GEOL360 Topics 9 and 10: Igneous & metamorphic geochemistry

9.1 Introduction

Igneous and metamorphic geochemistry are usually covered in some detail in petrology classes, since geochemical techniques are very powerful in deciphering the history of rocks.

The more important aspects of igneous geochemistry include major and trace element modelling, deciphering isotopic signatures, and geochronology of igneous events. Metamorphic geochemistry involves the study of the redistribution of elements between different phases (minerals and fluids) as the phase assemblage changes in response to changing pressure and temperature. Geochronology of metamorphic events is also very important, and often more complex than igneous geochronology. A brief summary of some facets of igneous and metamorphic geochemistry that we have already met previously:

Major element modelling: knowledge of phase equilibria (igneous phase diagrams) allows us to predict what crystals should fractionate from a cooling magma. This can be tested by major element analysis.

Trace element modelling: once we know which phases were crystallizing, knowing the distribution coefficient of different trace elements between melt and crystals will allow us to predict trace element trends (often the trace elements are used to infer what minerals remained in the source after melting).

Isotopic signatures: different sources have different isotopic characteristics (remember CHUR, the depleted mantle, etc.) Interpretation of these requires modelling mixtures of different materials with different concentrations and isotopic ratios, which can get complicated (especially for radiogenic systems).

Geochronology: radiogenic isotopes can be used not just to infer the age of crystallization of an igneous rock, but in some cases also magma chamber residence times. In metamorphic rocks, pressure-temperature-time paths can be constructed, giving important information about the rates of crustal processes such as tectonic burial and exhumation. Different systems with different closure temperatures can record cooling paths over long times.

Thermodynamic modelling can be used to predict the phases present in a given metamorphic rock composition as a function of pressure and temperature. Kinetics is a constant problem in metamorphic petrology, although slow kinetics is useful in preserving high pressure metastable phases (e.g. garnets, mantle diamonds).

Stable isotopes can also be applied to thermobarometry in metamorphic rocks, e.g. $\delta^{18}$O distribution between quartz and various other minerals.
9.2 Metamorphism and Melting in the Himalaya and Brazil

Instead of a lecture, I am going to do a colloquium-style talk, although with more pausing to explain the geochemical aspects. This talk integrates both igneous and metamorphic petrology, with substantial use of geochemistry for deciphering petrological and geochronological problems.

Below is the abstract, and on the following pages is a summary of the talk. I strongly encourage you to take more notes than I provide here – if nothing else, it is good practice. Please ask questions as they occur to you during the talk (or write them down and ask me at the end if you prefer).

Abstract:

Hot Rocks in High Places: Metamorphism and Melting in the Himalaya and Brazil

Melting during collisional orogeny is a very important geological process, affecting the chemistry, dynamics and thermal evolution of mountain belts. Melting of continental crust requires a region of “fertile” source materials, containing either a hydrous fluid or hydrous minerals, and high temperatures. Melting results in both the chemical differentiation of the crust, including the redistribution of heat-producing elements, and in an abrupt decrease in the strength of the crust, which may lead to “orogenic collapse”. One approach to investigating melting during orogeny is to study the resulting granites; another is to examine the evidence preserved in the metamorphic rocks left in a source region once melt has been extracted. I use both approaches to deduce the pressure-temperature-time paths followed during metamorphism, melting, and exhumation. I combine this information with structural, geochemical, and geochronological data, to reconstruct events deep within the crust during orogeny.

I will discuss two examples of melting in collisional mountain belts; the western Himalaya in northern Pakistan (Cenozoic orogeny) and the Araçuaí belt in eastern Brazil (Neoproterozoic orogeny). In the tectonically active western Himalaya, granites as young as 1 Ma are now exposed in cliff faces at altitudes of over 5000m. Vigorous erosion is currently exhuming deep crustal levels at a rate of several km/m.y., causing three different melting episodes within the last ten million years. In the Araçuaí orogen, formed during the assembly of west Gondwana, an unusual plate tectonic setting led to the development of a high, narrow plateau of thick crust. The plateau collapsed once melting initiated in the mid-crust, and exhumation by lateral spreading led to further melting of both the crust and mantle. From the beginning to end of this collision, a total of six different granite suites were produced over a 100 million year period.
Talk outline:

1. Introduction: metamorphism, melting and exhumation in mountain belts

There are several significant remaining problems in the study of deep crustal rocks brought to the surface in mountain belts:

(i) What triggers melting? How does the crust melt more than once?
(ii) How quickly does melting occur, and for how long does melting continue?
(iii) How are deep rocks exhumed (get to the surface), and how fast?

