2021) Precam Res 352, 106001
Partial Melting of Metasedimentary Rocks in the Deep Levels of Continental Arcs: Insight from the Late Cretaceous–Eocene North Cascades Arc, Washington, USA

Gordon, S.M.¹, Sauer, K.B.¹, and Miller, R.B.²

¹Nevada Geosciences, University of Nevada, Reno, Nevada, 89557, USA, staciag@unr.edu
²Geology Department, San José State University, San Jose, California, 95192

The incorporation and burial of metasedimentary rocks into the mid to deep crust of collisional orogenic belts and arcs can provide fertile material for the production of small, outcrop-scale partial melts to orogen-scale, leucogranite units and potentially flare-up events in continental magmatic arcs. In exhumed mid to lower crustal terranes, migmatitic paragneisses and orthogneisses are common, but it is not always clear if the leucocratic material formed in situ or whether it was generated at a deeper level and emplaced and subsequently deformed at its present position. The crystalline core of the Late Cretaceous–Eocene North Cascades continental arc, Washington, exposes upper-amphibolite-facies metasedimentary rocks and orthogneisses in addition to arc plutons. The ~9–12 kbar Swakane and ~8–10 kbar Skagit gneisses include metasedimentary rocks that are interpreted to have originated as forearc sedimentary rocks that were underthrust into the active arc system. The origin of migmatites within these two deeply exhumed units have been the focus of debate. To better understand the partial-melting history of metasedimentary rocks within the crystalline core of this ancient arc, seven ~5–35 cm thick, layer-parallel leucosomes and 6 dikes and other felsic intrusive material were collected for bulk chemistry analysis and split-stream, LA-ICP-MS U-Pb zircon geochronology and trace-element chemistry. Hf-isotope compositions were then obtained from a subset of zircons. The studied layer-parallel leucosomes were all strongly deformed and, based on their textures and shared deformation and interlayering with the host metasedimentary rocks, were interpreted as likely in situ melts. Crystallization ages of layer-parallel leucosome samples of the Skagit Gneiss range from ca. 69 to 48 Ma. In comparison, similar samples from the Swakane Gneiss have dates clustered tightly from ca. 73–66 Ma. The dikes and larger bodies of late felsic material that intrude the Swakane Gneiss crystallized from ca. 74–68 Ma. Many of the crystallization ages from the leucosomes and dikes from both units overlap with the timing of sediment incorporation. Two of the Skagit layer-parallel leucosomes yielded radiogenic zircon εHf values ranging from +11.9 to +8.8. Zircons from one of the Skagit leucosomes also yielded a very limited range of εHf, values of +6.1 to +3.4, despite grains from the metasedimentary rocks yielding more variable εHf values. Conversely, zircons from small bodies of non-deformed felsic material that intrude the Swakane had a wide range of εHf, values from +12.3 to -15.6, suggesting some sediment-source melt. The majority of the leucosomes did not contain apatite or monazite and overall had low P₂O₅ amounts (≤ 0.01 wt. %) despite the abundant apatite in Swakane and Skagit metasedimentary rocks. These results suggest that many of the strongly deformed leucosomes within the gneisses were not in situ melts from the host metasedimentary rocks, but likely were derived from a deeper, more radiogenic source. In this arc setting, the incorporation of the metasedimentary rocks to deep crustal levels with temperatures >650–800 °C did not result in significant partial melting and thus likely did not contribute to the observed arc flare-up magmatism.
Recent advances in geochronological techniques now allow the ability to efficiently decipher the timing and duration of geological processes in complex high-grade polymetamorphosed terranes. Here we revisit the central segment of the Mesoproterozoic Grenville Front Tectonic Zone, marking the southeastern boundary of the Archean Superior Craton. The zone exposes parautochthonous Archean rocks that underwent mid- to high-pressure granulite facies metamorphism of uncertain age. The granulite-facies metamorphic assemblages have been either interpreted as Archean and associated with the final stages of the Superior craton assembly, or as the result of Mesoproterozoic late-Grenvillian thrusting, based on cross-cutting relationships and traditional geochronology methods such as U-Pb zircon and 40Ar-39Ar mica dating. In this contribution, we provide new age constraints for granulite-facies metamorphic assemblages through multichronometer in-situ LA-QQQ-ICPMS dating within GFTZ migmatitic paragneiss, mafic granulites, and granulite-facies coronitic metagabbro, combined with in-situ trace element mapping.

Six samples, in which garnet shows bell-shaped and occasionally sharp and oscillatory lutetium growth zoning, yield garnet Lu-Hf isochrons with identical Archean dates of c. 2.6 Ga. Sparse analyses of material trend toward Grenvillian ages (c. 1 Ga) in one sample from which garnet shows lutetium zoning consistent with post-growth fluid-assisted disturbance. Semi-concordant coronitic metagabbros interpreted as metamorphosed diabase of Proterozoic dike swarms returned Lu-Hf garnet and U-Pb titanite c. 980 Ma growth ages, whereas all investigated GFTZ samples returned exclusively Mesoproterozoic Rb-Sr biotite cooling ages, notably a c. 920 Ma main population.

Overall, our results indicate that the widespread granulite-facies assemblages within the Grenville Front Tectonic Zone are dominantly Neoarchean in age, highlighting a rare exposure of Archean deep crust in the southeastern Superior Craton. Our results also confirm a granulite-facies Grenvillian metamorphic overprint that is almost exclusively expressed within the coronitic metagabbro dykes. It is remarkable that despite having reached mid- to high-pressure granulite facies conditions, the Proterozoic overprint did not cause recrystallization in Archean granulites and migmatites, perhaps pointing to some kinetic control on reactions in dry restitic lithologies. The results presented herein demonstrate the potential of in-situ isotopic geochronology on rock-forming minerals like garnet and biotite in disentangling the complex evolution of polymetamorphic terranes.
Garnet U–Pb dating as a robust petrochronometer for granulites
Marschall, H.R.1,2, Millonig, L.J.1,2, Beranoaguirre, A.1,2, Albert, R.1,2, Kutzschbach, M.2,3, Hezel, D.C.1,2, Schmidt, A.1,2, and Gerdes, A.1,2

1Institut für Geowissenschaften, Goethe Universität, Altenhöferallee 1, 60138 Frankfurt am Main, Germany
2Frankfurt Isotope & Element Research Center (FIERCE), Goethe Universität, 60138 Frankfurt am Main, Germany
3Institut für Angewandte Geowissenschaften, TU Berlin, Ernst-Reuter-Platz 1, 10587 Berlin, Germany

Orogenic processes typically proceed through a number of tectonic stages in which rocks are subjected to burial, heating, exhumation and cooling. The rates and durations of the prograde stages are commonly poorly constrained, because the minerals typically used for age dating mostly form late in the process during decompression and the onset of cooling, or because they possess closure temperatures that are lower than the metamorphic peak temperatures. In-situ garnet U–Pb geochronology is an emerging technique that has the potential of unraveling the prograde- and peak-metamorphic history with the extraction of pressure, temperature and temporal information from the same rock-forming mineral. It may thus make garnet the ideal petrochronometer.

At FIERCE, we perform garnet laser-ablation ICPMS U–Pb geochronological analyses of metamorphic garnet with typically ≤0.1 µg/g U (Millonig et al., 2020; Shu et al., 2024, Bartoli et al., 2024). A range of samples of (ultra-)high temperature (UHT) metamorphic granulites and of lithospheric-mantle garnet peridotite from several different localities have so far been investigated. The success of in-situ U–Pb dating of garnet by LA-ICPMS is compromised where garnet grain size is too small (or growth zones are too narrow), inclusions are too abundant, or where common-Pb concentrations are too high (i.e., U/Pb ratios are too low). Yet, many garnet samples, in particular in granulites and peridotites, pass this screening and yield robust age information. The precision of the recovered ages ranges from 1–3 % in many cases, which allows for a meaningful distinction of polynmetamorphic events and of different stages within individual orogenic cycles (Shu et al., 2024; Bartoli et al., 2024; Kotkova et al., 2024). High-resolution trace-element mapping, including U, Th and Pb is employed to interpret zones of garnet growth, resorption and cracking-healing events and to monitor the distribution of U–Th–Pb in the garnet grains vs. inclusions and other heterogeneities.

In some cases, garnet records distinct ages of several stages of metamorphism, and ages of older garnet growth zones are not reset during subsequent UHT metamorphism exceeding 900 ºC. Garnet U–Pb ages of lower-crustal granulites from the Kaapvaal Craton were not even reset by temperatures in excess of 1050 ºC, demonstrating that this geochronometer remains robust at the extreme end of crustal metamorphism (Shu et al., 2024). Similarly, garnet in mantle peridotite records ages of grains or growth zones that predate the onset of cooling by tens of millions of years (Millonig et al., 2023; Kotkova et al., 2024).

We conclude that the U–Pb system in garnet has an ultra-high closure temperature and that garnet U–Pb ages from crustal metamorphic rocks have to be interpreted as crystallization ages. LA-ICPMS garnet U–Pb dating provides accurate, precise and geologically meaningful insight into the timescales of prograde to peak metamorphism and the P–T–t history of polynmetamorphic terrains. This opens the door to investigating mountain-building processes, complementing the information from other petrochronometers, which mostly record the collapse and exhumation of orogens.

References:
Millonig LJ et al. (2020) Earth Planet Sci Lett 552, 116589
Shu Q et al. (2024) Contr Min Pet 179, 49
Bartoli O et al. (2024) J Petrol (accepted with minor revisions)
Millonig et al. (2023) EGU conf abstr EGU-11252
Kotková et al. (2024) emc2024 conf, Dublin, abstract
In-situ Lu-Hf dating of garnet: a novel new tool for granulite geochronology
Murphy, D.M.¹, Glorie, S.², Emo, R.B³, Schrank, C.E.¹, and Kamber, B.S.¹

¹School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, QLD 4000, Australia; david.murphy@qut.edu.au
²Department of Earth Sciences, University of Adelaide, SA 5005, Australia
³Institut für Geologie und Mineralogie, Universität zu Köln, Cologne, German

Geochronological studies in high-grade metamorphic terranes are essential for the temporal reconstruction of tectonic and associated magmatic events and to understand uplift histories. Typically, these studies deploy a variety of radiogenic isotope chronometers with different closure temperatures to reconstruct time-temperature evolution paths. Geochronometers based on rock forming minerals, such as garnet, are particularly attractive because of the wealth of petrological and geochemical information that can be gleaned from them.

Conventionally, garnet has been dated by hand-picking, digestion, chemical separation, and analysis of the U-Pb, Pb-Pb, Sm-Nd, and Lu-Hf isotope systems. Important tectono-metamorphic information has been obtained with garnet geochronology, particularly for constraining the timing of relatively high-temperature processes that are preserved thanks to the high closure temperatures (~600°C or higher) of these systems. However, solution-based garnet geochronology is not only time- and labour-intensive but the resulting multi-chronometer dates are also often complex. Complexities arise from mineral inclusions, elemental zoning, multiple generations of garnet growth, isotopic disequilibrium with the whole rock, and unexpectedly low parent/daughter ratios, yielding insufficiently radiogenic isotope ratios for precise dating. These factors can result in datasets devoid of chronological information, and, in the worst situation, potentially untrustworthy spurious age dates.

The development of Laser-Ablation Inductively-Coupled-Plasma tandem mass spectrometry (LA-ICP-MS/MS) has opened new opportunities for in-situ dating. The advent of Q-ICP-MS with reaction gas technology allows beta decay radiogenic isotope systems to be utilised for in-situ isotope analysis. For Lu-Hf, where Lu is effectively separated from Hf through reaction with NH₃, this allows for in-situ analysis of garnet (Glorie et al. 2024) and apatite and other rock forming and accessory phases. The technique is fast, and conventional LA-ICP-MS can be used to screen samples into those with sufficiently high Lu concentration and low common Hf, thereby avoiding the disappointment of unradiogenic Hf besetting the solution-based approach.

In this study, we present Lu-Hf data for large (>5 mm) chemically zoned garnets from Palaeoarchean granitoid gneisses from the East Pilbara Terrane (Wiemer et al. 2016) to assess if the garnet grew in one or more tectono-metamorphic event and to understand the post-magmatic history of deformed gneisses on the margin of a typical Archaean granitoid dome.

More broadly, we are participating in efforts to characterise a wider suite of garnet-bearing granulites, including lower crustal xenoliths from eastern Australia, to better understand the conditions that lead to favourable Lu/Hf systematics for dating. Our on-going work has highlighted the propensity of clinopyroxene, ilmenite, and rutile to sequester Zr and Hf and the strong incorporation of heavy REE into garnet, certainly in the absence of zircon, which is typical for refractory lower crustal mafic xenoliths. Study of these contrasting garnet-bearing lithologies is expected to provide useful constraints on expected garnet age and concentration of Lu and Hf in garnet that can provide reliable geochronological information.

References:
Emo RB et al (2023) Lithos 436, 106976
Simpsone et al (2021) Chemical Geology 577, 120299
Garnet Lu–Hf speed-dating reveals complexities in the metamorphic history of the Narryer Terrane, Western Australia
Tucker, N.M.¹, Kemp, A.I.S.¹, Hammerli, J.², Clark, C.³, Rankenburg, K.⁴, and Ribeiro, B.V.³

¹School of Earth Sciences, University of Western Australia, Perth, Australia; naomi.tucker@uwa.edu.au
²School of the Environment, Washington State University, Pullman, USA
³School of Earth and Planetary Sciences, Curtin University, Perth, Australia
⁴John de Laeter Centre, Curtin University, Perth, Australia

In situ Lu–Hf geochronology is a relatively new analytical technique that allows for rapid acquisition of age data from garnet in a petrographic context. This technique is significant as it allows the timing of peak metamorphism to be directly dated. When coupled with pressure–temperature (P–T) modelling, trace element partitioning with zircon and monazite, and in situ dating of these accessory phases in the same sample, a robust P–T–time history for the rock can also be reconstructed. This multi-mineral petrochronology approach is particularly valuable when investigating terranes with long, complex and cryptic metamorphic histories. Here, we present a campaign-style study to date garnet-bearing samples from across the Narryer Terrane in Western Australia.

Texturally, the analysed samples contain minerals that appear to coexist in equilibrium, and forward phase equilibria modelling indicates that these mineral assemblages formed at peak P–T conditions of 5.5–6 kbar and 880–920°C (Tucker et al., 2024). Zircon from the same samples suggest that peak metamorphism occurred at ca. 2690–2660 Ma though rare older analyses hint at an earlier metamorphic record with possible events at ca. 2800 Ma, ca. 3000 Ma and ca. 3300 Ma (Hammerli et al., 2018; Tucker et al., 2024). Preliminary data from this study reveal garnet ages that span one billion years (ca. 2900 to 1900 Ma), and an old metamorphic monazite component (to ca. 3100 Ma), providing evidence for multiple high-temperature thermal pulses both before and after the main Neoarchean event. Metamorphic events in the Narryer Terrane are seemingly heterogeneously recorded by garnet, zircon and monazite, each encapsulating different information about the high-temperature Archean–Paleoproterozoic terrane evolution. While Neoarchean metamorphism is generally agreed to have been the most pervasive high-temperature event to have affected the Narryer Terrane, it did not completely obliterate all evidence for earlier metamorphic episodes.

References:
Tucker NM et al. (2024) Journal of Metamorphic Geology 42, 425-470
Ultra-fast metamorphic reaction during regional metamorphism

Liu, J.H.1,2,3, Lanari, P.2, Tamblyn, R.2, Forshaw, J.B.2, Piccoli, F.2, Zhang, Q.W.L.1,2,3, Dominguez, H.2, Markmann, T.2, Reynes, J.2, Hermann, J.2, Rubatto, R.2, Li, Z.M.G.3, Jiao, S.J.1, and Guo, J.H.1

1State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences; Beijing, 100029, China; liujiahui@mail.iggcas.ac.cn
2Institute of Geological Sciences, University of Bern; Bern, 3012, Switzerland
3College of Earth and Planetary Sciences, University of Chinese Academy of Sciences; Beijing, 100049, China

Constraining the timescales of metamorphic processes is critical to understanding geodynamics on Earth. It is generally accepted that the rates of metamorphic mineral reactions in nature are significantly slower than in laboratory experiments. For example, the timescales of mineral growth during regional metamorphism (0.04–17 million years) are five to eleven orders of magnitude longer than in laboratory experiments (hours to months). This discrepancy is attributed to several rate-limiting mechanisms affecting metamorphic reactions in natural settings (Baxter, 2003). However, it may also because rapid mineral growth cannot be accurately measured by radioisotope dating in natural rocks due to insufficient temporal resolution. Geospeedometry is a high-temporal resolution technique used to infer timescales from the inversion of chemical diffusion profiles, which offers great potential to probe short durations on the order of days to years.

Here we report an ultra-fast metamorphic reaction within a year, constrained by diffusion modeling on frozen-in chemical gradients of trace elements preserved in metamorphic garnet across a corona texture in a metagabbro during regional metamorphism. This metagabbro is partially transformed into granulite preserving coarse-grained igneous plagioclase and clinopyroxene. The igneous relics are partially resorbed and locally replaced at their boundaries by fine-grained three-layered corona, including amphibole + quartz + plagioclase + garnet ± orthopyroxene ± clinopyroxene ± biotite. Metamorphic P-T conditions were estimated to be ~800 C and 0.8 Ga, and metamorphic age measured to be ~1845 Ma. Trace element compositional maps (Lanari and Piccoli, 2020; Markmann et al., 2024) measured on this metagabbro show a systematic decrease of HREE + Y content across garnet grains from the igneous clinopyroxene region to the igneous plagioclase region. This trend was interpreted as HREE + Y elements being released from igneous clinopyroxene and diffusing in the intra-crystal melt medium driven by chemical potential gradients, then inherited and frozen in the garnet grains during their growth. To estimate the diffusion timescale, a global multi-profile & multi-element diffusion modeling was developed in MATLAB, inverting a diffusion timescale of 11 (+260-10) days from the HREE + Y chemical diffusion profiles, which constrain a duration of metamorphic reaction.

These timescales are much shorter than those previously obtained from nature, but are similar to laboratory-based results. Based on these findings, we propose that ultra-fast pulses of mineral reaction may be common in nature under fluid/melt-present conditions as elemental diffusion and mass transport in an aqueous fluid or melt are significantly faster than those in the mineral lattice. However, rapid mineral reaction is challenging to identify due to insufficient temporal resolution of radioisotope dating and difficulty preserving chemical gradients during subsequent metamorphic reactions in common rocks. This study offers a conceptual basis to link ultra-fast geological events, such as seismicity, to changes in density, volume and strength caused by ultra-fast metamorphic reactions.

References:
Lanari P & Piccoli F (2020) IOP Conf Ser Mater Sci Eng 891, 012016
Markmann et al. (2024) Chem Geol 646, 121895
Mechanism to generate hot crust in Earth’s Middle Age
Jiao, S.J.1,2,†, Jiang, H.H.1,2,†, Mitchell, R.N.1,3, Zhao, G.C.4,5, and Guo, J.H.1,2,3

1State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2Innovation of Academy for Earth Science, CAS, Beijing 100029, China
3College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Chinese Academy of Sciences, Beijing 100049, China
4Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong
5State Key Laboratory of Continental Dynamics, Northwest University, Xian 710000, China
Emails: jiaoshujuan@mail.iggcas.ac.cn

The enigmatic Earth’s Middle Age (1.8-0.8 Ga) is a period of environmental stasis and reduced tectonic activity, characterized by thin orogenic crust, both hot metamorphism (i.e. ultrahigh-temperature metamorphism) and magmatism (i.e. A-type granite and anorthosite), and slow cooling and exhumation rates (e.g. Brown and Johnson, 2019; Sobolev and Brown, 2019; Spencer et al., 2021; Tang et al., 2021; O’Neill et al., 2022; Zou et al., 2023). Here, we newly compiled a dataset of >10,000 detrital zircon, and found secular change of Ti contents show a consistent trend with metamorphic T/P and whole-rock Zr contents of felsic magmatic rocks, of which all proxies certify hot crustal condition in the Middle Age, with a peak at ca. 1.1-1.0 Ga during the Grenville-aged orogenesis. The synchronous rapid drops of the three proxies at 1.0-0.9 Ga signal the subsequent transition to cold subduction.

Mechanism to generate the hot crust in the Earth’s Middle Age is ambiguous. It was suggested that the incomplete breakup of the Columbia supercontinent to form Rodinia might have caused mantle warming below supercontinent (Coltice et al., 2009). By combination of geological records during the Mesoproterozoic, mantle warming is difficult to occur in Middle Age and unlikely the major reason. It was also proposed that the lack of sediments was the reason to reduce plate tectonic activity and therefore cause subduction slowdown in Middle Age (e.g. Sobolev and Brown, 2019). While, it is true subduction slowdown may have caused warm thermal conditions on slab top, whether it can influence the Moho conditions underlying the overriding plate (e.g. back-arc settings) is not straightforward. Hot, wide, continental back-arcs were then proposed to explain the enigmatic magmatic and metamorphic records in Middle Age (Roberts et al., 2023). Thin lithosphere due to the model can explain the formation of UHT metamorphism, A-type granites and massif anorthosites that dominated in Middle Age, but geological features of these rocks do not support a wide back-arc setting, instead suggest post-collisional extension or delamination. Therefore, here is a new model, the extensive post-collisional orogenic collapse due to lithospheric delamination is proposed to explain the generation of hot and thin crust in Middle Age, and the subsequent switch to cold ambient mantle after ca. 1.0 Ga.

References:
O’Neill et al (2022) Scientific Reports 12, 10460
Roberts et al (2023) Tektonika 1, 1
Tang et al (2021) Science 371, 728-731
Earth has been cooling by up to 100°C/Gyr since c. 3 Ga, as confirmed by compositional variations of primary mantle melts through time (Herzberg et al. 2010). However, before c. 3 Ga it is unclear whether heat loss was in balance with the remaining internal (primordial and radiogenic) heat or whether the mantle was warming to a peak at c. 3 Ga (Labrosse & Jaupart 2007). During metamorphism, crustal rocks follow $P$–$T$–$t$ paths that record the changing spectrum of transient geotherms during orogenesis, which we parameterize using the thermobaric ratio ($T/P$ at the metamorphic peak). $T/P$ is characteristic of the tectonic setting (Brown & Johnson 2018), and insofar as metamorphic pressure can be translated to depth, can be viewed as a proxy for the transient thermal gradient recorded at the metamorphic peak ($T/P ∼ T/z$).

Counterintuitively, the highest $T/P$ ratios, which are recorded by ultrahigh temperature (UHT) granulites, occur in the Mesoproterozoic and are unrelated to the maximum in mantle $T$. However, this should not be a surprise: to understand Earth’s thermal history we model the mean secular trend of mantle $T$, whereas the $T/P$ of UHT granulites reflects the specific (local) contributions from crustal (radiogenic) and mantle heat, and the amount of thickening and/or thinning of the lithosphere driving metamorphism. Thus, secular cooling of the mantle and metamorphic $T/P$ have different length scales and times frames. So, why do the highest $T/P$ values occur in the Mesoproterozoic rather than the Neoarchean? Notably, metamorphic pressures were lowest in the Mesoproterozoic (Brown & Johnson 2018), indicating thin lithospheric settings for UHT metamorphism, and cooling rates of metamorphic rocks were slower (Brown et al. 2022; Zou et al. 2023).

The size of the largest fragments of continental lithosphere increased from Archean cratons to Paleoproterozoic ‘continents’, and from late Neoarchean/early Paleoproterozoic supercratons (Superia and Sclavia) to late Paleoproterozoic and late Mesoproterozoic supercontinents (Columbia and Rodinia). During assembly of a supercontinent, the pace of plate tectonics may slow, decreasing the rate of global cooling, whereas during breakup, plate tectonics may speed up, increasing global cooling; a continental aggregate insulates the underlying mantle, potentially increasing temperature (Lenardic 2017). Depending how the transition from Columbia to Rodinia was accomplished, a continental aggregate, at a minimum the Nuna megacontinent (the keystone of Columbia; Wan et al. 2020), may have been largely maintained throughout the Mesoproterozoic. A plate slowdown during the Proterozoic proposed by Sobolev & Brown (2019) and modeled by O’Neill et al. (2022) demonstrates that such a scenario could have generated higher mantle temperatures, with mantle-derived melts emplaced at the Moho or into the lower crust, enabling the production of anorthosites and Rapakivi granites, and giving rise to the highest thermobaric ratios of UHT granulite metamorphism. Thus, the late Archean peak in mantle $T$ reflects the beginning of secular cooling of Earth, whereas the Mesoproterozoic peak in $T/P$ reflects a slowdown in the pace of plate tectonics and the supercontinent cycle.

References:
Brown M et al. (2022) J Geol Soc 179, jgs2022-050
Herzberg C et al. (2010) EPSL 292, 79–88
O’Neill C et al. (2022) Sci Reports 12, 10460
Wan B et al. (2020) Sci Adv 6, eabc5491
Zou et al. (2023) EPSL 607, 118055
Granulites as products and filters of basalt passage through continental crust
Kamber, B.S.1, Emo, R.B.2, Murphy, D.T.1, Gust, D.A.1, and Conway, E.J.1

1School of Earth & Atmospheric Sciences, Queensland University of Technology, Brisbane, Australia; balz.kamber@qut.edu.au
2Institute of Geology and Mineralogy, University of Cologne, Germany

Steady state geotherm temperatures at the base of typical (30-35 km thick) stable continental shields are below 500°C and even with higher radioactive heat production of the past, rarely exceeded 650°C. Yet globally, the deepest crustal xenoliths sampled by basalts that erupted through such crust are mostly granulites and not amphibolites. This implies formerly elevated temperatures that could have arisen from earlier crustal thickening, elevated heat flux into the base of the crust through thinned mantle lithosphere, emplacement of magma into the lower continental crust (LCC), or a combination of these processes. Petrological studies of LCC xenoliths that have advocated partial melting and igneous underplates have typically focused on two endmember scenarios.

Firstly, prograde conductive heating at quite invariant pressure, leading to partial melting with sequential extraction of critical melt fractions. In this scenario, the remaining granulite is a residue strongly depleted in incompatible and heat producing elements (HPE). Secondly, fractional crystallization of a stalled basaltic underplate in the LCC. The resulting granulite is seen as a cumulate rock, depleted because pyroxenes and olivine do not accommodate HPE. The distinction between these two scenarios has proven difficult due to non-unique geochemical pathways and lack of preserved original structures in the well-equilibrated granulites (Rudnick & Taylor, 1987). Here we argue, based on comparison of observed mineralogy and geochemistry of LCC granulites with outputs from thermodynamic modelling (Emo & Kamber, 2022), that most studied granulite xenoliths do not represent endmembers but are products of melt-solid interaction in the LCC, according to the reaction:

Resident LCC minerals + Incoming high-Mg basalt melt -> Modified minerals (granulite) + Escaping modified melt

At high melt/solid ratios, the first main effect of the above reaction is to exhaust the LCC in hydrous resident phases (mostly amphibole, quartz and titanite) instead precipitating pyroxenes, ilmenite or rutile, and garnet. This yields refractory, HPE-depleted two-pyroxene-plagioclase or plagioclase-clinopyroxene-garnet granulites. The second effect is seen in the modified basaltic melt, with lower MgO and elevated alkali-element concentration at a largely unchanged or slightly lower SiO₂ content than the original underplate. Such ‘basalts’ are technically sodic trachybasalts – hawaiites – common constituents of intercontinental ‘basalt’ provinces. In our model, the lowering in both MgO and SiO₂ arises from the crystallization of pyroxenes with SiO₂ of 52-57 wt% rather than olivine at LCC pressures. Depending on depth (i.e., <~10 kbar), the melt become enriched or depleted in TiO₂, according to which Ti-phases participate in the reaction. The surprisingly monotonous LCC granulite mineralogy and chemical uniformity of global erupted intracontinental ‘basalt’ provinces (e.g., Niu, 2021), other than TiO₂, suggest that the extent of melt/solid interaction could be buffered. One parameter capable of governing the extent of melt-solid interaction is the density contrast between solids and the modified liquid. Maximum contrast (highest eruptibility) is achieved with hornblende exhaustion and maximum pyroxene or clinopyroxene-garnet crystallization in the solid before excessive plagioclase formation. At this stage of melt modification, the MgO content is reduced to 7-8.5 wt%, which is the observed mode of most intraplate ‘basalt’ provinces (e.g., Kamber&Ossa Ossa, 2015).

References:
Emo RB & Kamber BS (2022) Earth Planet Sci Lett 594, 117742
Kamber BS & Ossa Ossa F (2023) Treatise on Geochem, 3e
Graphite formation in deep crust during granulite facies metamorphism is documented in the Proterozoic gneisses of the Lofoten-Vesterålen Complex, northern Norway. Regionally distributed graphite zones are hosted in banded gneisses dominated by orthopyroxene-bearing quartzofeldspathic gneiss, including marble, calc-silicate rocks and amphibolite. The schist has major graphite, quartz, plagioclase, pyroxenes, biotite ($\text{Mg#} = 0.67-0.91$; $\text{Ti} < 0.66 \text{ a.p.f.u.}$) and K-feldspar/perthite. Pyroxene is orthopyroxene ($\text{En} = 69-74$) and/or clinopyroxene ($\text{En} = 33-53$, $\text{Fs} = 14-34$, $\text{Wo} = 44-53$).

Although graphite is usually described in pelitic rocks or as vein deposits in the granulite facies rocks, we document graphite in assemblage with metamorphic orthopyroxene.

Phase diagram modelling (plagioclase + orthopyroxene ($\text{Mg#}$-ratio = 0.74) + biotite + quartz + rutile + ilmenite + graphite-assemblage) constrains pressure-temperature conditions of $810-835 \, ^\circ\text{C}$ and $0.73-0.77 \, \text{GPa}$; $\text{Zr-in-rutile}$ thermometry $726-854 \, ^\circ\text{C}$. COH-fluids stabilise graphite and orthopyroxene; high $\text{Mg#}$-ratio of biotite and pyroxenes, and apatite $\text{Cl} < 2 \, \text{a.p.f.u.}$ indicate importance of fluids during metamorphism.

Stable isotopic $\delta^{13}\text{C}_{\text{graphite}}$ in the graphite schist is -38 to -17‰; $\delta^{13}\text{C}_{\text{calcite}}$ of marbles +3‰ to +10‰. Samples with both graphite and calcite present give lighter values for $\delta^{13}\text{C}_{\text{calcite}} = -8.7$‰ to -9.5‰ and heavier values for $\delta^{13}\text{C}_{\text{graphite}} = -11.5$‰ to -8.9‰. $\delta^{18}\text{O}_{\text{calcite}}$ for marble shows lighter values ranging -15.4‰ to -7.5‰ (Engvik et al. 2023). We interpret the graphite origin as organic carbon accumulated in sediments contemporaneous with the Early Proterozoic global Lomagundi-Jatuli isotopic excursion, while an isotopic exchange between graphite and calcite reflects metamorphic and hydrothermal re-equilibration.

The high-ordered graphite (< modality 39%) and biotite with a strong-preferred orientation defines the well-developed foliation. Increased graphite content resulted in high-conductivity zones with a contrast to the host low-conductive crust (Rodinov et al. 2013; Engvik et al. 2021). Enrichment of graphite resulted in zones with strong schistosity and a sharp strain gradient towards host massive granulite gneiss. The presence of graphite causes strain localisation in the granulite facies crust, reducing crustal strength and may thereby influence continental architecture and evolution of collision zones.

References:
Engvik AK et al. (2023) Minerals 13(10), 1279
Engvik AK et al. (2021) Terra Nova, https://doi.org/10.111/ter.12545
Rodinov A et al. (2013) NGU Report 2013.044
Behavior of barium isotope fractionation during crustal anatexis

Gu, X.F.  1,2, Huang, F.  2, and Liu, Y. C.  2

1School of Carbon Neutrality of Science and Engineering, Anhui University of Science & Technology, Hefei, Anhui 231131, China,gfxu@ustc.edu.cn
2School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China

Anatexis plays a key role in the evolution of continental crust, and is the important mechanism for the chemical differentiation of continental crust. The melts generated by crust anatexis experience segregation, aggregation, ascent and emplacement, then form granite intrusive body, while migmatites are often thought to represent fossil partially molten source regions of granites. Thus, migmatites can provide important constraints on the behaviors of element migmatite and isotope fractionation during crustal anatexis and granite formation. To explore the behavior of Ba isotope fractionation during crustal anatexis, we studied the Ba isotopic compositions of migmatites and Mesozoic granitoids from the Dabie orogen, central China, both of which were derived from partial melting of the Triassic gneisses at 110-140 Ma.

The results show that the Mesozoic granitoids have consistent $\delta^{138/134}$Ba (-0.13 ~ 0.06‰) with the gneisses (-0.04 ~ 0.04‰), implying limited Ba isotope fractionation during the formation of these granites. In contrast, $\delta^{138/134}$Ba of the melanosome (M) and leucosome (L) in the migmatites remarkably vary from -0.23 to 0.69‰ and -2.20 to 0.08‰, respectively, with $\Delta^{138/134}$Ba$_{L}$-$M$(= $\delta^{138/134}$Ba$_{L}$ - $\delta^{138/134}$Ba$_{M}$) varying from -2.45 to -0.08‰. Such huge Ba isotope fractionation cannot result from either fractional crystallization, accumulation, or equilibrium, incongruent to non-modal melting. Instead, the extreme low $\delta^{138/134}$Ba values of the leucosomes may originate from the external fluids involved in the melting reaction (biotite + plagioclase + quartz + H$_2$O → amphibole + melt), which could be magmatic fluids derived from the underplating magma and usually characterized by very light Ba isotopic compositions (Deng et al., 2022; Guo et al., 2020). So far, the published data show that $\delta^{138/134}$Ba of the normal granites (Ba > 200 µg/g) mostly falls in the range of -0.1‰ to 0.1‰, basically consistent with the average $\delta^{138/134}$Ba of the upper crust (0.00 ± 0.05‰), and the characteristics of high Ba contents and very low $\delta^{138/134}$Ba values that is similar to the studied leucosomes has not been observed in any granite plutons. This may mean that the granite intrusions were formed mainly by fluid-absent melting rather than fluid-present melting.

References:
Deng GX (2022) Earth Planet Sc Lett 194, 117724
Guo HH (2020) Geochem Perspect Let 16, 6-11
Lithosphere-scale fluid transfer in the central Pannonian Basin: carbon and noble gas isotope composition of deep fluid inclusions and groundwaters

Spráňitz, T.¹, Lange, T.P.¹²,³,⁴, Hencz, M.¹, Porkoláb, K.¹, Kővágó, Á.²,⁴,⁵, Gelencsér, O.²,³, Créon, L.⁶, Palcsu, L.⁷, Tóth, Á.⁸, Erőss, E.⁹, Rouchon, V.¹⁰, Szabó, Cs.¹,², Kovács, I.J.¹, Torók, K.¹¹, Koptev, A.¹², Cloetinhg, S.¹³, and Berkesi, M.¹

¹ MTA-EPSS FluidsByDepth Lendület Research Group, HUN-REN Institute of Earth Physics and Space Science, Csatkai Endre utca 6-8, Sopron 9400, Hungary; spranitz.tamos@epss.hun-ren.hu, berkesi.marta@epss.hun-ren.hu
² Lithosphere Fluid Research Lab, Eötvös Loránd University, Hungary;
³ Doctoral School of Environmental Sciences, ELTE Eötvös Loránd University, Budapest 1117, Hungary;
⁴ MTA-EPSS Lendület Pannon Lithoscope Research Group, HUN-REN Institute of Earth Physics and Space Science, Sopron, Hungary;
⁵ Doctoral School of Earth Sciences, ELTE Eötvös Loránd University, Hungary;
⁶ CAMECA, 29 Quai des Gresillons, Gennevilliers 92230, France;
⁷ Isotope Climatology and Env Research Centre, HUN-REN Institute for Nuclear Research (ATOMKI), Hungary;
⁸ Copernicus Inst of Sustainable Devel, Utrecht Univ, Princetonlaan 8a, 3584 CB, Utrecht, The Netherlands
⁹ József and Erzsébet Tóth Endowed Hydrogeology Chair, Eötvös Loránd University, Hungary;
¹⁰ IFP Energies Nouvelles, Rond-point de l’Echangeur de Solaize BP 3, Solaize 69360, France
¹¹ Supervisory Authority for Regulatory Affairs, Budapest, Hungary
¹² Helmholtz-Zentrum Potsdam - Deutsches GeoForschungsZentrum GFZ, Germany
¹³ Tectonics Research Group, Department of Earth Sciences, Utrecht University, Netherlands

Stable isotope composition of CO₂ is a powerful tool to trace lithosphere-scale volatile transport like Earth’s degassing and global carbon cycling. Fluid inclusions (FI) entrapping CO₂-rich fluids provide direct evidence on paleofluid migration events that took place at different levels of the deep lithosphere. On the other hand, deep fluid signature can also be detected in dissolved gases of much shallower-seated groundwaters, indicating the lithosphere scale connection of deep and shallow fluids from the upper mantle, through the crust and up to the Earth’s surface. We present here preliminary results of the ongoing project FluidsByDepth, which aims to give contributions to the understanding of non-volcanic natural CO₂ degassing in the central Pannonian Basin. A comparative study has been carried out by determining the carbon and noble gas composition of deep lithospheric fluid as well as shallow groundwater’s dissolved gases in the Bakony-Balaton Highland Volcanic Field, Hungary.

A detailed characterization and thus careful selection of FI was carried out within xenoliths from multiple levels from the lithosphere upbrought by Mio-Pleistocene alkaline basalt volcanism. This was also supported by the results on previous studies made on the same xenoliths in the sample series. Moreover, groundwater was sampled considering the geohydrologic flow directions and hence was made at discharge areas.

Stable isotope compositions of FI were estimated both by crushing technique and Raman spectroscopy. One further goal of this study is to test the applicability to calculate δ¹³C-CO₂ isotope compositions of fluids based on in situ Raman spectroscopic measurements. We applied this method on fluid inclusions in xenoliths, including harzburgite, lherzolite, websterite, mafic, felsic and metamorphic granulites, which sampled both the upper mantle and the lower to upper crust. In total 129 individual FI were selected in different host minerals, such as clinopyroxene, orthopyroxene, olivine, plagioclase and garnet.

The δ¹⁸O and δ¹³C stable isotopic ratio of the sampled groundwaters indicate meteoric origin and show no sign of an additional deep basin (metamorphic, magmatic) contribution. In contrast, the δ¹³C isotopic ratio of the dissolved CO₂ gases shows a narrow range (-5.2 – -9.6) and suggests mantle origin with slight organic sedimentary overprint. Stable isotopic ratios of dissolved helium also clearly indicate mantle origin for specific domains of the volcanic area.

Our results highlight the indirect role of preceding monogenetic upwelling channels as well as their relation to groundwater discharge areas in recent mantle degassing, which serve as an important contribution to understand post-rift CO₂ emission systematics of the area and deep carbon cycle.

80
Earthquake induced instantaneous garnet growth and deformation preserved in lower-crustal pseudotachylytes
Michalchuk S.P.1*, Zertani S.1, Markmann T.A.2, Lanari P.2, Rubatto D.2, and Menegon L.1

1The Njord Centre, Departments of Geosciences and Physics, University of Oslo, Oslo, Norway
2Institute of Geological Sciences, University of Bern, CH-3012 Bern, Switzerland
*Corresponding author: stephen.michalchuk@geo.uio.no

Many metamorphic processes leading to mineral growth are thought to occur near equilibrium conditions and to take considerable time, on the order of hundreds of thousands to millions of years. However, earthquakes are geological events that occur almost instantaneously and are frequently recorded as pseudotachylytes consisting of coseismic derived quenched frictional melt. In the dry, impermeable, and metastable lower continental crust, earthquake-induced fracturing during continental collision is a mechanism by which fluids may be introduced and kickstart metamorphic reactions that lead to rheological weakening. Understanding the chemo-mechanical processes operating during an earthquake rupture and the resulting mineralization associated with the formation of a pseudotachylyte can provide insight into the transformation of the continental lower crust. In this study, we examine the geochemical and deformation microstructures of mutually intergrown garnet grains that formed “cauliflower” garnet aggregates from a lower-crustal pseudotachylyte, which recorded the immediate post-seismic processes in the aftermath of an earthquake.

The pseudotachylyte vein collected from an anhydrous anorthosite-troctolite host rock in Lofoten, Norway is characterized by pristinely preserved quenching microstructures in the matrix such as plagioclase and clinopyroxene microlites, cauliflower garnet aggregates, survivor lithoclasts of both plagioclase and orthopyroxene + olivine from the host rock, and coronas of cauliflower garnet at the interphase boundary between plagioclase and orthopyroxene. There is a lack of hydrous phases such as amphibole or biotite. Quantitative compositional maps transecting the entire ~1 cm pseudotachylyte vein show an irregular or patchy garnet geochemical pattern, with pyrope and spessartine contents higher in coronitic garnet around survivor lithoclasts of orthopyroxene + olivine. Electron backscattered diffraction data indicate that the coronitic garnet grains in contact with orthopyroxene have many low-angle boundaries orientated roughly perpendicular to the phase contact, while garnet grains further away from the orthopyroxene contact generally have a progressively increasing misorientation profile gradient without sharp jumps. Orthopyroxene grains are elongated, have straight grain boundaries, form triple junctions, have very little amount of internal deformation, and have a shape-preferred orientation perpendicular to the pseudotachylyte vein wall.

Collectively, the microstructures indicate the anhydrous pseudotachylyte melt quenched extremely quickly and is largely preserved in a pristine state without any recrystallization. Garnet grew in a narrow temperature window while the melt was quenched rapidly to an ambient upper amphibolite temperature of ~700 ºC. In the short duration of mineral growth, garnet captured the incipient diffusion of major and minor elements from the frictional melt and was able to record the strain relaxation that localized along the interface at the pseudotachylyte vein margin with the wall rock during quenching. Although seismic fracturing and the formation of pseudotachylyte can be achieved in the anhydrous lower crust, fracture healing and melt quenching are extremely fast processes and may not leave enough time for a fluid to infiltrate and kickstart metamorphism and facilitate deformation. The preservation of garnet zoning, the lack of amphibole, and the lack of subsequent mylonitization of the pseudotachylyte are all consistent with the rocks remaining dry after the earthquake. This enabled the preservation of instantaneous processes recorded in the garnet microstructure.
Earthquake-induced fracturing of the dry, strong, and metastable granulitic lower continental crust is a key agent in creating fluid pathways to allow the infiltration of aqueous fluids into the highly reactive host rocks, thereby kickstarting metamorphic reactions and rheological transitions (Jamtveit et al., 2019). Pseudotachylytes (quenched frictional melts produced during seismic slip) and their extensively fractured damage zones are ideal structures for creating transient porosity and permeability networks that enable fluid infiltration into lower-crustal dry rocks. Metamorphic and rheological transformations of the granulitic lower crust are dependent on the availability of aqueous fluids, whether externally sourced or locally produced. As long as there is a continuous supply and redistribution of aqueous fluid, viscous creep will occur in hydrated shear zones localized along faults initially characterized by frictional melting and wall-rock damage (Menegon et al., 2017). However, if the infiltrated fluids are consumed by reaction products, further metamorphic reactions and the associated weakening effects will eventually become sluggish and inefficient under fluid-absent conditions, and the shear zones may eventually harden (Bras et al., 2021; Michalchuk et al., 2023). Thus, understanding how fluids are redistributed in the deep orogenic crust in the aftermath of an earthquake is essential to constrain the rheological transition from dry and strong granulites to wet and weak shear zones.

When feldspar-rich granulites are infiltrated by aqueous fluids under eclogite facies conditions, breakdown reactions of plagioclase to form clinozoisite-bearing assemblages are ubiquitous. Although fracturing and pseudotachylyte formation may have played an important role in triggering the initial fluid infiltration, the redistribution of the infiltrated fluid primarily occurs via reactive fluid flow that exploits the porosity created by the negative volume change during eclogitization reactions (e.g., Zertani et al., 2022). In this situation, deformation is not necessary to feed fluid flow, as exemplified by the many occurrences of "eclogitic fingers" that developed by static fluid-rock interaction in granulites from Holsnøy, western Norway.

Fluid infiltration also occurs in feldspar-rich granulites at conditions where plagioclase is stable (amphibolite facies conditions), where reactive fluid flow is not the main mechanism for fluid redistribution. However, amphibolite facies ductile shear zones exploiting pseudotachylyte precursors are invariably hydrated compared to their granulate host rocks, as shown for example in Nusfjord, Lofoten, northern Norway. In this situation, fluid flow only occurs in conjunction with deformation within the fine-grained pseudotachylyte vein and its intensely fragmented wall-rock damage zone, both of which are capable of deforming by grain boundary sliding and creep cavitation, thereby generating and maintaining a dynamic porosity in the high-strain zone. Thus, deformation is essential to trigger fluid flow in the absence of metamorphic reactions associated with volumetric deformation. This comparison indicates that the evolution of the granulitic lower crust during continental collisions is controlled by the transient interplay between brittle (and locally seismic) deformation, fluid-rock interaction, mineral reactions, and creep.

References:
Bras E et al. (2021) Tectonophysics, 819
Jamtveit B et al. (2019) JGR: Solid Earth, 124
Michalchuk SP et al. (2023) JGR: Solid Earth, 128
Garnet coronitic structures on the interface of felsic-mafic/restitic lithologies: possible evidence of fluid and/or melt movement during the ultra-high temperature metamorphism of the Oaxacan Complex, Southern Mexico
Ramírez-Salazar, A.1*, Almazán-López, M.M.2, and Ortega-Gutiérrez, F.1

1Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria 04510, Mexico City, Mexico; corresponding author email: r.s.anthonyy@gmail.com
2Posgrado en Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria, 04510 Coyoacán, Ciudad de México, México

The Oaxacan Complex is a well-exposed granulitic terrane located in Southern Mexico. It experienced ultra-high temperature metamorphism (T = 895–916°C and P = 0.83–0.99 GPa; Ramírez-Salazar et al., 2023) at the latest stages of the amalgamation of Rodinia (~990 Ma; Solari et al., 2003). Melt microstructures and rare syn-tectonic pegmatites show that the ultra-high temperature metamorphism (UHTM) was contemporaneous to partial melting (Ramírez-Salazar et al., 2023), while the presence of fluid-rich minerals in calcisilicates suggests fluids were present at the metamorphic peak in some parts of the Complex (Ortega-Gutiérrez, 1984). Our recent fieldwork and petrographic observations indicate that infiltration and movement of fluids and melt might have occurred simultaneously in some areas. Meta-felsic rocks of the Anorthosite-Mangerite-Charnockite suite within the predominantly metasedimentary El Márquez Unit, display millimeter to meter size mafic and Al-rich “enclaves”. Reaction-like coronitic structures composed by garnet and biotite occur on the “enclave”-felsic host interface. Further petrographic inspection shows that some coronitic garnets are associated to spinel-corundum-plagioclase-ilmenite-garnet symplectic microstructures within the Al-rich enclaves, pointing to its restitic nature. Moreover, biotite associated to the coronitic structure displays skeletal-like textures, and preliminary results indicate that the biotite grains are rich in Cl. These preliminary observations suggest that partial melting contemporaneous to Cl-rich fluids infiltration occurred during UHTM. The interpretations are non-conclusive yet, but the coronitic structures found in the Oaxacan Complex might provide insights into the melt-and fluid-driven reactions and processes occurring at extreme temperature and high-pressure conditions.

References:
Ramírez-Salazar et al. (2023) Int. Geol. Rev. 65.8, 1331-1353
UHT garnet in the Bakhuis Granulite Belt, Suriname, South America
De Roever, E.W.F.¹ and Huizenga, J.M.²

¹Dept. of Earth Sciences, VU Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands – ederoever@ziggo.nl
²Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432

The Paleoproterozoic Bakhuis Granulite Belt (BGB), ca. 3000 km² in size, consists mainly of mafic and intermediate granulites, with minor metapelitic granulites. The BGB shows conventional Ultrahigh-Temperature (UHT) assemblages, with Al-rich orthopyroxene + sillimanite ± sapphirine in a small (50 km²) area of metapelites in the NE. Metapelite occurrences elsewhere in the BGB mostly show the for UHT metamorphism unique assemblage cordierite + sillimanite ± Al-rich orthopyroxene (Nanne et al., 2020). This assemblage could be formed at UHT conditions because the cordierite is rich in CO₂ (up to 2½ wt.% CO₂), with little H₂O. The assemblage was estimated to have formed at a pressure of ca. 11 kbar at 950-1050°C (De Roever et al., 2023). The high CO₂ level would imply CO₂ fluid phase saturation during UHT metamorphism. Fluid inclusions (FI) are common in quartz and feldspar. The FI contain pure CO₂, which could be derived from a local source (which was not found) or an external source. Carbon isotope analysis of CO₂ in FI indicates a possible mantle source. Without CO₂ influx the cordierite assemblage could not have been formed.

Recently, the UHT assemblage garnet ± sillimanite was recognized locally in metapelite. The garnet cores show abundant exsolution of Ti-rich needles, suggesting that the cores consisted of Ti-bearing garnet before exsolution during retrograde metamorphism. EPMA analysis of garnet with exsolution using a wide beam suggests an average Ti level corresponding to a formation temperature of ca. 1000°C. The assemblage is not related to the orthopyroxene and cordierite assemblages mentioned above, because the garnet does not occur together with orthopyroxene and in cases contains orthopyroxene relics. Furthermore, the orthopyroxene and cordierite assemblages were formed at a high oxidation state, as they are accompanied by magnetite and titanohematite, whereas the garnet + sillimanite assemblage coexists with rutile. In the two main occurrences, areas of ca. 10 km² in size, coinciding with an aeromagnetic anomaly, the garnet ± sillimanite assemblage is in part accompanied by accessory graphite flakes. Aeromagnetic anomalies are common in the BGB, in part due to the widespread occurrence of magnetite. However, geophysical investigation (with drilling) of the two anomalies with garnet showed that the anomalies are caused by a few % of graphite (and sulphide). The graphite is considered to have been formed during UHT metamorphism together with garnet but also occurs in later deformation zones and fractures. The garnet grains frequently show fluid inclusions in their core. Analysis of one example showed the presence of pure CO₂.