In this talk I will discuss two case studies, first the western Himalaya (Cenozoic) and second the Araçuaí belt, Brazil (Neoproterozoic). In each case the problem is basically to understand how and why the crust melted several times during a single orogenic event, how long melting lasted, and how hot deep rocks were exhumed.

2. Background on melting, metamorphism, and exhumation

Consequences of melting:
• Chemical: differentiation of the crust,
• Physical: profound effect on the rheology (strength) of mountain belts
• Thermal: Latent heat required for melting may lead to uniform temperatures across a section of the crust. Also possible advection of heat by magmas

Requirements for melting:
• Need a protolith composed of “fertile’ materials.
• Heat – need to reach melting temperature and then supply latent heat
• Fluid – fluid influx into hot rocks can trigger melting.
• Pressure – can trigger dehydration melting reactions

Metamorphism:
Metamorphic facies = different mineral assemblages found at different pressure-temperature conditions
Geotherm = the curve of temperature vs. depth within the Earth. A typical stable continental geothermal gradient is around 15 to 20 °C / km.
It is common in orogenic belts to find rocks that have been metamorphosed under high temperature and low pressure conditions, i.e. we have unusually hot rocks at shallow depths. We also often find that they have melted.

Melting reactions:
Two different types of melting reactions, water-saturated and water-under-saturated (dehydration melting, where water is released by the breakdown of hydrous minerals such as muscovite, and can occur simply by decompression).

Exhumation vs. uplift:
Exhumation is the approach of deep rocks towards the Earth’s surface, and may be achieved by erosion or by extensional tectonics (“tectonic denudation”), i.e. basically normal faulting or ductile extension.
It is important to distinguish exhumation from “uplift”. If you uplift rocks but also uplift the surface there is no exhumation. Usually in mountain belts there has been a combination of surface uplift (to give us mountains) and exhumation (to bring initially deep hot rocks to the surface of the mountains). A consequence of rapid exhumation is that hot rocks approach the surface faster than they can cool by conduction, resulting in an increased geothermal gradient in the upper crust.

3. Tectonics of Nanga Parbat, northern Pakistan (western Himalaya)

*The Himalayan collision:*

The Himalayan mountain belt developed due to collision of India with Asia at about 60 Ma. The Tethys ocean, which lay between them, was completely subducted. In the western corner of the orogen, things were a bit more complicated in that the Kohistan-Ladakh island arc was trapped between India and the southern margin of Asia about 25 to 40 m.y. before the main Himalayan collision began.

Collision led to formation of a large area of very thick crust (the Tibetan Plateau), with a high mountain range at its southern edge (the Himalaya). By about 25 Ma, the mid-crust under the Himalaya had begun to melt and many granites were produced at this time.

By about 15 Ma, granite production had stopped and deformation was concentrated on thrust faults south of the high Himalaya. Apart from earthquakes due to motion on these faults, things in the central Himalaya have mostly been quiet since then.

About 10 Ma, unusual things started happening at the corners of the Himalayan orogen. In the west (Nanga Parbat syntaxis) and the east (Namche Barwa syntaxis), compressive stresses led to active faulting and the formation of very high mountains. Vigorous erosion of these high peaks, combined with continued uplift of the underlying rocks, has led to exhumation of deep rocks.

*The Nanga Parbat Massif*

In the western Himalaya, the Nanga Parbat syntaxis sticks out like a finger of Indian plate basement exhumed from under the Kohistan-Ladakh island arc. Cooling ages record the time at which the rocks cooled through a particular blocking temperature. In this case they are zircon fission track ages that record cooling through 250 °C.

Cooling age contours follow the outcrop pattern of the NPHM – youngest cooling ages correlate with highest mountains, indicating recent rapid cooling and tectonic activity.