The dominant and widespread UHT assemblage in metapelites throughout the BGB is cordierite – sillimanite ± orthopyroxene, associated with CO₂ fluid saturation. The UHT garnet ± sillimanite assemblage is rare and occurs only locally, i.e. in two small areas and at a few single locations, among the widespread assemblage with cordierite. The UHT garnet is not accompanied by contemporaneous cordierite or orthopyroxene but replaced a former orthopyroxene-bearing UHT assemblage, as indicated by remnants of orthopyroxene in garnet. The cordierite + sillimanite ± orthopyroxene assemblage is accompanied by magnetite and titanohematite, indicative of a high oxidation state. This is not in agreement with the occurrence of rutile in the garnet ± sillimanite assemblage, let alone with the reducing conditions during graphite formation. The cause(s) of this difference are being investigated.

References:
De Roever, E.W.F. et al. (2023) Contributions to Mineralogy and Petrology 178 : 26
Deciphering elemental behaviour during high-grade metamorphism using multi-phase quantitative compositional mapping by LA-ICPMS

Lanari, P.¹,² and Markmann, T.A.¹

¹Institute of Geological Sciences, University of Bern, Switzerland, pierre.lanari@unibe.ch
²Institute of Earth Sciences, University of Lausanne, Switzerland

Studying the behaviour of elements during high-grade metamorphism is a challenging task when partial melting is involved. Two fundamental limitations have restricted the use of natural samples for this purpose. The first limitation is related to the open system behaviour of partially melted rocks. In migmatites, the minerals present in a leucosome can be used to study the former melt composition at the time of crystallisation. Any further comparison with the residue to infer the melting history requires the assumption that the melt was immobile, which is unlikely due to the density and viscosity contrast between melt and solids. The second limitation is our ability to map the distribution of elements in domainal rocks. Minerals in migmatite are often chemically zoned, and large variations in major element compositions can cause significant matrix effects, making map calibration for trace elements challenging.

In this study we present a data reduction routine for multi-phase quantitative compositional mapping in chemically zoned minerals using LA-ICP-MS. Each mineral in the mapping area is individually calibrated using an independent element as internal standard with the option of a variable composition. This routine was implemented in the open-source software XMapTools (Markmann et al, 2024). Quantitative compositional mapping was applied to a migmatite sample from the El-Oro complex in Ecuador. This sample comes from a 30-m wide metasediment xenolith in the Marcabeli pluton and shows an exceptional record of partial melting in a closed system. The results allow the systematic behavior of these elements during partial melting to be retrieved and show that strong chemical potential gradients in major, minor and trace elements were established between the leucosome and the residuum during cooling. This dataset can also be used to identify domains of local equilibrium and to quantify disequilibrium gradients at the thin section scale. Implications for phase equilibrium modelling based on the bulk-rock composition will also be discussed.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 850530).

References:
Markmann et al. (2024) Chem Geol 646, 121895
Constraints on the origin of Archean hornblendites: an example from the Lewisian Gneiss Complex, NW Scotland

Garcia, M.F.T.1,2,*, Volante, S.2,1, Johnson, T.E.3, Diener, J.5, Hoffmann, J.E.4, Dziggel, A.1

1Department of Tectonics and Resources, Institute of Geology, Mineralogy, and Geophysics, Ruhr-Universität Bochum, Bochum, Germany
2Structural Geology and Tectonics Group, Geological Institute, Department of Earth Sciences, ETH Zürich, Zürich, Switzerland
3School of Earth and Planetary Sciences, The Institute for Geoscience Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
4Institut für Geologische Wissenschaften, Freie Universität Berlin, Malteserstraße 74-100, 12249 Berlin, Germany
5Department of Geological Sciences, University of Cape Town, South Africa

The deep levels of Archean continental crust are dominated by felsic gneisses of the tonalite–trondhjemite–granodiorite (TTG) series, with ultramafic–mafic rocks constituting a volumetrically minor yet key component with potential for constraining TTG source rocks. Many of these ultramafic–mafic rocks contain amphibole (hornblende), of which rare hornblendites (>90 vol.% modal hornblende) are preserved as pods or lenses within TTG gneisses. However, the origin of these hydrated ultramafic rocks and their relationship to their felsic TTG host rocks remains unexplored, complicated by subsequent metamorphic processes. In this study, we combine field observations, bulk-rock major and trace element data, phase equilibrium modelling, and in-situ mineral chemistry to constrain the origin of hornblendites from the mainland Lewisian Gneiss Complex in NW Scotland.

The studied hornblendites contain high MgO (up to 19 wt%), Cr (up to 5000 ppm) and Ni (up to 1000 ppm). Previous studies interpreted that the hornblendites may have been cumulates of their host TTG magmas, modified by multiple hydration and partial melting events. Additionally, they show similar Cr, Ni, and major elements (SiO₂, Al₂O₃, CaO and TiO₂) values to Archean komatiites and ultramafic-mafic rocks from the Lewisian, indicating that they may have originated from a similar primitive mantle source. Amphibole compositions vary from pargasite to magnesiohornblende cores to actinolite rims and actinolite-quartz symplectites, indicating different generations of amphibole. Phase equilibrium modelling illustrates that nearly monomineralic assemblages dominated by amphibole form under water-saturated conditions and at subsolidus or near-solidus temperatures. These lines of evidence suggest that hornblendite pods may have been fragments of ultramafic bodies containing primary hornblende, which acted as a water reservoir, retaining most of the water until temperatures reached 700-750°C. Warmer geotherms during the Archean likely favoured dehydration of hydrous high-MgO ultramafic-mafic rocks at deep crustal levels, leading to fluid-present melting of overlying basaltic rocks to produce TTG magmas. Alternatively, hornblendites could have been igneous cumulates or ultramafic xenoliths that were later fully hydrated and re-equilibrated at low temperatures (700-750°C), either in the magma source region or elsewhere within the magmatic system. In this scenario, external fluids may have played a crucial role in fully hydrating the ultramafic bodies. In either case, high-MgO hornblendite and ultramafic rocks appear to have been significant sources of fluids during the Archean, reflecting a pervasively hydrated crust. These ultramafic rocks carried water into the deep crust along cooler geotherms and released it during low-temperature dehydration. This process supplied essential water fluxes to the more enriched basaltic sources, facilitating crustal production.
Tracking a polymetamorphic history: garnet trace element mapping in a Sveconorwegian granulite.

Urueña, C.L.¹, Rubatto, D.², and Möller, C.³

¹University of Bern, Baltzerstrasse 1+3, Bern, Switzerland, cindy.uruena@unibe.ch
²University of Bern, Baltzerstrasse 1+3, Bern, Switzerland.
³Lund University, Sölvegatan 12, Lund, Sweden.

Garnet trace element mapping has become an increasingly important tool for deciphering complex metamorphic histories, especially in high-grade and partially molten metamorphic rock. Trace elements (TE), especially rare earth elements (REE), are sensitive to variations in the physicochemical conditions during the garnet growth and preserve a growth stage event at high temperatures where major elements tend to homogenize. Compatible TE uptake in garnet such as Y and heavy REE often follows Rayleigh fractionation, recording a growth zoning pattern. However, different distribution patterns can be used to identify disequilibrium processes, diffusion during thermal overprinting, and fluid-induced modifications (e.g., Moore et al. 2013; Rubatto et al. 2020).

This study investigates the metamorphic evolution of high-grade polymetamorphic migmatitic gneisses from the Eastern Segment of the Sveconorwegian Province in southwestern Sweden. In the studied area, Sveconorwegian high-pressure granulite-facies metamorphism (0.98 Ga) overprinted the earlier medium-pressure amphibolite-facies metamorphism of the Hallandian event (1.45 Ga; Ulmius et al. 2015). U-Pb dating of zircon and monazite confirms the polymetamorphic history, revealing the age of each event in different crystal domains (Piñán-Llamas et al. 2015).

Trace element mapping of Mn-rich garnet from a sillimanite-bearing migmatitic gneiss has been used to document the crystal evolution during the two distinct tectonometamorphic events. The major elements Ca and Mn are homogeneously distributed, whereas Mg shows a patchy distribution with enrichment towards the inner parts of the crystal and depletion in the rim. Although Fe is mostly homogenized, the outermost rim displays a Fe-enriched zone (< 50 µm). Notably, the TE patterns do not reflect the observed Mg and Fe distributions. The Fe-rich and Mg-poor rim is therefore interpreted as a result of diffusional re-equilibration at high temperatures during granulite-facies metamorphism.

TE distribution suggests multi-stage garnet growth. The garnet mantle shows a broad concentric band (~400 µm) enriched in Y and Dy–Lu followed by a rim strongly depleted in HREE. The core exhibits a moderate depletion in Y + HREE relative to the mantle. Zr shows a weak enrichment in the mantle, whereas Eu and Sm are slightly enriched toward the rim. The uncommon enrichment of MREE and HREE in the mantle compared to the core may be attributed to garnet growth under peritectic conditions during partial melting in the later metamorphic event. The low REE rim would thus represent subsolidus garnet growth during cooling at conditions where Fe and Mg re-equilibration occurred.

References:
Moore et al. (2013) J Metamorphic Geol., 31:663–689
Rubatto et al. (2020) Contrib Mineral Petrol 175:61
Two-stage metamorphism of the Sulkava granulite area, Southern Finland
Häkkinen, M.¹, Höltä, P.², Whipp, D.¹, Pownall, J.¹, and Cutts, K.²

¹Department of Geosciences and Geography, P.O. Box 64, FI-00014 University of Helsinki, Finland, miisa.hakkinen@helsinki.fi
²Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland

How the temperature rose so high is a long-standing question in the tectonic interpretation of the Paleoproterozoic ca. 1.83 Ga granulite areas in southern Finland. In the Sulkava area in southeastern Finland, progressive metamorphic zonation increases in grade southwards from the tectonic boundary, appearing to have no spatial relationship with coeval magmatism. This is at odds with the idea of advective heating of shallow crustal levels by rising magmas (Korsman, 1984), which has been suggested as the cause of the late heating event either in an accretionary setting or as the result of radiogenic heating of thickened crust (e.g., Kukkonen and Lauri 2009). Decompression heating in an extensional setting or magmatic underplating models (e.g., Stephens and Andersson, 2015) may be consistent with conductive-type metamorphic zones, but do not adequately explain the structure of the crust, which remains 50 km thick with no evidence of major later tectonic events.

Two principal metamorphic events at ca. 1.88 Ga and 1.83 Ga have been well established in the Svecofennian domain in Finland. The younger event produced voluminous granitic magmatism and migmatization in the southern parts of the domain, where many areas record no evidence of an earlier metamorphic event. Recent monazite dating in the Sulkava area (Salminen et al., 2022) clearly shows that both metamorphic events affected this area.

We have studied the Sulkava granulite area in southeastern Finland by means of field work, petrography, and phase equilibrium modelling in an effort to identify, separate and characterize the two main metamorphic events and re-evaluate the meaning of the metamorphic zoning in relation to the tectonic models. The study area extends further south than in the original study of Korsman, 1984.

In the northern, lower-grade parts of the study area, the older metamorphism associated with a N-S foliation is dominant. The younger event caused crenulation of the old cleavage and growth of new metamorphic minerals of hotter assemblages in an E-W trending direction with poikiloblastic andalusite, k-feldspar and cordierite preserving evidence of earlier foliations. Going southwards only the younger event is seen until almost the middle of the granulite area where there are N-S foliated high-grade gneisses, folded and recrystallized migmatites and gt-opx-crd rocks. Even further south the area principally consists of igneous rocks or diatexites, however isolated occurrences of lower grade gneisses make the metamorphic pattern complicated. The interpretation proposed here is that the earlier 1.88 Ga event already produced the southwards increasing metamorphic zonation but is only seen now where the second event was weak (north) or where the rocks were already significantly dehydrated/melted during the first event (south). A collisional setting for the 1.88 Ga event between a juvenile microcontinent and the Archean Karelian continent (e.g., Nironen, 2017) can best produce the first conductive-type zonation HT-LP metamorphism in the Sulkava area and the second event may then be related to thickening induced heating in the crust, magmatic advection (e.g., Kukkonen and Lauri 2009) and gravitational uplift of the granulite areas (Korsman, 1984).

References:
Nironen (2017) Geol Surv Fin Special Paper 60, 41-76
Salminen PE et al. (2022) Lithos 416-417
Pre-Variscan granulite under Alpine high-P: the Ruitor Massif, W-Alps
Guillot, F.¹ and Lanari, P.²

¹UMR 8187-LOG Univ. Lille –CNRS–Univ. Littoral Côte d’Opale-IRD, F-59000 Lille <francois.guillot@univ-lille.fr>
²Universität Bern, CH-

The Ruitor Massif in the Western Alps is part of the Grand-Saint-Bernard Nappe, across Savoy (F), Valle d’Aosta (I) and Valais (CH) (Sartori et al 2006). This pre-Carboniferous basement crops out between the internal border of the Zone Houillère (Upper Carboniferous), to the W, and the Combin-type Piemontese calcschists (~Mesozoic), to the E. Along a W to E section from Tarentaise to Valgrisenche, the Alpine main foliation rotates from E-dipping, through vertical, to W-dipping at the Ruitor internal border, and is classically interpreted as backthrust-related (Platt et al 1989). Near the southeastern end of the Ruitor Massif in Valgrisenche, peak Alpine metamorphic conditions have recently been estimated at 493-560°C and 2 GPa, based on Raman spectra of carbonaceous matter and on phengite Si-content (samples RU of Mendes et al., 2023).

In this presentation, we will focus on the peculiar mineralogy inherited from the protracted, polyphased history, detailing the assemblage from dark ocelli of a variegated micaschist, sampled at the SE-border of the Massif near the Rifugio degli Angeli in Valgrisenche: chloritoid Fe₈₃ Mn₄ Mg₁₃, garnet Al₅₈ S₃₂₃ Grs₁₅ Prp₄, paragonite with Na/(Na+k)>0.95, minor phengite with Si=3.33 apfu, plus ilmenite, allanite and rare zircon. Albite and quartz are not observed in the ocelli, but instead make up large portion of the leucocratic inter-ocelli walls. This anomalously Al-rich assemblage is compatible with a restite chemistry, and the past occurrence of Al-silicates.

Overall, the detailed geology of the Ruitor Massif, although of interest, remains poorly understood, with little geochemical and lithostratigraphic data.

References:
Bergomi MA et al (2017) Tectonics 36, 2950-2972
Mendes K et al (2023) Geology 51, 1153–1157
Granulite facies rutile: Exploring trace element zoning and homogenization
Lueder, M.1, Hermann, J.1, Tamblyn, R.1, Lanari, P.1,2, Rubatto, D.1,2, and Markmann, T.A.1

1Institute of Geological Sciences, University of Bern, Boltzerstrasse 1+3, 3012 Bern, Switzerland
2Institute of Earth Sciences, University of Lausanne, Géopolis, Quartier Mouline, 1015 Lausanne, Switzerland

Rutile is a common accessory mineral in granulite-facies rocks and frequently used as petrogenetic indicator, such as for Zr-in-rutile thermometry, indentifying source geochemical reservoirs through Nb/Ta-ratios, and U-Pb dating. However, intra-grain variabilities of trace elements in rutile and their capacity to retain primary zoning are rarely considered.

We present results from laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) mapping on granulite-facies rutile. To evaluate intra grain variabilities of trace elements and assess diffusive resetting of trace elements in rutile at high temperature conditions, we compare these results with rutile formed at lower temperatures or higher pressure.

Generally, trace elements in granulite facies rutile are mostly homogeneously distributed. Minor, patchy zoning is observed for Nb and Ta, resulting in relatively homogeneous Nb/Ta-ratios of 11–13. Additionally, rutile can contain zircon exsolutions. In a sample from the Ivrea zone, Western Alps, homogeneous, exsolution-free areas record cooling temperatures of 850 ± 10 °C (2370 ± 170 μg/g Zr), while areas with high density of zircon exsolution features records temperatures of up to 950 ± 110 °C (5580 ± 324 μg/g Zr). We interpret that exsolution-free areas within the grain have diffusively lost Zr, recording cooling temperatures. Zircon exsolutions prevent Zr loss to the host matrix, and analyzing rutile with nano-scale zircon inclusions returns close to peak temperatures. Rutile from a high-T eclogite-facies samples from Alpe Capoli, Central Alps, shows core-rim zoning in multiple trace elements, with relatively flat concentration gradient. Nb/Ta-ratios vary more strongly with values between 13–25, while Zr-temperatures are constant within the uncertainty of the method (690–700 °C, 280–310 μg/g Zr). In contrast, rutile from amphibolite-facies samples from Val Malenco, Central Alps, show very pronounced primary zoning with sharp boundaries between zones. Nb/Ta-ratios vary within a similar range as observed in high-T eclogite facies rutile (12–21). However, Zr is zoned significantly (31 ± 2 μg/g to 48 ± 2 μg/g), leading to distinctly different calculated Zr-temperatures (463 ± 3 °C to 490 ± 2 °C), which might be related to temperature variations or Zr-undersaturation during rutile growth.

The systematically different zoning observed in these samples is interpreted as evidence of diffusive re-homogenization of trace elements in granulite-facies rutile, and consequently altered trace element signatures. To evaluate the implications for rutile as petrogenetic indicator mineral at granulite facies conditions, original low-T trace element zoning and diffusion processes in rutile need to be further investigated.
Zircon as a window on magmatic interaction between mantle-derived magmas and granulitic lower crust exposed in Ivrea-Verbano zone, northern Italy
Passos do Carmo, C.\(^1\), Laurent, O.\(^1\), Vanderhaeghe, O.\(^1\), Galli, A.\(^2\), and Tavazzani, L.\(^2\)

\(^1\)CNRS, UPS, IRD, Géosciences Environnement Toulouse, 14 Av. E. Belin, 31400 Toulouse, France
\(^2\)Department of Earth Sciences, ETH Zurich, Sonnegstrasse 5, 8092 Zurich, Switzerland

The significance of magmatic processes involved in the differentiation of the continental crust remain debated. Specifically, two endmember models are invoked to explain magmatic rocks that form the continental crust: fractional crystallization of partial melt from the mantle or melting of crustal lithologies. However, both processes generally operate together, such that a substantial fraction of continental silicic magmas are effectively hybrid in composition [1], but the respective contributions of both crustal and mantle endmembers remain difficult to address.

In the Permian Sesia Magmatic System of the Ivrea Verbano Zone (IVZ), granulite facies rocks are intruded by the Mafic Complex (MC) in the lower crust, and amphibolite to greenschist facies rocks are intruded by hybrid granites at upper crustal levels. Multiple lines of evidence, based on bulk rock composition, suggest that mantle- and crustal-derived magmas interact in the lower crust, which lead to formation of hybrid granites in the upper crust [2], [3]. However, the mechanisms by which these hybrid magmas were generated are not yet assessed at the outcrop, microscopic, or mineral scale. In this study, we present an integrated multi-scale sampling dataset, focused on zircon U-Pb dates, trace element and Hf isotopic compositions.

Within the MC at the Val Sessera locality, at a kilometre to metre scale, the contact between gabbro and migmatitic paragneiss is systematically marked by charnockite with various proportion of Px-Grt-Pla-Qz. Charnockite is intermingled with the gabbro and in textural continuity with leucosome veins concordant to discordant relative to the foliation of the migmatitic paragneiss. This association, along with bulk and mineral compositions, indicate that charnockites are intermediate hybrid magmas generated in the lower crust, from which melt was extracted to form granites in the upper crust [2], [4].

Zircons display four morphological textures, defined by core-rim relationships and textural positions (albeit in different proportions from a lithology to another). The first zircon generation corresponds to rare, highly corroded zircon cores in gabbros/charnockites interpreted as xenocrysts from metasedimentary lithologies. The oldest magmatic zircons from mafic lithologies are texturally and compositionally similar to those of typically granitic melts and interpreted as crystallized from hybrid liquids corresponding to a first large-scale hybridization step. Bright rims and individual CL-bright crystals are distinctly posterior, and, based on trace elements composition, may record re-injection of less evolved melt in the hybrid mush zone. The ca. 30 Ma span of U-Pb dates observed in these zircons and the complex relationships of their textures are indicative of a long-lived system possibly associated to the development of a deep crustal hot zone [5].

Overall, we propose that zircon is a key mineral for understanding the processes happening in long-lived high-temperature systems; furthermore, we suggest that the onset of a deep crustal hot zone in IVZ led to assimilation, hybridization, zircon crystallization, and ultimately generation of granitic magma.

References:
[4] Passos do Carmo et al. (2023) 10th Hutton Symposium, 63-64
Granulites- Energy source for future: Case study from beach placers of eastern coast of India and Sri Lanka
Mohanty, S.

Department of Geology and Geophysics, IIT Kharagpur, India. Email id: samikshyamohanty18@gmail.com

The growing worldwide demand for nuclear and green energy has generated considerable economic interest in the exploration of rare earth elements (REEs) and radionuclides. The delineation of REEs and radioactive elements and proper extraction and utilization of these elements for recent technological innovations will definitely improve the availability of indigenous resources for the economic development of any country. The present study reveals potential source of these REEs and radionuclides that are enriched within the granulite terranes, found as radioactive minerals such as zircon and monazite. These heavy minerals are extracted from the beaches associated with these granulite terranes. Two such high-grade terranes are the Eastern Ghats Mobile Belt (EGMB) and Wanni Complex (WC) from the east coast of India and Sri Lanka respectively. The EGMB and WC predominantly comprise of khondalite and charnockite, which serve as source rocks for REEs and radionuclides. Continued weathering and erosion in tropical climates facilitate the transportation and deposition of these detrital minerals as placer deposits. Using in-situ gamma-ray spectrometry, HPGe analysis, and INAA, the abundance of heat-producing elements such as uranium (U), thorium (Th), and potassium (K) was determined. Radioactive counts in the granulite terranes vary from 10 to 120 µR/h depending on the abundance of radioactive minerals in different lithologies. Analyses from river banks, acting as transportation mediums, and the berm region of associated beaches reveal total REE content varying from approximately 5.2 to 23.83 times and 20 to 90 times higher than the Universal Continental Crust, respectively. The Th/U ratio is higher in beach sediments, indicating the prevalence of radioactive heavy minerals throughout the beaches associated with granulite terranes. Concentrations of REEs in beach placers range from 79 to 4099.18 ppm, with a predominance of LREE over HREE. The concordant geochemical nature of radioactive minerals and REEs suggests that the heavy minerals are derived from charnockite granite gneisses, whereas khondalite are the secondary source rocks, as evidenced by the presence of higher Mg. Summarizing all the facts, the significant enrichment of radionuclides and REEs in granulite terrains designates them as a potential source for both nuclear and green energy.