In total, NP summit to Indus river is 20 km horizontal, 7 km vertical relief; greatest topography found on any continent. Active uplift and erosion, no normal faulting.
4. Igneous petrology at Nanga Parbat

Two types of “granites”
- Leucogranites (white granites with small quantities of biotite, muscovite and tourmaline, in addition to quartz and feldspars). They have been dated as young as 1 million years old.
- Also small bleached zones containing big cordierite crystals, intergrown with K-feldspar and containing rounded inclusions of quartz. Cordierite is a hydrous mineral that contains iron and magnesium, and it forms in place of garnet at low pressures. These seams often occur in reverse shear zones.

Quartz (SiO₂) – Albite (NaAlSi₃O₈)– Or (KAlSi₃O₈) diagram
Major element analysis shows leucogranites are consistent with being true melt compositions. They are similar to experimentally determined compositions. Cordierite seams are variable and too rich in alkali feldspar to be simple melts.

Rb/Sr vs. Ba diagram
Good trace elements to use for modelling melting reactions are abundant in the melt (for easy analysis), and reside in the major minerals that participate in the melting reaction. Rb, Sr and Ba satisfy these criteria very well for granites. We can model their abundances in the melt relative to the source, which varies with melting reaction. The leucogranites formed by muscovite dehydration melting. Cordierite seams are distributed all over the place with no obvious pattern.

Accessory Phase Thermometry
We can get a temperature of melting using accessory phase thermometry – the solubility of zirconium in granitic melts varies very strongly with temperature, so if we measure the Zr content of the granites we can obtain a temperature of melting. This is calculated to be about 720 °C, which coincides with muscovite melting at a pressure of about 7 to 8 kbar.

REE diagram
This shows that both Nanga Parbat leucogranites and High Himalayan leucogranites (from Nepal) have high REE abundances. Cordierite seams show the opposite trend (positive Eu anomaly), and are very depleted in REE. Cordierite seams are also depleted relative to the adjacent gneisses from which they formed. This suggests that cordierite seams might be restites, i.e. the left-overs from melting after melt has been removed.

Rb/Sr vs. Ba diagram
The idea of seams being restites matches very well with the predicted trends in Rb/Sr vs Ba. The melting reaction produced a granitic melt that was removed, and peritectic cordierite and K-feldspar (solid phases that grew as the melt reaction proceeded). The rounded quartz crystals were presumably left over from incomplete melting of the protolith gneiss. Thermobarometry suggests temperatures of about 640 °C at 3 to 4 kbars, exactly on the wet granite solidus. We conclude that fluids, probably focused along shear zones, managed to infiltrate hot rocks, and resulted in a brief pulse of water-saturated melting to produce the cordierite seams.
5. Metamorphic petrology at Nanga Parbat

Reaction textures
Metapelitic rocks (metamorphosed shales and other aluminous metasediments) are very useful since these contain garnet and other useful minerals. Use reaction textures to decipher geological events, e.g. cordierite overgrowing garnet indicates decompression since cordierite is stable at lower pressures. e.g. spinel and quartz. They are not in contact, and hence not in equilibrium with each other. If they were, it would indicate temperatures in excess of 850°C (very hot – we have no evidence of this). Biotite and sillimanite are breaking down, and cordierite (and sometimes spinel) are growing.

Petrogenetic grid
By constructing a petrogenetic grid, we can calculate roughly what reactions should occur at what pressures and temperatures. A “pseudo-section” shows the different minerals that should be present in a rock of fixed bulk composition as we change pressure and temperature (remember the phase rule!). The mineral assemblages we observe at Nanga Parbat indicate decompression.

Thermobarometry
The compositions of the minerals can be analyzed by electron microprobe. Using a thermodynamic database we can calculate quantitative pressures and temperatures at which these mineral compositions would be in equilibrium. Here we find temperatures of about 720 °C at pressures of about 5 kbar.

Pressure-temperature path
We have now used three different melting reactions (leucogranites, cordierite blobs, and spinel zones) to fix points on the P-T path followed by rocks currently exposed at the surface in the core of the NPHM.

6. Modelling rapid exhumation at Nanga Parbat

Argon-argon dating and cooling ages
The Ar-Ar method of dating records the time at which minerals cooled through a particularly temperature, much like zircon fission tracks only higher temperatures. Muscovite records cooling through about 450 °C, and biotite through about 350 °C.

Rapid cooling (T-t) and conversion to exhumation rate (z-t)
Cooling at Nanga Parbat is very rapid, about 200 °C per million years. Previous workers calculated exhumation rates (mm per year or km per million years) by combining the cooling rate with an assumed geothermal gradient. For example, assuming a moderately steep geotherm of about 30 °C / km, this cooling rate translates to about 7 mm/year. BUT that would require 70 km of exhumation in the last 10 million years and we would be seeing the mantle exposed at Nanga Parbat – this is not the case!
Remember that rapid exhumation brings rocks to the surface faster than they can cool by conduction. So the geotherm becomes steeper during exhumation, and we cannot assume a particular geotherm.

**Thermal modelling**
To avoid assuming a particular geotherm I used a one-dimensional numerical thermal model (donated by Kerry Gallagher at Imperial College London). This allows us to calculate the geotherm for different exhumation rates, as well as the P-T-t evolution of rocks now exposed at the surface. We know from structural cross-sections that the total amount of exhumation at Nanga Parbat must have been about 30 to 35 km in the last 10 million years. Here are several different models, either using roughly steady exhumation at 3 to 3.5 mm/y, or using accelerating exhumation. We can compare the models with temperature-time constraints from geochronology (a U-Pb age from Smith et al. (1994), and the argon ages). The accelerating exhumation model does not match the data. Models with steady exhumation at 3 to 4 mm/y fit the data best.

**Pressure-Temperature-Time path, Nanga Parbat**
Now we compare the predicted P-T-t path of the best fit thermal model, fits very well with the results from petrology, giving confidence in the calculated exhumation rate, about 3 mm.y (not 7 mm.y) – but still rapid!

7. **Summary of processes at Nanga Parbat**

*Nanga Parbat as a bivergent wedge*
This shows the same information as the P-T-t path, but in a block diagram of the Nanga Parbat Massif. Note the two reverse shear zones with opposite sense of vergence (hence the “bivergent wedge”), that uplift Nanga Parbat and squeeze deep rocks out from its center. Since exhumation is entirely by erosion at Nanga Parbat (glaciers and landslides, but no normal faults), the exhumation rate also tells us the erosion rate and the amount of sediment that is removed each year.

*Nanga Parbat compared with the High Himalaya*
In the High Himalaya at about 25 Ma, a wedge of high-grade rocks was exhumed rapidly by a combination of thrust faulting and normal faulting along two parallel shear zones. This arrangement lasted about 7 million years before thrusting moved further south into the foreland. The High Himalaya and Nanga Parbat are two exhumational end-members; erosion and tectonic denudation (and possibly geometric end-members too).

8. **Tectonics of the Araçuaí belt, Brazi**

Now we leave Cenozoic to Recent orogeny in northern Pakistan, and turn to the other side of the world, and to a much older orogenic belt, resulting from the assembly of Gondwanaland (a supercontinent) at the end of the Proterozoic and the start of the Cambrian.
The Araçuaí orogen in eastern Brazil resulted not from two separate continental masses colliding, but from the closure of an arm of the ancient Adamastor ocean. At about 550 million years ago, the São Francisco and Congo cratons were continuous (they only got separated during rifting of the southern Atlantic in the Mesozoic). The Araçuaí belt was initially a rift basin that opened up at about 900 Ma, and looked a bit like the Red Sea today: in the south it had oceanic crust, and in the north it had rifted continental crust but no sea-floor spreading.

Subduction closed the sea in the south, and was followed by collision in the south and rift inversion in the northern segment. Closure led to obduction of an ophiolite in green (a remnant of the sea floor), and subduction-related magmatism in the south. In the north, rift inversion involved crustal thickening, metamorphism and magmatism – so much that we cannot explain it. This is the "granite problem".

9. Metamorphic petrology on an east-west traverse

Metamorphic traverse from west (low grade turbidites) to east (migmatites). Mineral assemblage changes: Cordierite replacing staurolite indicates increasing temperatures and probably lower pressures. Sillimanite is stable, so high T. To the east of the large granite belt, we find meta-sediments are much higher grade gneisses. Garnet and cordierite porphyroblasts, and some partial melting.