Keywords: Granulite, Rare earth element, Radionuclide
Unravelling contrasting post-metamorphic peak tectonic evolutionary histories from a single high grade terrane: a case study

Ghosh, A.* 1, Samantaray, S. 1, Chatterjee, S. 1, Maitra, A. 1,2, Bose, S. 1,3, and Gupta, S. 1

1Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721302, India
(*Corresponding author. Email address: anujghosh95@kgpian.iitkgp.ac.in)
2School of Ocean and Earth Science, University of Southampton, Southampton, United Kingdom
3Wadia Institute of Himalayan Geology, Dehradun 248001, India

The Eastern Ghats Province (EGP) is a granulite facies terrane in India that preserves evidence of ultra-high temperature (UHT) metamorphism correlatable with the Neoproterozoic assembly of the supercontinent Rodinia. There have been suggestions that the part of the EGP north of a major intra-province structural feature called the Mahanadi Shear Zone (MSZ) experienced a tectonic history that is separate from the rest of the belt. This study aims to evaluate if the tectonic evolution of the northernmost parts of the EGP differs from the rest of the terrane, how this relates to the rest of the EGP, and to explore the evidence for UHT metamorphism north of the MSZ that has not been previously reported. In recent years, the tectonometamorphic evolution of a high grade terrane has been reconstructed using Pressure-Temperature (P-T) pseudosections calculated at constant bulk composition. This has been applied in this study to rock samples collected from four regions, two each from the north and south of the MSZ. P-T pseudosections were calculated using PERPLE_X (v.7.1.3) after determining the effective bulk compositions (EBCs) of specifically chosen domains within thin sections of khondalites from the Khurda and Nayagarh regions respectively, south of the MSZ. The obtained results confirm that the rocks record near UHT peak conditions, based on the respective stable equilibrium mineral assemblages: melt+garnet+K-feldspar+plagioclase+ilmenite+quartz and melt+garnet+cordierite+K-feldspar+plagioclase+ilmenite+quartz, followed by isobaric cooling to below the solidus. Isothermal decompression is recorded in the subsolidus region. Based on previous studies, peak conditions were inferred to be either synchronous with or post-dating the development of the penetrative fabrics (S1/S2). North of the MSZ, three rock samples from the Angul region: a garnet-cordierite bearing metapelite, an augen gneiss and a mafic granulite were selected. The peak P-T conditions obtained for the garnet-cordierite bearing metapelite is 1100-1150°C at 5-7 kbar, based on the stable equilibrium assemblage melt+garnet+cordierite+plagioclase+ilmenite+quartz. Similarly, the peak P-T conditions obtained for the garnet-cordierite bearing metapelite is around 800-850°C and 7 kbar. Garnet breakdown to a symplectite of orthopyroxene+plagioclase indicates decompression dominated cooling in the subsolidus regime following peak pressures. Thus, based on metamorphic studies, the overall post-metamorphic peak history for the northernmost EGP reported from the three samples are isobaric cooling from peak UHT followed by cooling and loading (consistent with the development of S1/S2 evident from the augen gneiss) and finally decompression dominated cooling. This indicates that there are significant differences in the post-peak temperature histories north and south of the MSZ signifying potential differences in the post-metamorphic peak tectonic evolution of the EGP north and south of the Mahanadi rift.
Re-visiting Lower Crustal Xenoliths from Northeastern Australia
Conway, E.J.¹, Murphy, D.T.¹, Emo, R.B.², and Kamber, B.S.¹

¹School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, Australia; emmjordan.conway@hdr.qut.edu.au
²Institute of Geology and Mineralogy, University of Cologne, Germany

Cenozoic intraplate basaltic volcanism in eastern Australia has exhumed a rich suite of mantle peridotite and rarer lower crustal xenoliths (LCXs). They provide a great opportunity to explore deep-seated processes in the Australian mantle lithosphere, Moho and lower crust as direct, rapidly exhumed samples of otherwise inaccessible portions of the lithosphere. Past studies on LCXs from northeastern Australia (Queensland) have majorly featured in attempts at constructing the composition of the lower continental crust (LCC) (e.g. Rudnick & Taylor, 1987; Sutherland and Hollis, 1982).

The Queensland LCXs are overwhelmingly mafic and represent two granulite-facies assemblages: two-pyroxene-plagioclase-ilmenite and clinopyroxene-garnet-plagioclase-rutile. They have been revisited through combined geochemical and petrological modelling in work by our group (e.g., Emo & Kamber, 2022) confirming that the local LCC is very refractory, strongly depleted in incompatible and heat producing elements (HPE), having experienced melt extraction at very high temperatures (950-1050°C). The LCXs are sampled directly from the deep crust and differ markedly in mineralogical variety and HPE depletion from terrain granulites. They are not predisposed to the same tectonic complications and slow exhumation as lower crustal terrain granulites.

Our recent work has highlighted the role of melt-solid interaction in forming the LCXs, whereby basaltic under- or interplates apparently interacted with existing resident LCC near the Moho. The resulting process is a form of Assimilation-Fractional-Crystallisation (AFC), whereby both the resident LCC and the basalt are modified in mineralogy and chemistry, respectively. Thermodynamic modelling indicates that at P > 10 kbar, AFC leads to clinopyroxene-garnet-plagioclase-rutile residues that may potentially delaminate. The current work sets out to study a rarer xenolith population of ‘garnet websterites’ sometimes co-occurring with the granulites. Their mode is dominated by garnet and clinopyroxene (70-90%; see image), with some orthopyroxene, plagioclase, oxides and minor (secondary?) scapolite. These rocks have only received limited attention but have been compared to ‘pyroxenites’ from Salt Lake crater in Hawaii, even though they could also be mafic granulites.

Figure 1: PPL image of ‘garnet websterite’.

In our ongoing study, we are determining the geochemistry and formation processes of these rocks. The aim is to establish whether they are cumulates (e.g., Lu et al., 2018), deep AFC products or foundered, originally more plagioclase-rich granulites to compare them with “arclogites” (Lee & Anderson, 2015). Constraining their origin is important for understanding whether garnet-pyroxenite delamination is also possible in intraplate settings as a tectonic environment of net continental growth.

References:
Emo RB & Kamber BS (2022) Earth Planet Sci Lett 594, 117742
Partial melting of eclogite in Central Himalaya and its contribution to Miocene climate change
Zhang G.¹

¹The Key Laboratory of Orogenic Belts and Crustal Evolution, MOE, School of Earth and Space Sciences, Peking University, Beijing, China

The presence of eclogite is a widely accepted indicator of the onset of modern-style plate tectonics. However, eclogite is rarely preserved in many heavily granulite-overprinted orogens, which are particularly common across ancient metamorphic terranes (i.e., Archean and Paleoproterozoic terranes). Here, we show that eclogite melting processes may be principally responsible for the poor preservation of high-pressure records. We demonstrate eclogite melting via detailed petrological, geochronological, and geochemical analyses on eclogites and separated centimetric leucosomes from the central Himalaya. The central Himalayan eclogites were overprinted by strong granulite-facies metamorphism, such that omphacite is only sparsely preserved. Thermodynamic modeling results indicate the eclogite experienced two types of anatetic reactions: phengite dehydration melting at high pressure in the presence of omphacite, and subsequent omphacite-dominated melting during exhumation. Omphacite-dominated melting is characterized by the jadeite breakdown, releasing Na and Al into the melts. This melting mechanism subsequently forms a less sodic clinopyroxene and high Na₂O/K₂O melts. These Himalayan findings appear relevant to early Earth explorations because of the high thermal gradients and intense granulite-facies overprints, implying that partial melting of eclogite dominated by omphacite breakdown could have erased early high-pressure records of modern-style plate tectonics.

Furthermore, we found calc-silicate zones produced from eclogite melt–carbonate interactions that resulted in significant CO₂ emissions from the same area. The interactions occurred at high temperatures (685–828°C) in the lower crust (1.2–1.4 GPa) during the middle Miocene (ca. 17–14 Ma). Decoupled Sr–O isotope ratios suggest that calc-silicate zones were produced by eclogite-derived granitic melts infiltrated carbonates during exhumation. Estimates of the C budget indicate that 1.27 tons of CO₂ was liberated during the formation of each cubic meter of calc-silicates, and <4% of the C remained at the reaction site. Map analysis suggests granite pluton areas vary from <10–1705 km² in the Himalaya and each pluton contributed to carbon outfluxes of up to 1361 tons/yr. In this collisional orogeny, deep Earth degassing due to melt–carbonate interactions released 0.14–0.18 Pg/yr CO₂ during the middle Miocene. The release of such a large CO₂ reservoir into the atmosphere ultimately enhanced the global Miocene climate warming event.

References:
Hönisch B et al. (2023) Science 382
Entrainment of peritectic garnet in granite petrogenesis: evidence from metapelitic enclaves in S-type garnet granitoids
Wang, L.-J., Guo, J.-H., and Huang, G.-Y.

Entrainment of restite or peritectic assemblage has been proposed to account for the relatively mafic granites. In the eastern part of the Khondalite Belt of North China Craton, the paraautochthonous, high-temperature (>900 °C), 1.93 Ga, S-type Liangcheng garnet granitoids contain a distinctive type of metapelitic enclave, which reflect melt-restite separation. The metapelitic enclaves display variable shapes and have diffuse or transitional contacts with garnet-rich facies of the Liangcheng garnet granitoids. They are composed of garnet-K-feldspar-rich leucosome and mesosome (K-feldspar + garnet + biotite + plagioclase + spinel + quartz ± sillimanite). The metapelitic enclave shows significant heavy rare earth elements (HREE) depletion, indicating the loss of garnet-bearing melt. All the garnets in the metapelitic enclaves have similar major-element compositions to those in the garnet granitoids, and show remarkable HREE depletion, further confirming that HREE-rich garnets have migrated away. Large garnet poikiloblasts (up to 2cm) in the surrounding garnet granitoids are intergrown with quartz. Some of the garnets in the garnet granitoids display amalgamation features. We infer that a significant quantity of HREE-rich peritectic garnets from the metapelitic enclaves were entrained to the melt, migrated out of the enclaves into the magma, and then amalgamated to form composite garnets in the garnet granitoids. The entrainment of peritectic assemblage is probably an important process in S-type granite petrogenesis.

This work was supported by research grants No.42072220 from the National Natural Science Foundation of China.
Experimental investigation of H\textsubscript{2}O and CO\textsubscript{2} solubility in graphite- and fluid-saturated anatectic melt

Krona, M.\textsuperscript{1}, Tumiati, S.\textsuperscript{2}, Toffolo, L.\textsuperscript{2}, Bartoli, O.\textsuperscript{1}, Carvalho, B.B.\textsuperscript{1}, Dingwell, D.B.\textsuperscript{3}, and Cesare, B.\textsuperscript{1}

\textsuperscript{1}Dipartimento di Geoscienze, Università degli Studi di Padova, Italy, mikaelemma.krona@unipd.it
\textsuperscript{2}Dipartimento di Scienza della Terra “Ardito Desio”, Università degli Studi di Milano, Italy
\textsuperscript{3}Department of Earth and Environmental Sciences, Ludwig-Maximilian-Universität München, Germany

Current models of the geological carbon cycle consider carbonates as the main carriers of carbon into the Earth and largely overlooks the contribution from graphite-bearing lithologies (Plank & Manning, 2019). However, the melting of graphitic metasedimentary rocks in the lower continental crust may remobilize carbon (Cesare et al., 2005). Thermodynamic modelling of graphitic anatectic systems is not possible because the models do not account for carbonic species at suprasolidus conditions. Previous experimental studies have been conducted with carbonates, considering highly oxidized conditions, and these results cannot be extrapolated to graphitic systems (Carvalho et al., 2023). Hence, obtaining new solubility data on melt-bearing graphitic systems in the presence of a ternary H\textsubscript{2}O-CO\textsubscript{2}-CH\textsubscript{4} fluid is fundamental. The aim of this study is to improve our understanding of carbon mobility during anatexis in graphitic rocks.

In this study, experiments are carried out using a single-stage piston-cylinder apparatus (Univ. Milano). By utilizing the double capsule technique to control the oxygen fugacity of the experiment, the activity of water is maximized to simulate a fluid produced solely by dehydration (Connolly & Cesare, 1993). Haplogranitic glass is used as an analogue for an anatectic melt produced in the lower crust, and experiments are prepared with graphite and water as the source of the COH fluid. The speciation of the experimental COH fluid is quantified ex situ by quadrupole mass spectrometry (Tiraboschi et al., 2016). At 5 kbar and 900°C for an experiment duration of 24 hours, a fluid with XCO\textsubscript{2} = 0.57 is produced. Compared to the prediction made by thermodynamic models (XCO\textsubscript{2} = 0.5), the fluid is slightly enriched in CO\textsubscript{2}. This could be attributed to the effect of silica dissolution (Tumiati et al., 2017).

Going forward, the amount of H\textsubscript{2}O dissolved in the silicate glass will be determined using microRaman, and an attempt to quantify the dissolved CO\textsubscript{2} in the glass will be made. Moreover, the total H and C content of the silicate glass will be measured using nano secondary ion mass spectrometry to determine the solubility of H\textsubscript{2}O and CO\textsubscript{2} in the haplogranitic glass. Later on, the experimental data will be integrated into a thermodynamic model.

\textbf{References:}
Carvalho et al. (2023) Chem Geol 631
Tiraboschi et al. (2016) Geofluids 16, 841-855
Tumiati et al. (2017). Nat Commun 8, 616
Multiple high-pressure (HP) to ultrahigh-pressure (UHP) metamorphic terranes formed by continental subduction are overprinted by high-temperature (HT) or ultrahigh-temperature (UHT) metamorphism in the context of plate tectonic regimes, which reveal the tectonic evolution from subduction to orogenic collapse. The first centralized appearance of UHT metamorphism occurred in Neoarchean and several contemporaneous HP granulites or even eclogites have also been reported. However, the relationship between HP and UHT in Archean, when the plate tectonics are still in doubt, and its geodynamic processes and applicable tectonic model are poorly understood. Here we show a metasedimentary rock from Assynt block in NW Scotland recorded a completed process from HP to UHT at Neoarchean, which contains garnet, plagioclase, k-feldspar, sillimanite or kyanite, and biotite, accessory muscovite, corundum, spinel, rutile and zircon. Based on results from the microstructural reactions, thermometry, and the compositional isopleths in pseudosection we constrained the peak pressure metamorphism at 17-25 kbar and ~600 °C, and the peak temperature metamorphism at 900-1100 °C and 9-13 kbar. Zircon U-Pb age dated by SIMS shows that detrital zircon ages from ca. 2.9 to ca. 2.7 Ga, while the concordia age of metamorphic zircons is 2498 ± 6.4 Ma, with two apparent ages around 2.7 Ga. We confirmed a P-T path from HP to UHT at Neoarchean, and suggest that a thick and cold crustal root formed and experienced HP metamorphism at ca. 2.7 Ga due to plate subduction, then the cold and dense root delaminated, which leads to UHT metamorphism at ca. 2.5 Ga. The cratonic roots formed at ca. 2.7 Ga but then removed at ca. 2.5 Ga, consistent with the current thin lithosphere underneath Scotland measured by geophysical data.

References:
Brown M et al. (2018) Ame Min 103, 181-196
Dong J et al. (2024) Earth Planet. Sci. Lett. 638, 118743
Dumond G et al. (2017) Geology 45, 943-946
Priestley K et al. (2020) Geology 49, 190-194
Sajeev K et al. (2013) Gondwana Research 23, 526-538
Tappe S et al. (2011) Geology 39, 1103-1106
Wang HL et al. (2018) Tectonophysics 746, 562-571
Pfaffenbergite & “phase 430”, new mineral phases from melt crystallization in nanorocks
Ferrero, S.1, Lorenzon, S.2, Borriello, R.2,3, Mugnaioli, E.2, Borghini, A.4, Fuchs, R.5, Wirth, R.6, Schreiber, A.6, and Grew, E.S.7

1Department of Chemical and Geological Sciences, University of Cagliari, I-09042 Monserrato (Italy);
*Corresponding author: silvio.ferrero@unica.it
2Department of Earth Sciences, University of Pisa, I-56126 Pisa (Italy)
3Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, I-30172 Mestre (VE) (Italy)
4Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, 30-059 Krakow (Poland)
5Institute of Geosciences, University of Potsdam, D-14476 Potsdam (Germany)
6Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (GFZ), D-14473 Potsdam (Germany)
7School of Earth and Climate Sciences, University of Maine, Orono, Maine 04469 (USA)

The study of nanorocks (crystallized inclusions of anatectic melts) has been delivering in the last 15 years many intriguing novel insights into anatectic processes at depth. Although the main focus has been on the geochemistry of the partial melts, the systematic use of MicroRaman Spectroscopy (MRS) on nanorocks has revealed that the mineral phases crystallizing from the melt inside the inclusions on cooling are rather distinctive, i.e., rare feldspar polymorphs (kokchetavite, kumdykolite, syvatoslavite and dmisteinbergite) and the SiO2 polymorphs cristobalite and tridymite (Ferrero & Angel 2018; Wannhoff et al., 2022) are very common findings in these crystalline aggregates.

In the last 6 years MRS data collected in samples from numerous localities worldwide have been showing the presence in nanorocks of two novel crystal phases. For operational purposes we first identified them as “Phase 412” (Borghini et al., 2024) and “Phase 430” (Gianola et al., 2021; Ferrero et al., 2021), based on their prominent MRS vibrational modes at 412 cm⁻¹ and 430 cm⁻¹, respectively. Here, we present a crystallographic study of these two new mineral phases. Their crystal structures have been solved ab-initio and refined through three-dimensional electron diffraction (3DED) data, collected by a TEM (Gemmi et al., 2019).

“Phase 412” has been recently approved by IMA-CNMC with the name “Pfaffenbergite” (Bosi et al., 2024) based on its type locality Pfaffenberg in the Saxon Granulitgebirge (Bohemian Massif). This mineral has an ideal formula KNa3(Al4Si12)O32 and crystallizes in P6/mcc space group. Pfaffenbergite is isostructural both with kokchetavite (KAlSi3O8) and wodegongjieite (KCa3(Al7Si9)O32, Mugnaioli et al., 2022), a mineral recently found as an inclusion in corundum in chromitite from the Luobusa ophiolite (Tibet, China). The second mineral, “phase 430”, has the ideal formula K2Ca3(Al6Si14)O84 and P6/mcc space group. Preliminary results on “Phase 430” instead show that such phase consists of a feldspathoid-like tetrahedral framework with a completely new topology, currently still under investigation.

References:
Nanorocks in zircon from a garnet-free granulite: insights from petrography and major and trace elements compositions
Tedeschi, M.¹, Ferrero, S.², Wunder, B.³, Hermann, J.⁴, Borghini, A.⁵, Pettke, T.⁴, Lanari, P.⁴, Paiva-Silva, P.¹, Rubatto, D.⁶, Van Schijndel, V.³, Tollan, P.⁶, and O’Brien, P.J.⁷

¹CPMTC-IGC-Programa de Pós-graduação em Geologia, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil; mtedeschi@ufmg.br
²Dipartimento di Scienze Chimiche e Geologiche, Università di Cagliari, Monserrato, Italy
³GFZ German Research Centre for Geosciences, Telegrafenberg, 14473, Potsdam, Germany
⁴Institut für Geologie, Universität Bern, 3012 Bern, Switzerland
⁵Faculty of Geology, Geophysics and Environmental Protection, AGH University of Kraków, Kraków, Poland
⁶Eidgenössische Technische Hochschule, ETH, Zürich, Switzerland
⁷Institut für Geowissenschaften, Universität Potsdam, Potsdam, Germany

Partial melting and melt evolution and migration play an important role in the differentiation of continental crust. These processes affect metal transport and concentration, volatile cycling, and the mechanical properties of the crust. The study of nanorocks, i.e. crystallised melt inclusions (Bartoli & Cesare, 2020), has emerged in recent decades as a key approach in the investigation of melt evolution, as these inclusions are considered to retain pristine melt information (Cesare et al., 2015). While, most research has been carried out on nanorocks in garnet, melt inclusions in zircon are of growing interest because (i) none of the nanorock-forming major elements except SiO₂ are present in the host, (ii) zircon is formed by different (re)crystallization processes, and could therefore potentially record different stages of a metamorphic evolution, and (iii) the possibility of obtaining spatially resolved ages of the host.

Garnet-free granulites from the Guaxupé nappe (Brazil) record a complex history from protolith crystallization at ca. 2.55 Ga to ultra-high temperature (UHT) metamorphism at ca. 650-590 Ma (Tedeschi et al., 2018). The zircon crystals contain crystallized melt inclusions ranging in size from 1 µm to 15 µm distributed in cores and rims. MicroRaman spectroscopy combined with field emission gun electron probe microanalysis revealed that these inclusions consist of variable combinations of cristobalite/quartz, kokchetavite, kumdykolite, "phase 430", carbonate, pyroxene and, biotite and/or white mica. The re-homogenized nanorocks have a metaluminous to peraluminous mainly granitic composition. These results were compared with the composition of stromatic granulite from quantitative micromaps and bulk rock of outcropping segregated leucosomes. Trace element (TE) data show an enrichment of Rb, Cs, Ba and LREE in the nanorocks relative to the leucosomes. The lower concentration of CaO, MgO, P₂O₅ and TiO₂ and the TE signature suggest that the nanorocks represent melts formed at lower temperatures than those formed during UHT conditions recorded in the leucosomes. Thus, the nanorocks may have been trapped in zircon during prograde metamorphism. This hypothesis is consistent with the CL images and the U-Pb (LA-ICP-MS) data, which show that the nanorocks are hosted in zircon domains recording discordant dates in line with partial resetting of Archean ages, rather than being formed during UHT metamorphism in the Neoproterozoic. The homogenous composition of the inclusions and their location in cores and rims, disfavour the interpretation that the nanorocks record igneous crystallization.

References:
Bartoli O & Cesare B (2020) Rendiconti dei lincei 31,249-257
Cesare B et al. (2015) Lithos 239, 186-216
Tedeschi et al. (2018) Precambrian Research 316, 103-126
Melt inclusions trapped in peritectic minerals can record the earliest stages of melt generation and segregation during anatexis and provide insight into differentiation processes producing and modifying continental crust. Here we present a suite of polycrystalline melt inclusions, aka ‘nanogranites’, hosted in peritectic zircon from ultra-high pressure (UHP) eclogites in the D’Entrecasteaux Islands, southeastern Papua New Guinea (PNG). This terrane is the youngest known UHP terrane on Earth and is unique in that it was exhumed in an active rift. The PNG eclogites are exposed in quartzofeldspathic gneiss domes that preserve substantial evidence of partial melting, including abundant felsic leucosomes and dikes, and there are also large mappable granitoids. There is no field or petrographic evidence that the metabasite rocks melted; the only evidence is the nanogranite inclusions in the zircon. We focused on melt-inclusions in zircon from one eclogite to examine the relationship between the partial melting of eclogite and the geochemical evolution of the dikes and sills in this terrane.

To determine the composition of the melt that precipitated the zircons, we homogenized polycrystalline melt inclusions and measured their compositions using electron probe microanalysis. We performed two homogenization experiments at 775°C and 800°C and 1.5 GPa in piston cylinder devices at Syracuse University. In summary, we loaded ~25-30 mg of a zircon separate along with ~10 mg of distilled water into silver capsules that were run in 19-mm diameter NaCl-borosilicate glass-MgO assemblies. Experiments quenched to <100°C in <20 seconds. After experiments, the capsules contained zircons and aqueous fluid. During homogenization experiments, polycrystalline inclusions melted to form a homogeneous glass and a vapor bubble. The melt inclusion glass has a granitic composition similar to the dikes and sills in the gneiss domes. Future work will focus on characterizing the now-homogenized melt inclusions using electron probe microanalysis and phase equilibria modeling to constrain the pressure and temperature conditions of partial melting of the eclogite within this unique tectonic setting.
The sub- to supersolidus transition in the central Pyrenees, Lys-Caillaouas and Gavarnie-Héas
Kriegsman, L.M.1,2*, De Leijer, N.J.M.2, and Jordan, D.A.A.1

1Dept. of Research & Education, Naturalis Biodiversity Center, Darwinweg 2, 2333 CR, Leiden, Netherlands
2Faculty of Geosciences, University of Utrecht, Heidelberglaan 8, 3584 CS, Utrecht, Netherlands

Understanding partial melting is crucial when studying processes such as intracrustal differentiation and the mobility of critical metals within the continental crust. Within mountain belts, migmatites and deeply exposed granulites recorded the partial melting processes. In addition to being a location of melt production, migmatites also experience melt inflow from deeper sources. Furthermore, the interaction of crystallizing melts with restitic units leaves a retrograde overprint on peak mineral assemblages. This study focused on the interplay between these processes within a well-exposed transect in the Central Pyrenees.

A Variscan window is exposed beneath an Alpine nappe stack within the Gavarnie-Héas metamorphic dome and the western Lys-Caillaouas massif (Kilzi et al., 2016). This region features a transition from medium-grade metasediments to migmatites, progressing along a steep geothermal gradient of approximately 3-4 kbar. Fieldwork and detailed petrographic analysis reveal prograde metamorphic reactions, including the replacement of andalusite by sillimanite, subsolidus muscovite breakdown to K-feldspar, and the supersolidus breakdown of sillimanite, biotite, and quartz to form K-feldspar, garnet or cordierite, and melt. These reactions outline a clockwise pressure-temperature (P-T) path from low-grade to high-grade conditions. The Lys-Caillaouas and Gavarnie-Héas migmatites, both intruded by various magmatic rocks, exhibit notable differences in melt volume and composition, where the Gavarnie-Héas migmatites generally contain a higher melt concentration and more extensive biotite dehydration.

Geochemical analyses suggest wet prograde conditions with partial water loss during melting, followed by retrograde reintroduction of muscovite and chlorite. Peak metamorphic conditions were estimated at approximately 700°C and 3.5 kbar for Lys-Caillaouas and 730°C and 3.7 kbar for Gavarnie-Héas. Comparisons between leucosomes in migmatites and associated leucogranites highlight compositional similarities yet reveal distinct variations in element concentrations, indicative of differing melting degrees and fluid interactions. In certain Pyrenean samples, retrogression can be fully explained by fluids released from in-situ melts as investigated by mass balancing and trace element redistribution. However, other samples suggest the need for an external fluid source.