Thermobarmetry
The general pattern of no melting in the west but melting in the east is reflected in calculated P-T conditions. Also note geotherm is actually steeper in the west than in the east; steeper geotherm but shallower rocks so do not see melting. Remember thermal buffering of the crust – steep geotherms found near-surface but at depth geotherm may be gentle.

Rift inversion
The basic story of the northern Araçuaí belt is inversion of a rift basin. To achieve so much thickening (more than double), can either have a narrow channel bringing up deep rock as at Nanga Parbat, or have basement thickening as well. Since deep rocks are exposed over a wide area, we suggest that there has been thickening of the basement as well. We suggest that closure of this basin was externally "forced" due to collision between Amazonia and the São Francisco craton. Amazonia collided with the northwest edge of the SFC shortly before the Araçuaí basin closed.

10. Geochronology and the granite problem resolved (?)

Another unusual feature of the Araçuaí belt is the number of different granite suites produced following collision, six altogether (not counting pegmatites!). In chronological order they have been named G1 through G5 (there are two G3’s!) but their ages are not very well known. Steve Marshak and I have been collaborating with Jim Connelly at UT Austin to do U-Pb zircon dating.
10. Conclusions

Multistage crustal melting
(i) **What triggers melting? How does the crust melt more than once?**
   Can occur within a single orogenic cycle – have seen two examples. Caused by different melting reactions (Pakistan) or multiple thermal pulses from mantle (Brazil)
(ii) **How quickly does melting occur, and for how long does melting continue?**
    Nanga Parbat: three melting episodes within 10 Ma. Araçuaí: three discrete episodes (after subduction) which are each relatively short-lived.
(iii) **How are deep rocks exhumed, and how fast?**
    Orogenic collapse vs. steady state? Nanga Parbat is small “steady-state” geometry, driven by vigorous erosion. Araçuaí belt experienced orogenic collapse triggered by melting. Collapse triggered further melting.
Multistage melting can be the result of mantle input, for example here in Brazil, or simply the result of several different melting reactions occurring within the crust with no mantle involvement, for example at Nanga Parbat.

*Rates of processes*

Three phases: melting, melt extraction, and melt ascent / emplacement. All three were thought to be quite slow but have recently been shown to be very fast (geologically speaking – i.e. less than about 1 million years). Melt extraction and melt ascent rates have been revised recently with new experimental data on viscosity of hydrous magmas: Take a granite at 700 °C, dry viscosity is slightly over $10^{12}$ Pa.s and the granite behaves like a glass on laboratory timescales. Add 6 weight percent water and the viscosity drops to $10^5$ Pa.s, a reduction of 7 orders of magnitude (10 million times less sticky). For comparison, water has a room temperature viscosity of $10^3$ Pa.s and honey has a room temperature viscosity of about 10 Pa.s.

*Climate change*

Continental collision related to climate in two main ways, both involving CO$_2$ (greenhouse gas; more CO$_2$ in atmosphere, hotter Earth gets). Now recognized as having important long-term effects on climate. Metamorphism of carbonates releases CO$_2$ to atmosphere. Weathering of silicates shed from mountain belts draws down CO$_2$ and locks it back into carbonates. Important thing here is plate tectonic processes are generally thought to have climatic effects on timescales of tens of millions of years. Short-lived melting events in discrete bursts, and exhumation at 3 mm.y (lots of weathering) suggests effects may actually be sub-million year timescale.

9.4 Summary

Don’t forget the exam will cover everything we have learned this semester – I particularly recommend checking through the notes, making sure you understand how to do the homework questions, and getting a long sleep in beforehand.

The only equation that you have to know is $\Delta G = \Delta H - T \Delta S$

You should understand how to use the other equations we have met, but I will provide them in the question if you need them.

There will be a review session on Thursday May 2$^{nd}$ (reading day) at 10 am in room 258 NHB (usual classroom).

The final exam is on Monday May 6$^{th}$ at 8 am to 11 am in room 258 NHB.

Your geochem semester ends here.