References:

(*This project is part of the FluidNET research and training network on fluid-rock interaction, funded by EU’s Horizon 2020 Marie Skłodowska-Curie grant 956127.)
A re-appraisal of metamorphic conditions in the lower crustal section of the Serre, Calabria
Schenk, V.¹ and Karmakar, S.²

¹Heidelberg University, Germany; Volker.Schenk@geow.uni-heidelberg.de
²Indian Statistical Institute Kolkata, India

The application of conventional thermobarometry in combination with detailed mapping and an extensive petrographic study of the reaction history of meta-igneous and metasedimentary rocks of the Serre has led to the recognition of a ca. 7-8 km thick exposed lower crustal section of Variscan age in southern Calabria (Schenk, 1980, 1984, 1990). After a kinematic prograde evolution, peak conditions were reached under static conditions that led to the formation of symplectic-like Opx-porphyroblasts at the expense of Bt and Hbl in felsic and mafic granulites, and to Sil-Kfs symplectites at the expense of Ms in metapelites. Prograde Grt reaction rims around cordierite point to a late-stage increase in pressure. The main prograde Grt growth in metapelites occurred in the stability field of Sil, which constrains PT estimates and the prograde path. The results of conventional thermobarometry (Grt-Px; Grt-Crd; Grt-Bt) and the systematic shift of XMg in coexisting phases (Grt, Crd, Bt) has been interpreted as related to decreasing T and P in the lower crustal section from ca. 790 °C/7.5 kbar at the bottom and 690°C/5.5 kbar at the top. A petrographically mapped metamorphic bathograd in metapelites (Grt-Crd-Sil-Bt; XMg Crd 0.75) subdivides the metamorphic grade of the lower crustal section. The T at the top of the section (690°C) has been deduced from assumed St+Qz stability. However, the prograde nature of this assemblage is ambiguous. We have applied Zr-in-Rt thermometry (Kohn, 2020) to felsic granulites and metapelites of the whole section to improve temperature estimates. We obtained, in accordance with the results from conventional thermobarometry, a difference of about 100 °C for the base and the top of the lower crustal section. However, the Zr-in-Rt temperature estimates are about 60 °C higher (ca. 850 to 750°C) than estimates based on conventional thermobarometry. The slow isobaric cooling of the lower crust (2-3 °C/Ma at P of 5-3 kbar) that followed a near-isothermal decompression event during the Variscan orogeny is well constrained by consistent isotopic cooling ages (Hbl, Fsp, Bt) and breakdown textures of cordierite that led to Sil+And+Ky bearing assemblages. Isobaric cooling at elevated P is also documented by regrowth of Grt-Cpx-Qz assemblages after Grt breakdown in mafic granulites.

References:
Tectono-metamorphic evolution from ultrahigh temperature granulite to amphibolite facies metamorphism in the Central Domain of Assam-Meghalaya Gneissic Complex: NE India


Dept. of Geology and Geophysics, Indian Institute of Technology Kharagpur, India, 721302
*Email- samantarayshuvankar@gmail.com

Ultrahigh temperatures (UHT) during metamorphism testify to extreme and anomalous thermal conditions in the continental crust. The Assam-Meghalaya Gneissic Complex (AMGC), which constitutes the exposed basement to the foreland basin of the NE Himalayas, have not been known to host UHT rocks. The AMGC is part of an extended cratonic fragment of the Indian Peninsula, and is divided into three distinct domains based on geochronologic information: the Western Domain (WD), Central Domain (CD), and Eastern Domain (ED). The earliest metamorphic imprint in the region dates back to ~1.5 Ga, and peak P-T conditions of metamorphism were estimated by previous workers to be ~8 kbar, 850°C (Dwivedi et al., 2023). In this study, the metamorphic evolution was investigated from phase equilibrium modelling of spinel-bearing high-Mg metapelites in the system NCKFMASHTiO. The peak temperature assemblage is Opx + Spl + Kfs + Qtz + melt, which is estimated from the P-T pseudosection to stabilize at approximately 8-9 kbar, 950°C-1000°C. This UHT metamorphism (M₁) is synchronous with the D₁ deformation event that produces a planar fabric (S₁) defined by the UHT assemblage Spl + Opx + Kfs + Qtz. The D₂ event is associated with isoclinal folding (F₂) of the S₁ planar fabric, forming the S₂ fabric axial planar to F₂ folds. The D₁ event is followed by cooling, leading to the breakdown of the Spl + Opx assemblage to form Grt and Crd. Sillimanite is produced locally by the reaction Spl + Qtz = Grt + Sil, resulting in spinel grains rimmed by Sil enclosed within Grt. Perithetic textures developed owing to the exsolution of high-temperature feldspar solid solutions during cooling. The S₂ assemblage Grt + Crd + perithetic Kfs + Qtz + Bi + Opx ± Sil stabilized at < 750°C and 6-7 kbar (M₂) under sub-solidus conditions. The entire metamorphic spectrum from M₁ to M₂ is considered a continuous event. A later D₃ deformation event is associated with recumbent folding (F₃) of S₂, producing an S₃ fabric axial planar to F₃ folds under upper amphibolite-granulite facies conditions. During this event, the S₃ assemblage was reworked, producing Grt through biotite dehydration melting through the reaction: Bi₂ + Sil + Qtz = Grt + Kfs + Melt. The localized generation of melt, primarily around Grt₂, is visible in outcrop, and is thought to have consumed all sillimanite in the matrix, leaving it only as inclusions within both garnet generations. Late-stage retrograde evolution involved the breakdown of Grt₂ to form Crd via the reaction Grt₂ + Melt = Crd₂ + Bi₂ + Qtz. The S₃ assemblage Grt₂ + Crd₂ + Qtz + Kfs + Plg + Bi₂ ± Opx evolved along a decompression dominated path to stabilize below ~650°C and 4-5 kbar.

Previously published geochronological data suggests that peak UHT metamorphism took place at ~1.5 Ga and was limited to the western part of the CD, with a ~500 Ma thermal overprint which operated in the upper amphibolite to granulite facies conditions (Chatterjee et al., 2007; Kumar et al., 2017; Yin et al., 2010). The peak UHT metamorphism at ~1.5 Ga metamorphism can be correlated with the assembly of the supercontinent Columbia. The Neoproterozoic-Cambrian metamorphism reflects the reworking of the CD during the Pan-African Orogeny.

References:
Chatterjee N (2007) Precambrian Research, 152(1-2), 1-26
Dwivedi SB et al. (2023) Geosystems and Geoenvironment, 2(2), 100161
Metamorphism of Chicheng HP and UHT granulites, northern Trans-North China Orogen and its implication for the initiation of the modern plate tectonics
Zhang, D.1*, O’Brien, P.J. 2, Chen, Y.3, and Guo, J.3

1State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing, China
2Institut für Geowissenschaften, Universität Potsdam, Karl-Liebknecht Str. 24-25, 14476 Potsdam, Germany
3State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

When did the modern-style plate start and how did it evolved is a significant and disputed scientific question in Earth Science. The deep subduction of ultra-high or high-pressure eclogites is a crucial indicator for the initiation of modern-style plate tectonics. A few Paleoproterozoic eclogites have been reported to have undergone deep subduction, and they show strong relationships with the evolution of old orogens, they can indicate the operation of modern-style plate tectonics. This study presents evidence of eclogite evidence for the evolution of the Trans-North China Orogen, through the further examination of Chicheng metapelite. Special multiphase solid inclusions are found in Chicheng, and confocal Raman Imaging shows that they are mainly composed of kumdykolite, kokchetavite, cristobalite and muscovite. They may experience near ultra-high pressure metamorphism with peak metamorphic PT condition of 2.5-2.7 GPa, 950-1050 °C, re-calculated by THERMOCALC. The 1.9 Ga HP granulites in Trans-North China Orogen and the 0.34 Ga HP granulites in Bohemian Massif have the same kinds of metastable inclusions. The result implies that the initiation of modern-style plate tectonics probably occurred around 1.91 Ga in the northern part of the Trans-North China Orogen.

References:
A PHREEQC model for the transformation of gabbro into rodingite
Butek, J.¹, Fabre, S.², Duchene, S.³, Spišiak, J.¹, and Grégoire, M.³

¹Faculty of Natural Sciences, Matej Bel University, Tajovského 40, 97401 Banská Bystrica, Slovakia; juraj.butek@umb.sk
²Institut de Recherche en Astrophysique et Planétologie (IRAP), CNRS, UPS, Observatoire Midi-Pyrénées (OMP), 14 Av. E. Belin, 31400 Toulouse, France
³Géosciences Environnement Toulouse (GET), CNRS, UPS, IRD, CNES, Université de Toulouse, Observatoire Midi-Pyrénées (OMP), 14 Av. E. Belin, 31400 Toulouse, France

Rodingite is a pale Ca-rich and Si-poor metasomatic rock commonly occurring in association with serpentinites. This rock is characterized by specific mineral assemblages consisting of hydrated garnet, diopside, vesuvianite, epidote-zoisite, chlorite, or prehnite (Li et al., 2004). However, natural rodingites are significantly heterogeneous in mineral composition (Butek et al., 2022; Duan et al., 2022). Major factors controlling the mineral diversity as well as details on fluid-rock interactions leading to the evolution of mineral and chemical composition during rodingitization have not yet been fully constrained.

In this work, we use PHREEQC software (Parkhurst & Appelo, 2013) to present a geochemical model for the transformation of a mafic rock into vesuvianite-bearing rodingite at a temperature of 300°C. A series of thermodynamic calculations was run using the database SUPCRTBLT converted by SupPhreeqc (Zhang et al., 2020) into a format readable by PHREEQC. Fluid-rock interactions were modeled in a Na-K-Ca-Fe-Mg-Al-Si-H-O-C-S-Cl system without using solid solutions or kinetic factors. Through these simulations, we investigate the effect of fluid composition and progress of the metasomatic process on the formation of rodingites.

Our results show that significant fluid volume (high fluid-rock ratio) favours the formation of rodingites. We thus conclude that the metasomatic process requires an open system with a high input of hydrothermal fluid. Additionally, a decrease in the Si/Ca ratio in the metasomatized rock is correlated to an increase in the volume of incoming fluid and this ratio can eventually serve as a proxy to express the extent of transformation. Whole rock chemical and mineral composition in natural rodingites are well reproduced by the model. Furthermore, the diversity of mineral parageneses results mainly from different degrees of transformation and only to a lesser extent to the chemical composition of hydrothermal fluid or protolith. Concerning the fluid composition, the hydrothermal fluid doesn’t need to be especially rich in calcium to transform a mafic rock into rodingite, but it must be low in magnesium, silicon, and have a high pH, which is naturally controlled by serpentinization of surrounding ultramafic rocks.

References:
Butek J (2022) Lithos 432–433 106902
Parkhurst DL & Appelo CAJ (2013) Techniques and Methods 6–A43
Zhang G (2020) Comput Geosci 143 104560
Metamorphic history of garnet pyroxenites from western Qaidam Block: Insights into the root of Andean-type arcs
Teng, X.¹, Wei, C.J.¹, and Zhang, J.X.²

¹School of Earth and Space Sciences, Peking University, Beijing, China, tengxia@pku.edu.cn
²Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China

Andean-type arcs form above subduction zones where the overriding plate is the continental lithosphere (Ducea et al., 2015). It is believed that the crustal thickness of Andean-type arcs is up to 60-80km, but the exposures of deep roots of thickening continental arcs are rarely reported.

The Qaidam block is one of the Asian blocks once located on the northern margin of East Gondwana. Previous studies on high-grade metamorphic rocks from the Huatugou region, the western Qaidam Block, revealed that the Qaidam Block experienced ultrahigh-temperature (UHT) metamorphism (>910–915°C/0.9–1.4GPa) during late Ediacaran to early Cambrian (Teng et al., 2020).

Here, we present the petrography, whole-rock and mineral chemistry, and results of phase equilibrium modeling and U-Pb dating for garnet pyroxenites that occur as lenses within granulite-facies sedimentary rocks in the Huatugou region. Geochemically, garnet pyroxenites are characterized by low SiO₂ (43.98–44.64 wt.%), high FeO (17.33–17.72%) and TiO₂ (1.49–2.22%), and enrichments in heavy REEs and HFSEs (Nb, Ta), with low Sr/Y ratios (<2). The least retrograde garnet pyroxenite comprises clinopyroxene (39 vol.%), garnet (37%), plagioclase (12%), amphibole (9%), ilmenite (2%), and orthopyroxene (1%), with minor amounts of apatite, rutile, and quartz. The peak mineral assemblage comprises garnet, clinopyroxene, and ilmenite, which are separated by coronal plagioclase and amphibole with local occurrences of fine-grained orthopyroxene. Garnets are Al₉₈.5₁Prp₂₁.₂₄Grs₂₆.₃₂Sp₄ with inclusions of amphibole, clinopyroxene, quartz, rutile, and apatite. Clinopyroxenes are dominantly diopsides. Textures and chemistries of coarse-grained clinopyroxene vary systematically from core to rim: in the core zone, clinopyroxene contains decomposed fine-grained albite and quartz, and exhibits high X₄₄ (0.74–0.77) and X₆₆ (0.13–0.17) with Fe³⁺/Fe²⁺ <0.05; to mantle, the clinopyroxene contains abundant orthopyroxene lamellae with decreasing X₄₄ and X₆₆; the rim of clinopyroxene lacks of orthopyroxene lamellae and is replaced by the clinopyroxene + plagioclase symplectite in some grains. Amphiboles are pargasite with 0.03–0.29 pfu Ti, plagioclases vary from albite to bytownite, and orthopyroxenes are hypersthene. Based on petrographic observation and phase equilibrium modeling, the prograde condition is 860°C/1.6GPa using inclusion assemblage, the peak metamorphic condition is constrained to 960°C/1.88GPa, and retrograde condition of 920–950°C/0.55–0.78GPa is constrained for the final assemblage of clinopyroxene, garnet, amphibole, plagioclase, ilmenite, and orthopyroxene. Therefore, the metamorphic P-T path of garnet pyroxene is clockwise crossing the kyanite-sillimanite transition under UHT granulite-facies conditions.

In the garnet pyroxenite, valid rutile U-Pb ages are dominated by 487±5Ma (MSWD=1.06), consistent with apatite U-Pb ages (480±4Ma, MSWD=0.79). They are interpreted as the cooling (ca. 500°C) ages for garnet pyroxenite. The rest of rutile yield ages of 536–532Ma, consistent with zircon metamorphic ages given by Mg-Al-rich granulites in the Huatugou region (Teng et al., 2020), and interpreted as the timing of decompression to significant cooling.

To sum up, the metamorphic history of garnet pyroxenites from the Huatugou region suggests that the Qaidam block, located on the northern margin of East Gondwana, experienced crustal thickening before ca. 530 Ma during southward subduction of the Proto-Tethys Ocean. The peak pressure recorded by garnet pyroxenite indicates a crustal thickness of ca. 70km beneath the western Qaidam block, the thickest continental arc ever reported in Gondwana’s peripheral orogens during late Ediacaran to Cambrian (Cawood et al., 2021).

References:
Cawood PA et al. (2021) Earth Planet Sci Lett 568, 117057
Teng X et al. (2020) Gondwana Res 87, 118-137
Investigations on crustal growth and involved processes are pivotal for understanding mineral systems. Part of the solution relies on the interpretation of the relationship between migmatites and granite-greenstone complexes. The Paleoproterozoic basement in north-eastern Suriname provides a moderately exposed transect from the Marowijne Greenstone Belt (MGB) to migmatites and a granitoid-gneiss complex, and allows examining their geodynamic relationship. Field relationships suggest that migmatites have developed at the expense of amphibolite and paragneisses (metapelites and metagreywackes), and that the migmatites grade into diatexite migmatite and subsequently heterogeneous granite. Phase equilibrium modelling of the migmatites resulted in peak conditions of 760 (± 30) °C and 4.6 (± 0.6) kbar, consistent with a low- to medium-pressure / high-temperature metamorphic gradient. Petrographic analysis shows interstitial quartz in the mesosome connected to leucosome and plagioclase-rich melt inclusions within amphiboles in the migmatitic amphibolite, peritectic garnet associated to retrogression in migmatitic paragneiss, all suggesting that the migmatites are issued from partial melting and that they share a common protolith with the greenstones.

To further test this hypothesis zircon U-Pb geochronology was applied. However, the interpretation of U-Pb ages in migmatites is not straightforward due to a combination of inheritance and high-temperature metamorphism. Concordia plots show a wide spread along the concordia line from early to late Rhyacian (2300 - 2050 Ma) and many points plot between the concordia and the origin due to Pb loss. In this study we demonstrate that detailed textural analysis of cathodoluminescence images from individual zircon grains by means of characterizing different core/rim textures in combination with their Th/U signature allows to distinguish among inherited and metamorphic-magmatic ages. A variety of zircons is obtained from migmatitic paragneiss (metatextite), diatexite migmatite and heterogeneous granite which can be characterized in grains showing cores with oscillatory zoning or cores with convolute zoning, rims with a diffuse boundary attributed to in-situ dissolution-precipitation or rims with a sharp boundary surrounding a rounded core, discordant to internal zones suggesting crystallization of new zircon around an inherited core. All these grains are interpreted as detrital grains issued from erosion of a magmatic protolith and deposited with the other detrital sediments forming the protolith of the paragneiss, which have then been variously affected by high-grade metamorphism and partial melting. In contrast, some grains display continuous oscillatory zones from core to rim and are interpreted as magmatic grains crystallized in the melt during anatexis. As a result, a cluster of core measurements from the metatextite plot on the Concordia yield an average age of 2146 ± 13 Ma (n=11, MSWD= 1), which is interpreted as representing one of the sources of the sediment, protolith of the paragneiss. These inferred inherited ages coincide with the age of the greenstones of the Marowijne Belt (2.26 – 2.15 Ga). A cluster of metamorphic rims yields an age of 2087 ± 10 Ma (n=3; MSWD=0.34), which is assumed to represent the metamorphic age of the migmatite. Th/U ratios of these rims yield values between 0.08 – 0.41, consistently lower than their Th/U > 0.5 in cores. Among concordant analyses of the heterogenous granite, a cluster of analyses yields an age of 2072 ± 10 Ma (n=16, MSWD=3.1) which is interpreted as the age of the high temperature metamorphism and crystallization from the melt. Therefore, we argue that the migmatites in northeastern Suriname are indeed partially molten equivalents of the MGB.
Assembly of the Riacho do Pontal orogenic wedge, NE Brazil: constraints from monazite petrochronology and phase equilibrium modeling

Tesser, L.R.1,2, Ganade C.E.3, Forshaw J. B.4, Basei, M.A.S.1, Lanari, P.2,4, and Cioffi, C.R.1

1Institute of Geosciences, University of São Paulo, Brazil (ltesser.geo@gmail.com)
2Institute of Earth Science, Université de Lausanne, Switzerland
3Brazilian Geological Survey, Rio de Janeiro, Brazil
4Institute of Geological Sciences, University of Bern, Switzerland

The South Borborema Orogen (SBO) developed during the late Neoproterozoic closure of the Sergipano oceanic basin at the northern margin of the São Francisco Craton (Ganade et al., 2021). The geological evolution of the SBO, particularly its thermal-metamorphic history, remains a subject of debate. Discussion is focused on the western section of the SBO, known as the Riacho do Pontal belt (RPB), estimates for the timing of crustal thickening vary from 630 to 570 Ma (Brito Neves et al., 2015; Caxito et al., 2016). These ages are based on zircon U-Pb dating of syntectonic granites, with no previously reported monazite ages in this region. In the RPB, three main tectonic zones, namely, external, central, and internal, compose a roughly ~200 km long east-west trending orogenic wedge characterized by a predominant top-to-the-south nappe stacking geometry (Brito Neves et al., 2015; Caxito et al., 2016). To better understand the metamorphic history of this ancient collisional orogen, we have employed a combined study of X-ray mapping, phase equilibrium modeling, Zr-in-rutile thermometry, and in situ (LA-ICP-MS) monazite U–Th–Pb dating coupled with monazite–garnet trace element geochemistry on six metapelitic schist samples spatially distributed along the main tectonic zones. St-Ky-bearing micaschist from the external nappes experienced a clockwise P-T path from 5.5 kbar and 525 °C to 11 kbar and 660 °C, followed by post-peak decompression to 8.5 kbar and 675 °C. In the higher-grade internal zone, Ky-bearing migmatitic micaschist recorded prograde to peak metamorphic garnet growth from 7.5 kbar and 560 °C to 13.5 kbar and 670 °C, followed by post-peak decompression above the H2O-saturated solidus to 10.5 kbar and 680 °C. Monazite in these rocks displays complex Y + HREE zoning, interpreted to vary alongside garnet in the equilibrium assemblage. Three distinct samples from the external zone yield weighted mean monazite U-Pb ages of 630, 610, and 590-580 Ma, interpreted as the timing of prograde, peak, and retrograde metamorphism, respectively. The Grt-Chl-Ms schist sample from the central zone yields weighted mean monazite U-Pb ages of ca. 680 Ma for cores and ca. 630 Ma for rims, interpreted as representing two distinct tectonic cycles, the first related to pre-collision accretion and the second as a result of regional metamorphism overprint. In the internal tectonic zone, monazite–garnet Y+HREE partitioning systematics are remarkably consistent across all samples and yield a U–Pb age range of ca. 590–580 Ma, interpreted as recording the timing of H2O-saturated melting and decompression. The overall results indicate that deformation and HP-amphibolite facies anatexis in the internal zone (590–580 Ma) are younger than the peak barrovian metamorphism (Ky-St zone) in the external and central zones (630–610 Ma). This observation, suggests a shift in the strength and mass transport of the orogenic wedge, leading to out-of-sequence thrusting propagation. We hypothesize that H2O-saturated melting may have weakened the upper nappes in the internal zone, allowing a localized deformation away from the lower units. Furthermore, our data highlight the importance of recognizing that monazite can (re)crystallize at various stages along the metamorphic P-T path and may not exclusively provide timing constraints on "peak" metamorphism. Therefore, it is imperative to use multiple petrochronologic approaches to robustly constrain the rates and timescales of metamorphic processes.

References:
Tracing the evolution of granulites and associated rocks at 2.9 Ga Fiskenæsset Anorthosite Complex, SW Greenland

Basak, S. and Szilas, K.

Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark (sbasak@ign.ku.dk)

Fiskenæsset Anorthosite Complex (FAC), located in the Fiskenæsset region in SW Greenland is among the best preserved high-grade Archean complexes in the world. The region hosts a variety of rock types ranging from metaperidotites, garnetiferous amphibolites, garnetiferous pyroxenites, clino-orthopyroxene bearing anorthosites, amphibole bearing anorthosites, and chromitites. Several studies for decades have interpreted this region to be the result of a subduction zone setting which involved hydrous recycling of lithosphere and arc magmatism operating as early as Mesoarchean (Windley et al., 1973). While such interpretations are highly debated, the aim of our project is to constrain the detailed metamorphic history of the FAC rocks post its emplacement, which can be traced back as early as Neoarchean based on metamorphic U-Pb zircon ages from the region (Polat et al. 2010, Keulen et al. 2010). Therefore, knowledge of temporally constrained Neoarchean P-T history of the region can be used as fingerprints of the prevalent geodynamic and tectonic processes from at least Neoarchean and onward.

Here we report the result of studies on garnetiferous amphibolites and granulites and associated anorthosite rocks from FAC. The metamorphosed mafic rocks occur in addition to enclaves within regional anorthosites, as individual bodies in the region. It is also worth noting that the region also has the type locality and several occurrences of sapphirine bearing rocks that occurs east to these rocks. Using an integrated approach of petrography, detailed elemental mapping, geothermobarometry, phase equilibria modelling and Lu-Hf garnet ages, we constrained the metamorphic P-T-t history of the terrain. Our preliminary result shows that the rocks from Fiskenæsset have been subjected to multistage metamorphic events where the original mafic rocks were metamorphosed to an amphibolite (M1 metamorphism) at ~5-7 kbar and ~700°C to high grade granulite facies conditions (M2 metamorphism) possibly at ~11-12 kbar to temperatures ~900°C, where they often crystallized corundum and orthopyroxenes (~4 wt% Al₂O₃) first and eventually sapphirine during cooling, as substantiated by textural observations. A K⁺ rich fluid is further affecting these assemblages during retrogression in its evolutionary course (M3 metamorphism) leading to biotite crystallization. Our results corroborates that the peak metamorphic event at lower crustal depths can be traced back as early as ~2.63 Ga from in-situ Lu-Hf garnet geochronology. Compositional zoning formed by diffusion of Fe-Mg has been measured at garnet-biotite contact. These are being modelled currently to determine the actual cooling/decompression paths post M3 event and the timescales over which the individual processes described above occurred.

References:
The Ivrea Verbano Zone (IVZ) is a fossil continental crustal section formed during Variscan and post-Variscan tectono-magmatic processes. This section is well-exposed on the surface due to the Alpine collision. The metamorphic sequence mainly comprises metasediments, metavolcanic rocks, and subordinate marble lenses, which have undergone multiple high-temperature (HT) metamorphic processes that locally modified the original chemical composition of these lithologies. Evidence of the HT metamorphism is observable in the field due to the presence of leucosomes intruding all metamorphic lithologies and often occurring sub-parallel to the metamorphic foliation (Schnetger, 1994; Kunz et al., 2014). These bodies serve as indicators of partial melting; however, this process is poorly constrained from a geochronological and petrological standpoint. However, the specifics of this partial melting, such as which lithologies were melted and the extent of melting, remain debated within the scientific community.

Here we report the occurrence of quartz-diorite leucosome intruding the lower crust’s metamorphic rocks in the central IVZ along Val Sabbiola. This body aligns sub-parallel to the foliation of the host rock and comprises andesine, quartz, biotite, K-feldspar (less than 5% by volume), apatite, and various accessory minerals including amphibole, zircon, ilmenite, titanite, allanite, pyrite, and magnetite. Biotite, as the primary hydrated ferromagnesian mineral, offers significant insights into the geochemical properties of the parental melts. Biotites in this dyke exhibit relatively high Mg# (0.57–0.61) and are relatively depleted in trace elements such as Nb (~34.9 ppm) and Ta (~0.9 ppm). U-Pb zircon dating predominantly indicates a Lower Permian emplacement age (288.7 ± 3.9 Ma), aligning with the main magmatic pulse of the IVZ (approximately 292 to 282 Ma; Peressini et al., 2007). Additionally, a few zircon crystals record peak granulite-facies metamorphism around 316 Ma (Ewing et al., 2013). The Hf isotope has an average value of -6.2, suggesting crustal lithology segregation, with only one zircon crystal showing positive values.

Preliminary findings from field relationships, mineral chemistry, as well as zircon U-Pb dating and Hf isotopes suggest that the quartz-diorite likely originated from crustal-derived calc-alkaline melts. These melts were generated by anatexis of mafic protoliths during post-collisional high-temperature metamorphism associated with the emplacement of the large Mafic Complex.

References:
Kunz BE et al. (2014) Lithos 190, 1-12
Peressini et al. (2007) J Petrol, 48, 1185-1218
New constraints on the high temperature metamorphism of the Oetztal-Stübai Complex (Eastern Alps)

Piccin, S.1, Favaro, S.2, Minopoli, L.1, Poli, S.1, Sessa, G.1, Tiepolo, M.1, Toffolo, L.1, Tumiati, S.1, and Zanchetta, S.2

1Dipartimento di Scienze della Terra, Università degli Studi di Milano, Via Botticelli 23, 20133 Milan, Italy
2Dipartimento di Scienze dell’Ambiente e della Terra, Università degli Studi di Milano-Bicocca, Piazza della Scienza 4, 20126 Milan, Italy; e-mail: stefano.piccin@unimi.it

The Oetztal-Stübai Complex (OSC) of the Eastern Austroalpine domain is one of the largest tectonic units recognized in the Alps extending between western Austria (Tyrol) and northern Italy (Autonomous Province of Bozen/Bolzano). The OSC is a polymetamorphic unit made of crystalline basement consisting of metasedimentary rocks (paragneisses and micaschists) hosting numerous bodies of metagranitoids and metabasic rocks, along with subordinate metacarbonates and ultramafics of igneous origin. The Alpine metamorphism affecting the OSC increases in temperature from 300°C in the north-west up to 500°C in the south-east (Purtscheller & Rammlmair, 1982).

Pre-Alpine evolution of the OSC is testified by the crystallization of Cambrian mafic to ultramafic cumulates with MORB-like signatures preserved in pods and layers within the Central Metabasite Zone (CMZ) (Miller & Thöni, 1995; Konzett et al., 2005); an Ordovician high temperature event resulting in widespread intrusions of granitoids and partial melting of metapelites (e.g. Winnebach migmatites); occurrence of eclogites of Variscan age within the CMZ and subsequent pervasive re-equilibration under amphibolite facies conditions. However, structural relationships in the field do not rule out the possibility of a pre-Variscan high pressure event.

Extensive field work, microstructural and petrological analyses, and radiometric dating are being carried out in two key areas, Längenfeld and Reschenpass/Passo Resia. The two areas are similar in the occurrence of two Ordovician intrusions, the Sulztal type S granite (Längenfeld) and the Klopaier Tonalite (Reschenpass), for which we obtained by U-Pb LA-ICP-MS dating of zircons ages of 482.4 ± 1.5 Ma and 460 ± 0.83 Ma, respectively.

In the Längenfeld area, rocks belonging to the CMZ show various degrees of metamorphic reactions progress often resulting in symplectic relationships. Mafic to ultramafic rocks, characterized by exceptionally well preserved cumulitic textures, display the destabilization at high pressure conditions of anorthite-rich plagioclase to omphacite + corundum intergrowths bordered by garnet, which completely replaces plagioclase in some samples as confirmed by REE patterns determined by in-situ LA-ICP-MS. Within these cumulates, newly discovered layers of troctolitic composition show corundum-bearing coronas around olivine and granoblastic textures with increased anorthite content in plagioclase rims, implying a static phase of high temperature recrystallization. Associated metacarbonates are characterized by the presence of olivine (Mg/(Mg+Fe) = 0.95) and Fe-spinel.

Additionally, we found evidence of partial melting involving both metapelites and eclogites of the CMZ, resulting in corundum-bearing migmatitic gneisses and eclogite-derived melts. The Variscan age of CMZ eclogites has been assessed by Sm-Nd mineral and WR isochrons in Miller & Thöni (1995), but unpublished U-Pb zircon data (Sollner & Gebauer in Hoinkes & Thöni, 1993) points to an age of 497 Ma for this high pressure event. This hypothesis deserves further investigations on account of our field work and newly discovered field relationships, suggesting the existence of a pre-Variscan high temperature event post-dating an older eclogite facies metamorphism.

References:
Timing and Metamorphic Evolution of the Deep Crust of Adria in the Valpelline Series
Filippi, M.¹, Caso, F.¹, Farina, F.¹, Ovtcharova, M.², Piloni, C.B.¹, and Zucali, M.³

¹Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, via Mangiagalli 34, 20133, Milano, Italy
Corresponding author: marco.filippi@unimi.it
²Department of Earth Sciences, University of Geneva, rue des Maraichers 13, 1205, Genève, Switzerland

We have constrained the metamorphic evolution (P-T-t) of Permian granulites and migmatites of the Valpelline Series, a portion of the deep crust of Adria preserved in the Dent-Blanche nappe of the Western Alps (Austroalpine domain). This crustal section, compared to other preserved Permian deep crust sections in the Alps (e.g., Ivrea-Verbano zone, Malenco unit, etc.), lacks Permian mafic intrusions, whose emplacement is associated with significant transformations in the host rocks. This makes the Valpelline series suitable to constrain the regional tectonic evolution of these basements during Permian extension. In this study, we implemented a multidisciplinary approach combining petrography, multi-scale structural analysis, U-Pb zircon and monazite geochronology, and geochemistry. The metamorphic P-T conditions are estimated integrating thermobarometry, pseudosections, and Ti-in-zircon thermometry.

We identified two partial melting events in the metapelitic migmatites of the Valpelline Series: the first occurred at around 293 Ma under P-T conditions of 870 – 890 °C and 8 – 10 kbar, evidenced by the Pl + Grt + Opx + Qz + Bt + Kfs + Ilm assemblage. The T/depth ratio of this event (25 – 30 °/km) is interpreted as resulting from an initial phase of lithospheric thinning, which followed crustal thickening due to the Variscan event. The second event occurred at around 287 Ma under P-T conditions of 700 – 780 °C and 4 – 6 kbar, as shown by the Bt + Crd + Grt + Pl + Qz + Ilm ± Sill assemblage. This second event, characterized by a T/depth ratio of 40 – 50 °/km, corresponds to a more advanced stage of lithospheric thinning.

The presence of abundant granulite relicts within these rocks, locally with internal foliation discordant to the dominant foliation, further indicates that the structure and parageneses of the Valpelline Series were acquired during a retrograde exhumation path. The structural homogeneity of the Valpelline Series suggests a consistent deformation regime during the Permian, with deformation localized across the entire unit rather than along discrete fault zones.
Granulite xenoliths from the Arabian plate margin: Reworking of the East African lithosphere?
Warhaftig, N.¹, Elisha, B.¹, Haviv, I.¹, Boneh, Y.¹, and Katzir, Y.¹

¹Dept. of Earth and Environmental Sciences, Ben Gurion University of the Negev, Be’er Sheva, Israel; ykatzir@bgu.ac.il

The Arabian Nubian Shield (ANS) exposes ~10⁶ km² of late Neoproterozoic (870-580 Ma) upper continental crust formed during the East African orogenesis. Mantle and lower crustal xenoliths brought to the surface by Neogene alkaline basalts of the vast volcanic fields of the Arabian plate yielded late Neoproterozoic Nd isochron and model ages, indicating coeval formation of the whole Arabian lithosphere (McGuire and Stern, 1993; Stein and Goldstein, 1996). The NW margin of Arabia was shaped by several Phanerozoic Tethyan rifting events and more recently by the tectonics of the Dead Sea Transform (DST), a young plate boundary, separating the Arabian plate from the Sinai sub-plate. These events are well recorded by the Phanerozoic sedimentary cover and more rarely by the upper igneous crust of the Levant margin, however, was the deeper Neoproterozoic Arabian lithosphere also modified and possesses younger additions?

Here we study granulite xenoliths associated with Pliocene basalt and scoriae erupted from the Qarnei Hittin volcano, located a few km west of the DST in the eastern lower Galilee, northern Israel. The xenoliths are characterized by preferably oriented bands of plagioclase and clinopyroxene and minor orthopyroxene, and some include kelyphite (plagioclase + clinopyroxene + spinel) after garnet. Petrologically, they resemble previously studied granulite xenolith suites from this volcano (Gazit, 2005) and elsewhere in the Arabian volcanic fields (McGuire and Stern, 1993; Al-Mishwat and Nasir, 2004), considered as cumulates from mafic alkaline magma that crystallized and later recrystallized within the East African lower continental crust, which stabilized at ~600 Ma. One of our sampled mafic granulite xenoliths includes a granitic domain (quartz + feldspar) with sharp contact against the host granulite. In-situ U-Pb dating (LA-ICP-MS) of six zircon crystals from the granite domain yielded an age of 338 ± 34 Ma, overlapping an early Carboniferous thermal and magmatic event in the Levant arch (Kohn et al., 1992; Stern et al., 2014; Golan et al., 2018). Petrologic study to constrain the peak pressure-temperature conditions of granulite facies metamorphism and later decompression and U-Pb apatite geochronology of the host granulite are on their way, aiming to provide insight on possible post East African modifications of the Arabian lithosphere.

References:
Al-Mishwat AT & Nasir SI (2004) Lithos 72, 45-72
Kohn B et al. (1992) Tectonics 11, 1018-1027
Stern RG et al. (2014) EPSL 393, 83-93
Reconstruction of the Variscan history of the Texenna basement (Lesser Kabylia, Algeria)

Bouadani, C.1*, Chopin, F.1, Štípská, P.2, Bendaoud, A.3, Fettous, E.-H.3, Schulmann, K.1,2, Miková, J.4, and Bouzekria, N.5

1Université de Strasbourg, CNRS, ITES UMR 7063, 5 rue René Descartes, 67084 Strasbourg Cedex, France; bouadani@unistra.fr
2Centre for Lithospheric Research, Czech Geological Survey, Klárov 3, 11821 Prague, Czech Republic
3Laboratory of Geodynamics, Geology of the Engineer and Planetology, Faculty of Earth Sciences, University of Sciences and Technology Houari Boumediene, BP32 El Alia Bab-Ezzouar, Algiers, Algeria
4Laboratories of the Czech Geological Survey, Geologická 6, Prague, Czech Republic
5Ecole Nationale Supérieure de Kouba, Algeria

The Lesser Kabylia massif, situated within the internal zone of the Alpine Algerian Tell in the Maghrebides, hosts a basement of Precambrian to Paleozoic age (?). Despite the negligible tectono-metamorphic Alpine overprint, the pre-Alpine history of this basement remains poorly constrained.

To address this knowledge gap, we conducted a petrological and geochronological study on the basement in the Texenna area, which comprises two main units: (1) a high-grade metamorphic lower unit and (2) a low-grade metamorphic upper unit containing Cambrian-Ordovician to Silurian-Devonian strata. The high-grade metamorphic unit is dominated by mafic granulites and migmatites with a common assemblage of Cpx–Grt–Pl–Qz±Opx±Sp and Grt–Bi–Pl–KPl–Qz±Sill±Sp, respectively. Notably, the felsic granulites and migmatites occasionally contain garnet and sillimanite, which enabled us to infer peak P–T conditions of P > 8 kbar and T = 775 °C using pseudosection modeling in the Perple_X software. Zircon U-Pb dating by LA-ICP-MS revealed predominant Permian ages ranging from ca. 266–295 Ma, with notable Carboniferous populations.

Our findings demonstrate the presence of a Variscan basement in this part of the Lesser Kabylia. The observed medium-pressure high-temperature metamorphism may be attributed to the closure of the Paleo-Tethys Ocean or its intracontinental propagator tip near the edge of Gondwana and the southern part of the European Variscan belt, sealed during the Pangea formation.
Unusual slow-cooling of amphibolite-facies rocks in an orogenic belt (Bolu Massif, NW Turkey)

Demirkaya, I.1,2, Topuz, G.1, Wang, J.-M.3

1Istanbul Technical University, Eurasia Institute of Earth Sciences, TR34469 Maslak, Istanbul, Turkey
2Istanbul Technical University, Mines Faculty, Geological Engineering Department, TR34469 Maslak, Istanbul, Turkey
3State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, 19 Beitucheng West Road, Chaoyang District, 100029 Beijing, China

The Bolu Massif within the Tethyan belt comprises two different tectono-metamorphic units separated from each other by crustal-scale fault. These are (i) an underlying amphibolite-facies unit, ca. 50 km long and 8 km wide, and (ii) a subgreenschist-facies metabasic to acidic rocks intruded by late Neoproterozoic tonalite-quartz diorite. The tectonic contact between them is sealed by latest Cretaceous limestones. Amphibolite-facies tectono-metamorphic unit is dominated by magmatic amphibolite with frequent leucocratic sills/dykes and stocks of trondhjemite-tonalite composition. Also, minor metapyroxenite and serpentinite are present within the amphibolite. Amphibolite contains hornblende, plagioclase ±biotite, ±epidote, titanite, ±rutile, ±quartz and ±pyrite. Rutile forms either discrete grains or resorbed grains within titanite. Accessory minerals are apatite and zircon.

U-Pb dating on zircons from amphibolite and trondhjemitic sills and dikes record ages of 250-260 Ma. These age values are interpreted as the age of peak metamorphic conditions and partial melting. The U-Pb dating on titanite and rutile yielded ages of 231 ± 6 and 181 ± 6 Ma (2σ), respectively. Available K-Ar hornblende and Rb-Sr biotite data in the literature are 222-205 ± 8 and 161-155 ± 2 Ma, respectively (Bozkurt et al., 2013). Combination of all the age data with respective “commonly accepted” closure temperatures of isotopic systems suggests that cooling from the metamorphic peak to temperatures of 250-300 °C lasted ca. 100 Ma. Metamorphic peak conditions are constrained as 670-750 °C and pressures on 0.5-0.7 GPa.

The metamorphic peak (250-260 Ma) corresponds to the time of sporadic basic to acidic magmatism in the Istanbul Zone, and interpreted to have occurred in a back-arc rifting. On the basis of textural characteristics, we can rule out multiple processes of burial-exhumation. No intrusions of Triassic to Early Cretaceous age are known in the region. So, we can rule out the fast cooling followed by pulsed re-heating due to younger intrusions. Overall, dates from the different chronometers are in close agreement with the commonly accepted closure temperatures for the respective isotopic system. On the basis of the field relations and late Palaeozoic-Mesozoic stratigraphy of the Istanbul Zone, we interpreted this case as a post-extensional static relaxation of disturbed geothermal gradient.

References:
Bozkurt E et al. (2013) Tectonophysics, 595, 198-214
Metamorphism and formation age of pelitic granulite in the Jiapigou area, North China Craton

Zhou, X.W. 1, Guo, J.L. 1, and Xu, Q. 1

1Institute of Geology, Chinese Academy of Geological Sciences

The Jiapigou metamorphic terrane is an important part of the archean basement in the northeast of the North China Craton. It mainly consists of intensely foliated tonalititcrtondhjemitic-granodioritic (TTG) gneisses, weakly foliated syn-tectonic potassium granites, charnockites and a minor amount of metamorphic supracrustal rocks (Ge et al., 2003). There have been significant controversies over its metamorphic evolution, and especially its tectonic attributes of the Neoarchean metamorphic events (Sun et al., 1992; Zhai and Liu, 2003; Zhao et al., 2005; Guo et al., 2016). Therefore, based on detailed field geological investigation, several representative pelitic granulite(sillimanite/kyanite garnet biotite monzogneiss) samples were systematically studied on petrology, zircon U-Pb chronology, and zircon Lu-Hf isotope geochemistry.

Petrographic observation and phase modeling indicate that the pelitic granulite experienced three stages of metamorphism. The temperature peak metamorphic stage (M1) is characterized by the presence of garnet+sillimanite+perthite+plagioclase, with a probable PT condition of 0.7-0.8 GPa at ca. 820-850 °C. The pressure peak metamorphic stage (M2) is characterized by overprinting of kyanite from sillimanite, with a probable PT condition of 1.0-1.2 GPa at ca. 780-820 °C. The post-peak decompression and cooling stage (M3) is characterized by the presence of garnet+biotite+muscovite+plagioclase under PT conditions of 600-650°C, 0.60-0.65 GPa. The PT path shows anti-clockwise pattern, indicating a sinking process of supracrustal rock blocks in the magma caused by large-scale magmatic activity.

Zircon U-Pb and Lu-Hf analytical results show that the protolith ages of the pelitic granulite range from 2521 Ma to 2506 Ma, the metamorphic ages range from 2489 Ma to 2399 Ma (average age is 2482±7 Ma). The zircon Hf model ages are between 2.9 and 2.7 Ga with positive εHf(t) values (0.42-4.76), which is familiar to the zircon Hf isotope characteristics of the TTG gneiss in the area (Guo et al., 2016), indicating that the TTG gneiss might provide material for the pelitic granulite. Most evidence suggest that the Neoarchean tectonic thermal event in the eastern part of the North China Craton was likely related to lithospheric heating caused by mantle plume activity.

References:


Discovery and its tectonic significance of Paleoproterozoic high temperature pelitic granulites in Alxa Block, North China Craton

Liu, P.-H.1, Zou, L.2, Wang, W.1, and Ji, L.3

1Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China, lph1213@126.com
2Key Laboratory of Orogenic Belts and Crustal Evolution, MOE, School of Earth and Space Sciences, Peking University, Beijing 100871, China
3Chinese Academy of Geological Sciences, Beijing 100037, China

High-temperature (HT) pelitic granulites, a prominent feature of Paleoproterozoic orogenic belts, preserve a record of geodynamic processes during the early Precambrian (Neoarchean–Paleoproterozoic). Quantitative peak P–T conditions and metamorphic timing of these HT granulites can constrain the tectonic processes and metamorphic evolution in such a tectonic regime. Here, HT pelitic granulites are first reported in the Diebusige Complex in the eastern Alxa Block, western part of the Khondalite Belt (KB), North China Craton (NCC). The detailed petrographic studies show that one pelitic granulite sample preserve the peak middle-pressure granulite-facies mineral assemblage which is defined by garnet + biotite + perthite + plagioclase + ilmenite + sillimanite + melt, and another sample show corona textures around relict garnet. The “white-eye” structure of garnet indicates that the pelitic granulites probably have undergone a post-peak near-isothermal decompression. Phase equilibrium modelling constrain a peak conditions of ~875°C/0.72~0.84 GPa implying a high apparent geothermal gradient (33°C/km) for these pelitic granulites. Based on the corona textures of garnet and mineral assemblages, we identified a clockwise P–T path involving a near-isothermal decompression process for these HT pelitic granulites. In addition, metamorphic zircon and monazite LA–ICP–MS U–Pb dating yields two meaningful age groups at ~1945 Ma and 1878–1866 Ma, which are interpreted as representing the timing of the near peak HT granulite-facies metamorphism the retrogressive amphibolite-facies metamorphism. The new and published metamorphic data indicate that the HT metamorphic conditions of the Diebusige pelitic granulite from the Alxa Block may be the result of long-term slow uplift with heating under a high geothermal gradient.
Eclogite and medium-grade metamorphic rocks from northeastern Hainan Island, South China.
Hu, J.¹ and Liu, J.²

¹Institute of Geomechanics, Chinese Academy of Geological Sciences, 11 Minzudaxue Nanlu, Beijing 100081, China.
Email: hujuan1314@163.com
²Institute of Geomechanics, Chinese Academy of Geological Sciences, 11 Minzudaxue Nanlu, Beijing 100081, China.

The eclogites were firstly discovered at Chaotanbi on northeastern Hainan Island, South China (Liu et al., 2021a, 2021b; Xia et al., 2019). These rocks mainly of garnet, omphacite, hornblende, quartz and rutile/ilmenite, with or without zoisite or plagioclase. The rocks experienced a clockwise metamorphic evolution, with peak P-T condition of 820-860 °C and 17.0-18.2 kbar (Liu et al., 2021a).

Isotopic geochronology studies (Liu et al., 2021; Xia et al., 2022) have shown that the formation of Chaotanbi eclogite is at ca. 364 Ma, most of the metamorphic zircons have low U and Th contents, and metamorphic zircons give two cluster age, white and bright cores yielded at ca. 350-330 Ma, and grey homogeneous rims/grains gave ca. 310-300 Ma, combined with zircon internal structure and inclusion characteristics, the former is interpreted as the early metamorphic age, the latter as the eclogite facies peak and retrograde age, the latter is consistently with the isochron ages of Lu-Hf and Sm-Nd obtained recently (Hu et al., in preparation), and subsequent pegmatite intrusion at 295 Ma.

Trace element geochemistry (Liu et al., 2021; Xia et al., 2022) shows that the protolith age of the Chaotanbi eclogite is mainly tholeiitic basalt. Based on geochemical data, the Chaotanbi eclogites can be divided into three groups. N-MORB-type Group 1 was originated from relatively high-degree partial melting of a depleted spinel iherzolite mantle source slightly modified by slab-derived fluids. E-MORB-type Group 2 was derived from a deeper, enriched spinel and spinel-garnet iherzolite transition mantle source. IAB-type Group 3 was generated by partial melting of the deepest spinel-garnet iherzolite mantle source modified by subduction-related recycled components.

The age, geochemical and Sr-Nd isotopic data suggest that the protoliths of the Chantanbi eclogites formed in a late Devonian mature back-arc basin setting, which was linked to the Jinshajiang-Ailaoshan-Song Ma-Hainan back-arc system between the South China and Indochina blocks in response to the evolution of the eastern Paleo-Tethyan Ocean.

The relatively high P-T metamorphic rocks from northeastern Hainan Island might have been generated by oceanic subduction leading to collision of the Hainan continental block, or at least part of it, with the South China Block during the Carboniferous. This scenario is similar to transitional eclogite-HP granulite facies rocks in the European Variscan orogen of the western Palaeo-Tethyan tectonic domain.

In addition, the Mulantou paragneisses in northeastern Hainan Island record amphibolite-facies metamorphism under conditions of 717-771°C and 4.4-5.8 kbar (Hu et al., 2022). Zircon and monazites in the paragneisses yield U-Pb metamorphic ages of 250-235 Ma. These data, combined with the geochemical characteristics of associated granitoids, suggest that the paragneisses were formed in a transitional tectonic setting from compression to extension.

References:
Xiaochun Liu (2021a) Journal of Metamorphic Geology 39, 101-132
Xiaochun Liu (2021b) Acta Petrologica Sinica 37, 143-161
Mengmeng Xia (2022) Lithos 418-149, 106677
Juan Hu (2022) Journal of Asian Earth Sciences 240, 105446
Late Ediacaran-Early Paleozoic HP/HT metamorphism in the northern Qilian block manifests a long-lived advancing accretionary orogeny along Northern Gondwana

Zhang, J.X.1, Mao, X.H.1, and Teng, X.2

1Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China (zjx66@yeah.net)
2School of Earth and Space Sciences, Peking University, Beijing 100871, China

Abstracts should be During Ediacaran-Early Paleozoic, Gondwana was flanked by a system of peripheral accretionary orogens (Cawood et al., 2021). The previous data show that the retreating accretionary orogens characterized the Ediacaran-Early Paleozoic Gondwana margin, which is dominated by low pressure/ high-temperature metamorphism and relatively high geothermal gradients (Oriolo et al., 2021). Here, we present evidence of high pressure/high temperature (HP/HT) metamorphism with moderate geothermal gradients from the northern margin of Qilian block in northern Tibet, which is considered as a continental fragment from East Gondwana.

The HP mafic granulites and felsic granulite are identified along the northern margin of the Qilian block. The peak mineral assemblage of mafic granulite is garnet + plagioclase + clinopyroxene + hornblende + ilmenite + quartz. The phase equilibria indicate that the peak P-T condition is 11-14 kbar and 800-900°C. The peak mineral assemblage of the HP felsic granulites is garnet + plagioclase + K-feldspar + kyanite + rutile + quartz, recording a peak P-T condition at 13 kbar and ca. 800°C. The peak pressure conditions of HP granulites correspond to crustal depths of ~40–45 km. The petrographic observation, mineral chemistry and phase equilibria indicate that the mafic and felsic granulites have experienced an Isothermal decompression P-T path after the peak stage. The HP mafic granulite and local garnet-cumulate represent mafic residues via dehydration melting involving breakdown of amphibole with anatectic garnet growth.

SHRIMP and LA-ICP-MS U-Pb dating results of zircons show that the protolith crystallization ages of mafic and felsic granulites are 1110- 1140 Ma and the metamorphic ages ranging between 460 Ma and 550 Ma. Monazite U-Pb datings of felsic granulites yield metamorphic ages between 455 Ma and 510 Ma, and rutile U-Pb datings give a cooling age at ca.450 Ma.

The Late Ediacaran-Early Paleozoic HP/HT metamorphism is interpreted to occur in continental arc lower crust (arc root), suggesting that the northern Qilian block experienced crustal thickening related to the southward subduction of the Qilian ocean (Proto-Tethyan ocean). Combined dextral transpressive deformation (Wu et al., 2024), we suggest that the northern Qilian block represents a long-lived advancing accretionary orogeny along the northern Gondwana. Our study indicate that the Ediacaran-Early Paleozoic orogeny along the periphery of Gondwana involved in both advance and retreat accretionary orogenesis in different domains.

References:
Cawood PA et al. (2021) EPSL 568, 117057
Oriolo S et al. (2021) Geoscience Frontiers 12, 109-130
Wu Y (2024) GSA Bulletin 136, 1889-1915
Identifying overprinting metamorphism in granulite-facies rocks via the application of LA–ICP–ToF–MS monazite U–Th–Pb age mapping

De Vries Van Leeuwen, A.1,2,3, Payne, J.4,3, Hand, M.1,3, Wade, C.2,1,3, and Morrissey, L.5,3

1Department of Earth Sciences, The University of Adelaide, Adelaide, SA, Australia
2Department for Energy and Mining, Geological Survey of South Australia, Adelaide, SA, Australia
3Mineral Exploration Cooperative Research Centre, Kensington, WA, Australia
4UniSA STEM, University of South Australia, Mawson Lakes, SA, Australia
5Future Industries Institute, University of South Australia, Mawson Lakes, SA, Australia

Corresponding author email: alexander.devriesvanleeuwen@adelaide.edu.au

Identifying overprinting metamorphic events in rocks which have previously attained suprasolidus conditions can prove troublesome. This is largely due to the refractory and thus unreactive nature of suprasolidus rocks when compared to their subsolidus counterparts. Consequently, the timing and nature of such overprinting metamorphic events can often be obscure and challenging to constrain. The Mulgathing Complex of the central-western Gawler Craton of South Australia is a prime example of a terrane exhibiting such behavior. The region attained suprasolidus conditions of ~7.0 kbar and 850 °C during the c. 2470–2420 Ma Sleafordian Orogeny (Halpin et al., 2016). Following this, between 1730 and 1690 Ma, the craton experienced a second amphibolite-to-granulite-facies metamorphic event known as the Kimban Orogeny. In the Mulgathing Complex, the expression of this event is restricted to terrane-scale shear zones which yield Kimban-aged metamorphic monazite (e.g., Swain et al., 2005). This overprinting event has also been identified to the south-east in the Sleaford Complex which was once contiguous with the Mulgathing Complex. In the Sleaford Complex, the expression of overprinting Kimban-aged metamorphism is pervasive, being readily identified in rocks distal from major shear zones (e.g., Dutch et al., 2010). Given that the Sleaford Complex experienced similar suprasolidus P–T conditions during the Sleafordian Orogeny (~4.5–6.0 kbar and 750–780 °C; Dutch et al., 2010), it begs the question as to why the expression of the Kimban Orogeny is not more pervasive throughout the Mulgathing Complex.

Unfortunately, unlike the Sleaford Complex, the Mulgathing Complex lacks the luxury of extensive outcropping exposures. Instead, the majority of available sample inventory exists in the form of drillcore, severely impeding the interpretation of structural relationships and our ability to link these with grain-scale metamorphic features. An initial attempt to identify the presence of Kimban-aged metamorphism in the Mulgathing Complex (i.e., outside of major shear zones) was conducted using conventional monazite U–Th–Pb spot analyses attained via laser-ablation inductively coupled plasma mass spectrometry (LA–ICP–MS). This attempt proved inconclusive, with few spurious analyses alluding to the presence of Kimban-aged overprinting metamorphism. As such, to elucidate the presence of a Kimban-aged overprint we employed a novel approach to rapidly generate high spatial resolution U–Th–Pb age maps of monazite via laser-ablation inductively coupled plasma time-of-flight mass spectrometry (LA–ICP–ToF–MS). These data reveal the presence of thin, discontinuous, Eu-rich monazite rims (~1–10 µm) which yield Kimban ages and mantle complexly zoned Sleafordian-aged cores. As demonstrated, such small and irregularly shaped domains are difficult to identify and analyse using conventional spot dating techniques, often resulting in mixed analyses and inconclusive data. This method offers a promising new way to analyse such features which are common in complex metamorphic rocks.

References:
Swain GM et al. (2005) Precambrian Res 139, 164–180
Dutch RA et al. (2010) J. metamorphic Geol. 28, 293–316
Archean metamorphic terranes are traditionally suggested to have cooled significantly slower than their Phanerozoic counterparts. Many have argued that this contrast in metamorphic timescale reflects changes in Earth’s tectonic regime (Chowdhury et al., 2021; Brown et al., 2022). However, diffusion chronometry-based cooling rate data on Precambrian rocks are very limited. We present a case study of metamorphic timescales on the Neoarchean Quetico metasedimentary belt of the Superior Province, which has been hypothesized to represent a fore-arc accretionary prism. Metamorphic grade decreases from the center of the belt (upper-amphibolite to granulite facies) to the northern and southern margins (greenschist facies). We combine conventional thermobarometry and phase-equilibrium modeling to constrain the peak temperatures and pressures and estimate metamorphic cooling rates from major element diffusion in garnet. The resulting cooling rates from across the subprovince exhibit large variability, with the fastest estimates comparable to those from the Phanerozoic eon and the lowest rates slower by two orders of magnitude. We then discuss the uncertainties and potential biases in determining diffusion timescales. The results will contribute to the diffusion chronometry data available on Precambrian orogens for assessing any fundamental change in global tectonics.

References:
Chowdhury et al. (2021) Gondwana Res 93, 291-310
Brown et al. (2022) J Geol Soc London 179
Variable Hf signatures in zircons of granitic bodies (can) already form by magma mixing in the source region
Fischer S.\textsuperscript{1}, Prave, A.R.\textsuperscript{1}, Cawood, P.A.\textsuperscript{1,2}, and Hawkesworth, C.J.\textsuperscript{1,3}

\textsuperscript{1}School of Earth \& Environmental Sciences, University of St Andrews, St Andrews, UK (sf67@st-andrews.ac.uk)
\textsuperscript{2}School of Earth, Atmosphere \& Environment, Monash University, Melbourne, Australia
\textsuperscript{3}School of Earth Sciences, University of Bristol, Bristol, UK

The Hf isotopic composition of the zircons in evolved continental crustal rocks (i.e. granitoids) can vary by as much as 9 εHf units, both amongst cogenetic zircon from a single sample\textsuperscript{[1]} or from different samples across the same pluton\textsuperscript{[2]}. Proposed explanations for this include: magma mixing of crust- and mantle-derived magmas with different Hf isotopic composition\textsuperscript{[1,3]}, a heterogeneous (crustal) source\textsuperscript{[4]}, variable dissolution of pre-existing zircon during disequilibrium melting which causes variable amounts of zircon-derived (“old”) Hf to individual melt batches (“zircon effect”)\textsuperscript{[5]}, or localised dissolution-(re)precipitation resulting in transfer of variable Hf isotopic compositions from inherited zircon domains to new magmatic domains\textsuperscript{[2]}.

We have measured Hf isotopic composition, U-Pb age, O isotopes, and trace elements in zircons from a mafic migmatite as well as co-eval, unmelted mafic units of a Archaean crustal cross-section (Kapuskasing uplift, Superior Province, Canada). A ~20cm-wide felsic sheet (melt channel) which cross-cuts the mafic migmatite is in petrographic continuum with the leucosomes of the host migmatite. Zircons from the felsic sheet show a significant and continuous spread of ~4 εHf units. Based on zircon morphology and trace element data, the more radiogenic Hf analyses can be matched to the zircons in the mafic migmatite and the unmelted lithologies. Thus, these zircons were likely derived directly from the migmatite. The less radiogenic zircons in the melt channel are distinctly different in morphology and trace element composition and must have been inherited from a different, but presumably nearby, rock unit. Zircon domains with Hf isotopic compositions in between these two endmembers form a mixing trend.

Our findings show that hybridisation of intracrustal melts and formation of a highly variable zircon Hf isotopic record typical of evolved crustal rocks can be achieved entirely within small melt channels hosted in the melting region. They also highlight the power of, and necessity for, a careful and holistic analysis of zircon and its diverse range of proxies compared to restricting analytical campaigns to age and Hf data alone.

References:
A multidisciplinary investigation of pluton formation and melt production in the deep crust: case study from the El Oro Complex, Ecuador

Dominguez, H.¹, Lanari, P.¹, Tamblyn, R.¹, and Riel, N.²

¹Institute of Geological Sciences, University of Bern, 3012 Bern, Switzerland
²Institute of Geosciences, Johannes Gutenberg University Mainz, J.-J.-Becher-Weg 21, D-55128, Mainz, Germany

The El Oro Complex, located in southwestern Ecuador, represents a tilted section of continental crust from the Ecuadorian forearc. The lower part of this complex experienced partial melting due to the intrusion of a gabbroic magma during a brief period of time in the Triassic. This process led to the formation of an S-type pluton, known as the Marcabelí granitoid. The brevity of this event offers a unique opportunity to explore the mechanisms of melt formation and transport within the continental crust, from deep to shallow levels.

In this study, we present a thermal model integrated with thermodynamics to simulate partial melting and melt extraction under various scenarios throughout the Triassic metamorphic history of the El Oro Complex. At each timestep, we simulate the evolution of temperature and mineral assemblages of the sequence, extracting melt from the model when a liquid percolation threshold is reached. The effects of fractional crystallisation and mineral entrapment on the melt composition are explored and the results are compared with new field and geochemical data. U-Pb geochronology and trace element analyses were also performed on zircons from the granitoid and migmatites, providing better constraints on the timing and duration of the pluton emplacement. The results of the numerical models show that contamination from the gabbroic melt is required to reproduce the natural data and could explain the observed spread in the bulk rock chemistry. This study shows that the combination of these different approaches offers new insights into the melting processes of the deep continental crust.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 850530).
U-Pb ages and Hf isotopes in zircon from charnockites and mafic granulite enclaves of the Luis Alves Craton, Southern Brazil

Basei, M.A.S.1, Tesser, L.1, Bhattacharya, S.2, Chatterjee, S.2, and Ghosh, A.2

1Geoscience Institute, University of São Paulo, Rua do Lago 562, SP, Brazil Postcode: 05508080 (baseimas@usp.br)
2University of Calcutta, Kolkata, (None) INDIA

The Luis Alves Craton corresponds to a continental fragment that occurs between Ribeira (N) and Dom Feliciano (S) Neoproterozoic belts, in the southern part of Brazil. Its basement consists of gneisses and migmatites among which high-grade metamorphic associations characterized by the presence of orthopyroxene can be found. Two large outcrops (Volkswagen and Infrasul) expose massif-type charnockite-enderbite gneisses with two types of mafic enclaves. These two localities were examined in detail with both locations displaying excellent outcrops of orthoerived charnockitic rocks with clear evidences of magmatic differentiation as the main process to explain the compositional variation found. Centimetric to metric bands of amphibolites, enderbites, charnockites (predominant rock), and mafic granulite enclaves occurs. Pink leucogranite cross cutting the banding are also observed in both locations.

The predominant mineral assemblages of these rocks are: 1) Charno-Endebrite gneiss with Plag-Qtz-KFls-Opx-Cpx-Ilm-Bio; 2) Coarse-grained mafic granulite enclave present Hbl-Plag-Opx-Cpx-Ilm-Qtz and 3) Opx-Cpx-Plag-Ilm-Hbl-Qtz-Bio characterise the fine-grained mafic enclaves. Zircon is an ordinary accessory mineral. Hornblende-mafic granulite enclave is characterised by reaction texture of prograde hornblende breakdown to produce Orthopyroxene and plagioclase, indicating its restitic character also indicated by marginal Mg enrichment in the hornblende. In addition quartzo-feldspathic films at hornblende margin may suggest in situ melt. The fine-grained enclave on the other hand, could represent peritectic segregates. Charnockite-enderbite gneisses with garnet assemblages are observed only in the Infrasul quarry. In both locations but predominantly in Infrasul quarry there are common evidence of retrograde reactions involving orthopyroxene with presence of significant hydrous phases (Biotite and Amphibole) mainly distributed along a late foliation in the shear bands, with no reaction relation with either garnet or orthopyroxene.

New SHRIMP and LAICPMS zircon analyzes held in rocks from both localities yield different ages. In the Volkswagen outcrop the values are concentrated around 2.5Ga (enclaves of mafic granulites, enderbites and charnockites) while the leucogranite cutting the banding indicated 2.3Ga. On the other hand, in the Infrasul Quarry all ages of the five rocks analyzed are around 2.2Ga. The Hf isotopes of both locations are very similar, being impossible to establish a consistent difference between them. The vast majority of Epsilon Hf values (T1) is slightly negative (-9.0 to 0.0) and the model ages (TDM) are all predominantly Archean with values ranging from 3.0 to 3.2Ga proving the crustal origin of these rocks. When considered the differences in U-Pb ages and the similarities in the Hf model ages, it can be proposed that the studied charnockitic rocks were formed and metamorphosed in deep crustal levels, representing the melting at 2.5 of the material accreted at the base of the crust around 3.1Ga.

Unlike what was observed at the Volkswagen outcrop, the relatively high-temperature shearing and hydrous fluid infiltration observed in the Infrasul quarry, might have resulted in complete resetting of U-Pb isotopic system, so that the 2.5 Ga anatectic event was erased in the Infrasul quarry, whereas the Hf isotopic system did retain the memory of crustal anatexitis around 2.5 Ga.
Burial of supracrustal sedimentary material is one of the processes that contribute to the formation of the lower continental crust. We investigate the rate of this process in Permian lower continental crust from the Malenco Unit (eastern Central Alps), which represents one of several fragments of preserved Permian lower continental crust with a significant metasedimentary component that are now exposed in the European Alps. Zircon U-Pb analysis by secondary ionization mass spectrometry is used to constrain the age of protolith deposition and subsequent high-grade metamorphism of felsic, garnet-rich granulites. Detrital zircon cores, many of which are small (<50 μm), yield concordant dates ranging from 387 ± 21 Ma to the Paleoproterozoic, with the majority of the dates falling in the range 450–1000 Ma. For the seven cores in each sample that gave the youngest concordant dates, replicate analyses were carried out. None of these cores had all measured U-Pb dates agree within error, indicating significant disturbance by the Permian granulite facies metamorphism. A 206Pb/238U age of 424 ± 6 Ma for a core with two overlapping replicate analyses is the best available constraint on the maximum depositional age of the sedimentary protolith. This maximum depositional age also coincides with the first significant population in the probability density plot of detrital core dates, which is a double peak at ~425 Ma and ~450 Ma.

Zircon detrital cores are separated from metamorphic overgrowths by a small seam of zircon that is riddled with tiny inclusions of quartz, biotite and muscovite. The first generation of metamorphic zircon rims has a 206Pb/238U age of 272.9 ± 2.8 Ma, displays steep heavy rare earth element (HREE) patterns and a moderate negative Eu-anomaly, and gives Ti-in-zircon temperatures of 740–780 °C. The second generation of metamorphic rims has a 206Pb/238U age of 263.8 ± 2.6 Ma, a flat HREE pattern and a pronounced negative Eu-anomaly, and gave Ti-in-zircon temperatures of 780–810 °C. Collectively these observations indicate that the first zircon rim formed on the prograde path at the onset of partial melting where muscovite was present but the rocks contained little garnet and no K-feldspar. Therefore, the metapelites resided at lower amphibolite facies, subsolidus conditions up until the intrusion of a Permian gabbro, which was emplaced shortly after the formation of the first generation of metamorphic zircon and caused heating to granulite facies conditions and widespread partial melting. There is no record of high-pressure metamorphism preceding granulite facies conditions, indicating that felsic lower crust in the Malenco unit was not formed by relamination.

The Malenco unit was situated at the north-eastern active margin of Gondwana 420 Ma ago. Subduction-related accretion of sediments at lower crustal levels shortly after their deposition could explain the formation of this felsic lower crust that resided at subsolidus conditions for up to 100 My prior to Permian extension, gabbro intrusion and granulite facies metamorphism.
The effect of ultra-high temperature (UHT) and recrystallisation events on garnet U-Pb ages
Beranoaguirre, A.1, Corvo, S.2, Millonig, L.J. 1, Langone, A.2, Marshall, H.1, Albert, R.1, Shu, Q.3, Brey, G.P.1, and Gerdes, A.1

1Frankfurt Isotope and Element Research Center (FIERCE) and Department of Geosciences, Goethe-University Frankfurt, Altenhöferallee 1, 60438 Frankfurt, Germany. beranoaguirre@fierce.uni-frankfurt.de
2Department of Earth and Environmental Sciences, University of Pavia, via Ferrata 1, 27100 Pavia, Italy
3State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China

U-Pb dating of garnet by LA-ICPMS has become a powerful tool in metamorphic studies (e.g. Millonig et al., 2020) as it provides valuable time constraints for metamorphic reactions/conditions, in a relatively fast and affordable way. However, the approach is still in its infancy and many challenges regarding the behaviour of U and Pb need to be addressed or further investigated. For this communication, we have studied garnet crystals from the Kaapvaal craton and the Central Alps, where the U and Pb isotope systematics responded differently to the respective metamorphic histories.

On the one hand, we analysed garnet from 16 UHT granulite xenoliths from the Star mine (Kaapvaal craton, South Africa). The samples contain garnet (up to 80 vol% in some samples) and variable amounts of sapphirine, plagioclase, quartz, sillimanite, and accessory phases. The estimated pressure-temperature conditions for the samples are 1 GPa and 1050 °C (Shu et al., 2024). The U-Pb dates obtained from the studied crystals span 400 million years with well-defined maxima at 3.09, 3.01 and 2.75 Ga. Regardless of the metamorphic interpretation of the ages (see discussion in Shu et al. 2024), the garnet U-Pb data records the UHT history of the garnet, which is distinctively older than the kimberlite eruption of ca. 124 Ma. Moreover, zircon U–Pb dates from previous studies show a single dominant age peak at 2.72 Ga.

On the other hand, we studied two samples from the Cima di Gagnone unit (Central Alps, Italy). The samples represent metasediments (plagioclase + quartz + biotite + muscovite + garnet + kyanite ± staurolite + accessories) that envelope UHP-HT ultramafic lenses. The rocks experienced synkinematic recrystallisation at pressure-temperature conditions of up to 1.2 GPa and 700 °C, although samples from the immediate proximity of the ultramafic lenses record significantly higher PT conditions of up to 1.7 GPa and 850 °C in the presence of fluids, and devoid partial melting (Corvò et al., 2021). The garnet-bearing sample in contact with the ultramafic lenses gave a more precise garnet U-Pb date of 40.7 ± 1.5 Ma, compared to the “country rock” garnet, which yielded 38.6 ± 6.0 Ma. In addition, the latter sample contained analyses that indicate a Jurassic component, which may represent a partial recrystallisation process of the garnet or a so far unrecognised geological event.

Our results indicate that the U–Pb system in garnet has a very high closure temperature (likely ≥ 1100 °C) and thus can retain its original isotopic composition even under conditions at the most extreme end of crustal metamorphism that are capable of resetting zircon. Such older U-Pb garnet ages can only be reset by partial or complete recrystallisation.

References:
Corvò et al. (2021) Lithos 390–391, 106126
Millonig et al. (2020) Earth Planet Sci Lett 552, 116589
Shu et al. (2024) Contrib Mineral Petrol 179, 49
Garnet ages, cooling rates and heat production in the Sri Lankan granulites
He, X.1,2, Hand, M.2, and Dharmapria, P.3

1 State Key Laboratory of Coal Resources and Safe Mining, College of Geosciences and Surveying Engineering, China University of Mining and Technology, Beijing 100083, China
2 Department of Earth Science, The University of Adelaide, Adelaide SA 5005, Australia
3 Department of Geology, Faculty of Science, University of Peradeniya, Peradeniya, Sri Lanka

Sri Lanka lies at the conjunction of eastern and western Gondwana, linking the continents of India, Madagascar and East Antarctica via the East African and Kuunga orogens. The Precambrian basement of Sri Lanka underwent an extensive high temperature to ultrahigh temperature (HT-UHT) metamorphism during Gondwana assembly in Neoproterozoic-Cambrian transition. However, there has been ongoing debate on the heat sources as well as the duration of HT-UHT metamorphism and subsequent cooling.

The ambiguity surrounding the duration of high-T metamorphism stems from the potential complexity of multiple-stage growth and dissolution of accessory minerals during granulite facies metamorphism, and their compositional decoupling from the bulk silicate mineral assemblage. Consequently, Sri Lankan rocks show a continuous range of concordant accessory mineral U-Pb ages that span more than 100 Ma. Despite a considerable number of studies, the significance of this age data and the thermobarometric evolution is unclear. Furthermore, little is known about the cooling history of the Sri Lankan granulites.

We have collected a suite of garnet Lu-Hf ages, together with biotite Rb-Sr and apatite U-Pb ages across the three high-grade tectonic units in Sri Lanka. In the Highland Complex, which has been the focus of the bulk of metamorphic research in Sri Lanka, ultrahigh temperature granulite garnet gives Lu-Hf ages of ca. 600-580 Ma, while lower temperature granulites have garnet Lu-Hf ages of ca. 560-550 Ma. Additionally in some samples, garnets record ages of ca. 1.8 Ga. This confirms previous suggestions that at least part of the Highland Complex comprises high-grade Paleoproterozoic metamorphic rocks. Importantly, the isotopic preservation of c. 1.8 Ga garnet suggests that despite the thermal intensity of Late Neoproterozoic to Early Cambrian metamorphism, garnet can retain useful age information, and therefore potentially illuminate the metamorphic structure of the Sri Lankan crust during Gondwana assembly. In addition to outcrop samples, we have analysed garnet grains in beach sands from a number of locations. These show Lu-Hf ages peaks at about ca.1.8 Ga and 550 Ma, as well as much younger signal of ca. 500 Ma. The significance of the youngest age population is still unclear.

Biotite Rb-Sr ages in tectonic units in Sri Lanka cluster at ca. 490-480Ma. Apatite U-Pb ages span from ca. 480 to 460 Ma. Inferred cooling rates using the different closure temperature of those geochronometers range between 3.5–6.5 °C/Ma similar to the cooling rate of ≤ 7 °C/Ma from Southern India and Madagascar.

To better understand the hear sources for HT-UHT metamorphism we have collected regional-scale measurements of in-situ heat-producing elements to better characterise in-situ thermal sources. Volume averaging of rock types indicates terrain-scale U-Th concentrations would have generated around 2 micro Wm-3 at the time of median peak metamorphism. This suggests the generation of HT-UHT metamorphism in Sri Lankan required a significant contribution from mantle heat.
Granulites record long-lived Meso-Neoarchaean orogenic plateau

Hand, M.¹, He X.²¹, Morrissey, L.³, Glorie, S.¹, Payne, J.³, and Bockmann, M.⁴¹

¹Department of the Earth Science, the University of Adelaide, Australia
²China University of Mining Technology, Beijing, China
³Future Industries Institute, and STEM, University of South Australia, Australia
⁴Geological Survey of South Australia, Australia

The formation and rise of continental crust during the Archaean has been the focus of much attention, leading to the creation of various proxies and other arguments to evaluate crustal thickness. However, where Archaean crust is well-preserved, metamorphic data contributes useful information about crustal thickness and the potential duration of its thermomechanical stability.

Mesoarchaean crust in southern India contains granulite assemblages that formed at 1.1 GPa and 900°C at around 3.1 Ga. The granulites contain metapelitic rocks, implying the crust was appreciably thickened. Post-peak mineral assemblages are typified by the formation of kyanite-biotite assemblages in metapelite and garnet in mafic rocks. Notably, they lack evidence for reaction textures that denote significant pressure drop despite their thermobarometric sensitivity to such evolutions, implying the crust remained thick with respect to the thermal time scale.

Lu-Hf dating of garnet in mafic rocks that don’t appear to have experienced c. 3.1 Ga high-P granulite metamorphism, and therefore are probably deformed and recrystallized post c. 3.1 Ga intrusives, give ages around 2.5-2.6 Ga. These garnet-bearing assemblages formed at pressures similar to that of the c. 3.1 Ga metamorphism, and again record no reaction texture evidence for pressure drop.

Given the lack of evidence for exhumation of high-pressure c. 3.1 Ga assemblages and the similarity in pressures between c. 3.1 Ga and 2.5-2.5 Ga mineral assemblages, we speculatively interpret the data to reflect the long-term existence of thick Meso-Neoarchean crust. The inferred timeframe corresponds in part to the aggregation of Kenorland and encompasses development of the globally recognized c. 2.5 Ga granulite systems. We speculate the c. 3.1-2.5 Ga rocks in southern India are a fragment of a Meso-Neoarchean orogenic plateau.
Anatectic rocks witness thermal evolution and fluid action in the Himalayan orogen
Min Ji$^{1}$, Xiao-Ying Gao$^{1,2}$, and Yong-Fei Zheng$^{1,2}$

$^{1}$School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China (minji@mail.ustc.edu.cn; minji@ustc.edu.cn)
$^{2}$Key Laboratory of Crust-Mantle Materials and Environments & Center of Excellence for Comparative Planetology, Chinese Academy of Sciences, Hefei 230026, China

Anatectic rocks (e.g., leucosome, leucocratic dike, and granite), formed through crustal anatexis at convergent plate margins, offer valuable insights into the chemical differentiation and compositional evolution of the continental crust. Crustal anatexis is triggered by an increase in temperature, a decrease in pressure (i.e. increasing geothermal gradient), or the addition of water, and proceeds via different anatectic mechanisms for different source rocks. Consequently, anatectic rocks exhibit diverse petrological and geochemical features, making them potentially powerful recorders of thermal evolution and fluid action at convergent margins.

The Cenozoic Himalayan orogen presents an excellent opportunity to test this hypothesis. The metamorphic evolution history of the orogen from the early to late Cenozoic has been extensively documented. The Higher Himalaya, generally referred to as its metamorphic core, exposes a suite of anatectic rocks with different petrogenesis (e.g., dehydration and hydration melting) alongside their potential source rocks (e.g., metapelite, metagraywacke, and granitic gneiss). In doing so, we conducted a comprehensive study of petrology, geochemistry, and thermodynamic modelling on both the source rocks and anatectic rocks in the Higher Himalaya.

The Higher Himalayan metamorphic rocks experienced metamorphism with increasing geothermal gradients from the early to late Cenozoic. In contrast, the anatectic rocks mainly formed in the late Cenozoic, indicating high geothermal gradients of the orogenic lithosphere at that time. Notably, the Nd isotope compositions of Higher Himalayan leucogranites exhibit a progressive decrease with time. This trend reflects an increasing contribution of materials with enriched Nd isotope signatures, such as the Higher Himalayan metapelites. Phase equilibrium modelling of metapelite, metagraywacke, and granitic gneiss shows that metapelite with enriched Nd isotope composition is the most fertile source rock, while granitic gneiss with relatively depleted Nd isotope composition is the least fertile. If the source of leucogranites is a mixture of these three rock types, then with increasing geothermal gradients, metapelite would generate a greater proportion of melts compared to other rock types. Consequently, the progressively decreasing Nd isotope compositions of leucogranites can be attributed to the increasing geothermal gradients.

Boron isotope geochemistry was employed to trace the fluid action, due to the enrichment of heavy boron isotope in fluids compared to coexisting minerals and melts. In a suite of metapelites and their derived leucocratic dikes, the decreasing $\delta^{11}$B values in tourmaline from low- to high-grade metapelites suggest that dehydration metamorphism results in the upward migration of metamorphic fluids enriched in heavy boron isotope in the early Cenozoic, and the higher $\delta^{11}$B values of leucocratic dikes compared to their source rocks can be ascribed to the addition of these dehydration fluids enriched in heavy boron isotope during anatexis in the late Cenozoic. This spatiotemporally coupled dehydration-hydration melting process highlights the role of early metamorphic fluids on later crustal anatexis.

This work was supported by funds from the National Science Foundation of China (42202044 and 42072070) and the China Postdoctoral Science Foundation (2023M733365).
Development of U–Pb zircon dating using 2-4μm spot size by LA-ICP-MS

Kudo S.1, Niki S.2, Hirata T.2, and Kawakami T.1

1 Department of Geology and Mineralogy, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo, Kyoto, 606-8502 Japan
Email: kudo.shumpei.84x@st.kyoto-u.ac.jp
2 The University of Tokyo, Geochemical Research Center, School of Science, The University of Tokyo, 7-3-1 Hongo Bunkyo, 113-8654 Tokyo, Japan

Accessory minerals such as zircon, monazite, rutile and titanite crystalizes during igneous and metamorphic processes to form internal structures such as oscillatory zoning and sector zoning, which contains the age information of the geological events [1]. Combining the trace element concentrations and formation age data in each growth domain with temperature and pressure conditions of minerals that coexisted in equilibrium is crucial to extract the information of the host rock histories [2]. However, conventional analytical methods with several tens of μm spot size often struggle to resolve the distinct growth domains with as narrow as 10 μm. For example, the zircon geochronology has been challenging and scarcely reported in the Himalayan region due to thin metamorphic overgrowths [e.g. 3,4,5].

Previous studies have employed Secondary Ion Mass Spectrometry (SIMS) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) depth-profiling techniques to date several μm thick overgrowths [e.g. 6]. While these methods offer high depth resolution of 100 nm, several growth zones can be mixed within a single ablation volume, especially in minerals with intricate internal structures. In contrast, LA-ICP-MS analysis with several μm spots allows targeted analysis of individual growth zones based on internal structural observations. However, achieving sufficient analytical precision with reduced ablation volumes has been a challenge for practical applications in geology.

In our study, we aimed to achieve high-sensitivity U-Pb isotope ratio analysis by utilizing a newly developed in-house femtosecond laser ablation system with a focused laser beam (~2 μm) and a multi-collector ICP-MS. Femtosecond lasers produce fine particles during ablation, minimizing particle loss during ablation and transportation. In addition, the small particle size enhances ionization efficiency in the ICP, leading to improved sensitivity and reduced elemental fractionation.

U–Pb dating experiments were conducted with optimised conditions of the laser, totaling 20 points for zircon standards GJ-1 and Plešovice (PSV), with glass standards employed for Pb/U correction. The data were 608 ± 23 Ma (2SE) for GJ-1 and 288 ± 10 Ma (2SE) for PSV, respectively. The result of PSV data showed approximately 15% systematic younging from the reference value [7], while that of GJ-1 apparently matched with the literature value [8] within the error range. Pb contamination on the analysis surface was not removed before measurement by pre-ablation, thus GJ-1, which has a lower uranium concentration than PSV, possibly picks up the effects of lead contamination more strongly. In addition, high lead blank values during analysis may contribute to age underestimation.

In this presentation, we will further evaluate the precision and accuracy of the reference zircon age data obtained using the highly focused laser beam coupled with multiple-collector ICP-MS, and discuss the potential application of the present technique to metamorphic geochronology.

References:
Mechanisms of episodic brittle failure in deep continental crust; testing models in the Western Churchill Province, Canada
Flynn, C.¹, Mahan, K.¹, Shinevar, W. J.², Holyoke, C.³, Lipper, C.¹, and Sims, J.¹

¹Department of Geosciences, University of Colorado, Boulder, 2200 Colorado Ave., Boulder, CO 80309
²CIRES, University of Colorado, Boulder, 1665 Central Campus Mall 216 UCB, Boulder, CO 80309
³Department of Geosciences, University of Akron, 302 Buchtel Common, Akron, OH 44325

Deformation mechanisms in continental crust predict a transition from brittle fracturing in the upper crust to viscous creep and diffusive processes in the middle and lower crust. However, evidence for episodic brittle failure of an otherwise viscously deforming deep crustal shear zone in the form of variably mylonitized pseudotachylyte is preserved in the Athabasca granulite terrane in the Western Churchill Province of the Canadian shield (Regan et al., 2014; Orlandini et al., 2019). The ca. 1.89-1.88 Ga Cora Lake shear zone is 6 km wide and was active during a decompression and cooling path from 35-25 km paleodepths (1.1 GPa to 0.8 GPa) and from 800°C to 650°C, respectively. The shear zone is located along a domain boundary that juxtaposes the plagioclase-rich and mafic roots of a large tonalite pluton against granitoids, felsic granulites, and metasedimentary rocks with a high modal abundance of quartz. Recrystallized grain sizes range from 100 to 500 micrometers near the margins of the shear zone to less than 10 micrometers at the core (Orlandini and Mahan, 2020). Quartz and plagioclase recrystallized grain size paleopiezometry suggests that differential stresses were around 50 MPa during the development of mylonitic fabrics throughout most of the shear zone, but they locally exceeded 175 MPa near the highly strained core. Strength contrasts between discrete lithologic bodies near the domain boundary may have led to localized stress concentration and brittle failure. To test this, we are conducting detailed field mapping to better constrain the geometries of affected units, and we are characterizing microstructural variation in host mylonites and deformed pseudotachylyte veins to evaluate strain history and deformation mechanisms. We perform kinematic vorticity analysis on rigid porphyroclasts and recrystallized grains in mylonitized pseudotachylyte veins as well as mylonitic and ultramylonitic host rocks to determine the relative contributions of pure and simple shear and also the degree of strain partitioning between these parts of the shear zone. We construct a 2D viscoelastic numerical model to determine under what conditions the observed lithological contrasts concentrate stresses enough to nucleate lower crustal earthquakes. Inputs to the model include field-constrained geometric relationships, observed mineral modes and grain sizes, and experimentally derived flow laws. Future work will also include fourier transform infrared spectroscopy measurements for water content that will be used to calculate water fugacity for better constraints on appropriate flow laws.

References:
Orlandini and Mahan (2020) JSG 141, 104188
Reconstructing strain patterns in a deep crustal shear zone in the Canadian Shield: Evidence from kinematic vorticity analysis of host mylonite and sheared pseudotachylyte

Lipper, C.¹, Flynn, C.¹, Mahan, K.H.¹, Gestos, A.¹, and Holyoke, C.²

¹University of Colorado Boulder. 2200 Colorado Ave, Boulder, CO 80309. Christina.lipper@colorado.edu
²University of Akron. 302 E Buchtel Ave, Akron, OH 44325

Strain partitioning in shear zones is induced by strength heterogeneity due to thermal variations, lithology, and/or microstructural components such as grain size. The Cora Lake shear zone in the Athabasca Granulite terrane in the western Churchill Province of northern Saskatchewan, Canada, is an excellent natural laboratory to investigate strain partitioning in lower continental crust. This 4-6 km wide granulite-to-upper amphibolite-facies shear zone was active over pressure and temperature ranges of 1.1-0.8 GPa and 800-650 °C, respectively, and serves as a major boundary between two lithologically distinct domains (Regan et al., 2014). The NW side of the shear zone is characterized by protomylonitic 2.6 Ga granitoids and felsic granulite whereas the SE side is dominantly 3.2 Ga anorthositic and tonalitic gneiss with scattered lenses of mafic granulite. Mylonite and ultramylonite near the domain boundary host pseudotachylyte that is commonly overprinted by kinematically compatible viscous deformation. This overprinting deformation suggests that the pseudotachylyte was intermittently generated while the shear zone was active in the lower crust (Orlandini et al., 2019; Orlandini & Mahan, 2020). In the mylonitized pseudotachylyte veins, rigid clasts of garnet, clinopyroxene and orthopyroxene up to several hundred microns in mean diameter derived from fractured ultramylonitic wallrock are set in a sheared, fine-grained (d=10 microns) matrix of neoblastic garnet, pyroxene, plagioclase, quartz, and iron oxides. Rigid grain net analysis was employed to determine kinematic vorticity of the host mylonite in a variety of lithologies and mylonitized pseudotachylyte. The observed range of mean kinematic vorticity is 0.43-0.66 in the host rock and 0.66-0.86 in the pseudotachylyte. Thus, deformation in the host mylonite appears to have had a strong component of pure shear, whereas the mylonitized pseudotachylyte was dominated by simple shear, perhaps reflecting a weaker rheology in the pseudotachylyte due to finer grain size and conditions more favorable for diffusive deformation mechanisms (Menegon et al., 2017). We will also use X-ray computed microtomography to explore 3-D clast geometric variations. Our results will be important for understanding the kinematic evolution of the Cora Lake shear zone and for efforts to better constrain the occurrence of and mechanisms for formation of pseudotachylyte in shear zones below the classic frictional-viscous transition.

References:
Menegon et al. (2017) Geochemistry, Geophysics, Geosystems 18, 12, 4356-4374
Orlandini et al. (2019) GSA Bulletin 131, 403-425
Regan et al. (2014) Canadian Journal of Earth Sciences 51, 877-901
Crucial role of water-present melting in metagranite: Implications for the instigation of crustal-scale shear zones
Vanardois, J.1,2, Trap, P.2, and Marquer, D.2

1UMR 7063 Institut Terre et Environnement de Strasbourg (ITES), Université de Strasbourg, 67084 Strasbourg Cedex, France
2UMR 6249 Chrono-environnement, Université de Bourgogne-Franche-Comté, 25030 Besançon, France

Where, when, and why large-scale shear zones nucleate and propagate into the continental lithosphere are critical issues that challenge the research in tectonics. The East Variscan shear zone is one of the crustal-scale strike-slip faults that shaped the Variscan orogenic crust during late Carboniferous time. Field-based structural analysis and petrological observations demonstrate that suprasolidus high-strain deformation zones and metagranite occurrences are spatially correlated. Among the three dominant lithologies forming this orogenic middle crust (metapelite, metagraywacke, and metagranite), petrological observations and phase equilibrium modeling indicate that the latter is the first lithology that melts during collision induced heating, in response to H2O-fluid-saturated melting. Our field data and modeling suggest that the water-fluxed melting of metagranite has a primary rheological control on the localization, instigation, and growth of crustal-scale shear zones in the middle crust. Thus, the distribution and geometry of metagranite at the crustal scale could be regarded as critical parameters influencing the rheological inheritance governing the tectonic evolution and localization of bulk strain in the continental lithosphere.
Into the structure of the Permian deep continental crust: a multiscale approach to reconstruct migmatization in the Valpelline Series (Dent-Blanche Nappe, Western Italian Alps)

Caso, F.¹, Filippi, M.¹, Piloni, C.B.¹, Roda, M.¹, Farina, F.¹, Piazolo, S.², and Zucali, M.¹

¹Dipartimento di Scienze della Terra “A. Desio”, Università degli Studi di Milano, Via Luigi Mangiagalli 34, 20133 Milan, Italy; fabiola.caso@unimi.it
²School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds LS2 9JT, United Kingdom

Melt production in the deep continental crust and migration towards shallow levels are processes that contribute to the chemical differentiation of the continental crust. The Valpelline Series cropping out for ca. 15 km along strike within the Dent-Blanche Nappe in the Western Italian Alps, provides a broad and continuous observation of the deep crust. For this reason, is a key target for investigating processes such as partial melting, granulitization, and melt migration during long-lasting lithospheric extension in Permian times (ca. 20 – 30 Ma, Kunz et al., 2018).

In this contribution, detailed mapping and structural analysis of the Valpelline Series allowed characterize the heterogeneity of the deep crust. The Valpelline Series consists of migmatitic metapelite with different mineral assemblages (i.e., garnet-, orthopyroxene- and cordierite-bearing), migmatitic amphibolite and marble intruded by aplite and pegmatite dykes (Caso et al., 2024a). Three superimposed foliations are recognized: the S₁ foliation occurs only within granulitic boudins across the whole unit and rarely in the metapelites. The dominant foliation S₂, parallel to the alternation between leucosomes and melanosomes, is marked by different parageneses in different locations, recording different metamorphic conditions, consistent with exhumation from about 35 to 20 km depth within less than a 10 Ma interval. Lastly, the S₂ is locally further transposed into a late S₃ foliation extremely sillimanite-rich, localized in discrete metric-thick bands, and wrapping around garnet, cordierite, and orthopyroxene (Caso et al., 2024a, b).

The presence of several granitic plutons at shallow crustal levels along the entire margin of Adria suggests that melt extraction could have been a continuous and efficient process during the Permian, even in the Valpelline Series. Horizons extremely rich in sillimanite, where the S₃ is the dominant structure, could testify to the interaction between the extracted melts and their host rocks.

References:
Caso F et al. (2024a) Geol Mag 160(11), 1983-2009.
Caso F et al. (2024b) J Struct Geol 182, 105099.
Coupled monazite and titanite petrochronology to unravel the shear zones activity from mid- to low continental crust (Ivrea-Verbano Zone; Italy)

Corvò, S.¹,²*, Maino M.¹,², Bonazzi, M.¹,², Simonetti, M.³, Montemagni, C.⁴, Zanchetta, S.⁴, Piazolo, S.⁵, and Langone, A.¹,²

¹Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy; stefania.corvo@unipv.it
²Institute of Geosciences and Earth Resources of Pavia, C.N.R., Pavia, Italy
³Geological Survey of Italy, ISPRA, Roma, Italy
⁴Dipartimento di Scienze dell’Ambiente e della Terra, Università degli Studi di Milano – Bicocca, Milano, Italy;
⁵School of Earth and Environment, University of Leeds, Leeds, United Kingdom

Dating the time of shear zone activity remains still challenging. Here, we present the results of several studies from different mid/low-crustal shear zones exposed in the Ivrea-Verbano Zone (Southern Alps, Italy): the Anzola shear zone (ASZ), the Forno-Rosarolo shear zone (FRSZ) and the Premosello shear zone (PSZ) (Rutter et al., 1993; Simonetti et al., 2021; Corvò et al., 2023). Although the activity of these structures has been associated with the Mesozoic rifting phase (Petri et al., 2019), the age of their activities is still poorly constrained. In particular, we report an attempt to date the deformation by combining monazite and titanite U-Th-Pb data.

Studied shear zones share a sub-vertical attitude and a thickness between 100 and 500m. While the ASZ and the FRSZ formed at the amphibolite- to granulite-facies transition, the PSZ overprinted felsic and mafic granulites. The sheared rocks developed in a lithologically complex made of paragneisses, mafic rocks and minor calc-silicates. Paragneisses consist of Grt, Kfs, Plg, Bt and Sill; mafic rocks contain Cpx, Amph, Plg, Opx, and Grt whereas calc-silicates are made of calcite-rich and calcite-poor layers plus Amph, Px, Plg/Kfs and Grt. For in-situ U-Th-Pb dating purposes, we selected monazite from FRSZ and PSZ paragneisses and titanite grains from FRSZ and ASZ mafic rocks and calc-silicates (Corvò et al., 2022; Simonetti et al., 2023). Monazite from (ultra-)mylonitic paragneisses occurs in different microstructural positions (either included in porphyroclasts or along the mylonitic foliation) and commonly presents complex Th and Y chemical zoning. Titanite from mylonitic mafic rocks and calc-silicates (Corvò et al., 2022; Simonetti et al., 2023). Monazite from (ultra-)mylonitic paragneisses occurs in different microstructural positions (either included in porphyroclasts or along the mylonitic foliation) and commonly presents complex Th and Y chemical zoning. Titanite from mylonitic mafic rocks and calc-silicates are common along the foliation. Two types of titanite textures were identified: i) strongly zoned grains with LREE depleted rims/tips and ii) homogeneous grains. Both types show evidence for intracrystalline deformation (e.g., deformation twins and systematic crystal lattice bending).

U-Th-Pb dating across monazite and titanite revealed a contrasting behaviour of the two geochronometers. The Y-poor monazite domains give mostly Early Permian-Triassic ages, while the Y-rich domains provided late Triassic-Early Jurassic dates likely associated with fluid-assisted syn-deformational recrystallization. On the other hand, the titanite domains characterized by deformational features provide a lower intercept age at the Jurassic age. According to chemistry and isotopic data, while monazite recorded intense reactivity during Triassic ages, titanite locally developed syn-deformational rims or external domains providing Jurassic lower intercept ages. This contrasting behaviour could be interpreted as the result of different response to changing P-T-composition and fluid availability conditions during the same deformation history. However, the combination of petrochronological and microstructural results and the contrasting behaviour of the two independent geochronometers lets to constrain a long-lasting deformation of the shear zones throughout the Triassic until Jurassic time. In particular, during this time interval, the activity of shear zones in the Ivrea-Verbano Zone was, within error, simultaneously at different crustal levels.

References:
Corvò S et al. (2022) Lithos 106745
Corvò S et al. (2023) Earth Planet Sci Lett 620(C):118349
Simonetti M et al. (2021) Ofioliti 46(2):147-161
Simonetti M et al. (2023) J Struct Geol 104896
Chamrousse is located at the southern end of Belledonne massif in the External Crystalline Massifs (ECM) of the Western French Alps. The ECM are a privileged domain for understanding the construction of the Variscan basement (Guillot et al., 2009; Faure & Ferrière, 2022), as Alpine deformation rises only to a low degree of metamorphism (greenschist facies conditions (Rolland et al. 2003)) and is mainly localized in shear zones (Rossi and al., 2005). Identifying the ante-Variscan oceanic and continental domains whose amalgamation led to the construction of the belt remains a challenge.

The ophiolite of Chamrousse has been interpreted as the oldest and best preserved ophiolites in the Variscan terranes with an age of 496 Ma (Ménot et al., 1988). However new geochemical and geochronological data obtained in situ on zircon grains call into question the existence of a Cambro-Ordovician ocean at Chamrousse. The base of the complex was interpreted as volcano-sedimentary and sheeted dyke units. They are, instead, made up of banded mafic and felsic units, now transformed into amphibolite and leptynite, emplaced in a continental setting, during the Early Paleozoic rifting of the Gondwana northern margin. The ophiolite, composed of gabbros and serpentinites, outcrops at the Chamrousse summit and is of Lower Carboniferous age.

All the Chamrousse units are affected by ductile deformation accompanied by metamorphic recrystallizations previously attributed to oceanic extension (Guillot et al., 1992). However, this model has difficulty in explaining the pervasive deformation and remobilization of continental crust in the amphibolite facies. U/Pb dating of metamorphic apatite in the Cambro-Ordovician lithologies suggests that their deformation occurred during the opening of the oceanic domain. In addition, the localized intense mylonitization, sometimes up to barely the migmatitic stage, coupled with U-Pb dating of gabbros on zircons andapatites suggests that the Chamrousse ophiolite may have been intensely deformed during the oceanic stage (pre-Variscan stage) and to a lesser extent during the Variscan collision. Field and microstructural observations, coupling geochemical, geochronology and thermobarometric data reveal a complex and multiphase tectonic-metamorphic history.

References:
Seismic deformation and water-fluxed melting of the upper continental crust (N Sardinia, Italy)
Casini, L.¹, Corvò, S.²,³, Idini, A.¹, Ferrero, S.⁴, Langone, A.²,³, and Maino, M.²,³

¹Department of Chemistry, Physics, Mathematics and Natural Sciences, University of Sassari, Italy; casini@uniss.it
²Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy
³Institute of Geosciences and Earth Resources of Pavia, C.N.R., Pavia, Italy
⁴Department of Chemistry and Geology, University of Cagliari, Italy

Recent works have demonstrated that water-fluxed melting is an effective mechanism to produce large volumes of low-temperature silicic melts at relatively low pressure, with important consequences for localization of deformation and the rheology of the continental crust (e.g., Collins et al., 2016; 2020; Tafur & Diener, 2020). Yet, several arguments have been used to question the commonness and the overall effectiveness of water fluxed melting, of which the most relevant is the low porosity of metamorphic rocks in the source region of migmatites.

Here we present field and micro-structural observations, geochemical data, and the results of preliminary pseudosection modelling from the Punta Bianca massif, a late Carboniferous migmatitic complex exposed in N Sardinia, Italy (Casini et al., 2023; De Luca et al., 2023). Migmatites consist of quartz + biotite + plagioclase + K-feldspar metatexitic orthogneisses, garnet and cordierite-bearing diatexite and metatexites, derived from metasediments. Structural evidence and pseudosection modelling suggest that anatexis was episodic involving two main stages of partial melting. The first melting stage M1 is in the upper amphibolite facies (0.6-0.9 GPa, 740°C). Cordierite overgrowths replacing sillimanite suggests decompression followed cooling below the solidus at low pressures of about 0.2-0.3 GPa (Casini et al., 2023). The M1 migmatitic fabric is offset by fractures and pseudotachylyte-bearing faults suggestive of cooling to greenschist facies conditions. Garnet/cordierite-bearing M2 diatexites incorporate fragments of metatexitic orthogneiss deformed by pseudotachylyte, and migmatitic metasediments. Monazite and zircon U-Pb dating of different leucosomes and pseudotachylyte veins confirm the field relationships and indicate that brittle deformation likely occurred shortly before the M2 melting stage.

The absence of peritectic minerals in diatexite, the substantial increase of the melt to protholith ratio, and the relatively low temperature suggest water-fluxed melting during isobaric re-heating up to 750°C. The dense network of fractures and faults cutting through the metatexitic orthogneiss may account for the fluid budget of M2 by increasing the dynamic porosity of the metamorphic crust. Beyond providing access to external fluids, flash heating during co-seismic deformation may be responsible for boiling of biotite yielding to instantaneous release of a large amount of fluids in situ.

References:
De Luca et al. (2023) Journal of Maps 19, 2182721
Collins et al. (2016) Geology 44, 143-146.