

Student questions: David Kohlstedt colloquium on “Stress and Reaction-Driven Melt Segregation – Formation of High-Permeability Paths in the Mantle”

2/8/17

Question 1: What are the other causes of the alignment of the melt pockets at the grain scale?

Melt pockets align at the grain scale due to the applied stress. Melt extends into boundaries between grains that are being pulled apart, and melt leave boundaries between grains that are being pushed together.

Question 2: How could we tell the strength of the pressure of the reactive-melt infiltration?

The pressure can be measured directly with a pressure gauge, similar to one used to determine the pressure in bike or car tires.

Question 1: Why does pyroxene dissolves in the olivine?

Actually, the pyroxene dissolves in the melt. It's similar to sugar or salt dissolving in water. In this case, the water is saturated with sugar but still has capacity to dissolve more salt.

Question 2: How do dunite channels play an important role during melt channelization?

The dunite bodies are the high-permeability channels through which the melt traveled. When active, they contained probably 10% melt or more. However, as the melt supply became exhausted, the last little bits of melt were drawn out of the dunite leaving only a trace amount (<0.1%) behind.

Question 1: How can you tell where a particular melt or piece of crust is from?

The chemistry of the oceanic crust tells the story of its formation.

Question 2: I'm having trouble understanding how different parts of the mantle can be made by different substances depending on the region. I also do not understand how scientists can be so sure what the upper mantle, or even deeper parts of the mantle, are made of because it has never been reached. Do you believe that the common theories in this case could potentially be incorrect?

The common theories are undoubtedly largely correct, but many unanswered questions remain. For me, some of the cool bits of information about the mantle come from ophiolites. It's a wonderful experience to walk through an ophiolite, a walk through the mantle rather than the crust.

Question 1: What is causing the melts to only be partial melts?

The mineralogy plus the T,P conditions determine how much melt is formed at any depth. In particular, clinopyroxene is the first phase to disappear into the melt. Melting requires at least two and usually three phases, so once the cpx is gone, melting stops until the T,P conditions are again right for melting to occur (this time with olivine and orthopyroxene).

Question 2: How does the presence of volatiles in the melt effect the channelization areas?

Great question. To zeroth order, they simply lower the melting temperature. To higher order, it's a great topic for research.

Question 1: Is there a correlation between melt transport and composition of the melt? Do the different crystal structures of minerals hinder or aid in this transport?

There will definitely be a correlation between melt transport and melt composition. For example, if the melt velocity is high, it will be unaffected by the minerals that it passes during ascent. If it travels slowly, the melt will continuously equilibrate with the mantle rocks through which it travels. In general, the presence of pyroxene hinders melt movement at the porous flow scale, which olivine is happy to form melt tubes along triple junctions.

Question 2: Within the reaction layer between the partial molten rock and the reactive melt source, does the 2nd Law of Thermodynamics apply? Does entropy increase exponentially or is there a defined order in which the columns must form?

The 2nd Law does indeed apply. There is not a defined order for the formation of columns. We think, but have not demonstrated, that the channel population has a fractal structure.

Question 1: I love what you presented and I am looking into the mining industry. What is the most immediate application to mining of your research?

The most immediate application of our research to mining is probably in the chemistry. We have not really explored this aspect, but melt carries a lot of the important ore-forming elements.

Question 2: The shear fractures seem to be present at macro and micro scales. Do micro stresses often reflect the larger structural stress system of the environment at a macro level?

Absolutely. The work of Yasuko Takei at the University of Tokyo is a great example of coupling the micro to the macro.

Question 1: What is your hypothesis for why the melt forms tabular columns in the earth vs fingers in your experiments?

The tabular shape reflects the role of stress (deformation), whereas the cylindrical shape indicates the role of chemical reaction.

Question 2: Are there any cases where the small scale localized experiments that you did contradicted what was seen in an outcrop in the field?

The lab observations have generally not contradicted the field observations. Instead, we have discovered a number of phenomena in the lab experiments that were later recognized in the field.

Question 1: Are certain regions of the world more prone to having the flow channels discussed during the lecture? If so, why?

The primary field observations have been at mid-ocean ridges. The National Science Foundation supported an extensive investigation of spreading centers in the 1990s into the early 2000s. So we know a lot about these regions. A similar effort is in progress for subductions zones. Maybe we will find similar structures one of these days.

Question 2: Do the channels always flow out into the surface? If not, how do they affect the surface that over channelized flows?

The channels largely terminate in magma chambers and get exposed at the surface during later tectonic events that push some of the oceanic crust and upper mantle onto the crust.

Question 1: Why does the melt prefer to absorb the pyroxene rather than the olivine?

It's a good question for a petrologist. Basically, it relates to the phase diagram for a mantle mineralogy. Maybe a simple answer is that there's a lot more olivine available relative to the amount of pyroxene.

Question 2: What are some difficulties in reproducing the tubular style channels in your experiments that are preventing them from being seen?

The biggest problem we had was designing an experiment in which we could have a rather complex sample assembly with a sample between a source and a sink for melt. The figuring out how to apply a pressure gradient was a challenge in a rock at 1200oC.

Question 1: What factors/conditions determine whether the melt channelization is stress-driven or reaction-driven?

The experiments to date have only examined these two effects one at a time. Earth, however, finds it no problem to have both operating simultaneously. So, if both disequilibrium and stress are present, both will play a role.

Question 2: Does lack of pyroxene in the upper mantle stifle the otherwise smooth movement of melt towards the earth's surface?

Probably not. There is enough pyroxene to keep the channels open and melt flowing.

Question 1: When the channels are aligned and the melt has a continuous flow, will the channel stay roughly in this orientation or will shear stress be the only force that could alter the channels path?

In Earth, buoyancy controls the orientation of the channels. In experiments, the buoyancy force is too small to play a role, so we apply a pressure gradient to drive the melt flow.

Question 2: In the thicker areas of the mantle where there are more channels for melt, will a higher temperature create a higher strain rate for the melt?

Yes. The viscosity of melt and of solid decrease with increasing temperature, favoring higher strain rates.

Question 1: You mentioned there is a probability of missing the 'finger' when the slice is examined. What type of sensory technology is being used to detect where a channel might be along a screen?

The primary tool that we use is an x-ray CAT scan. Once we locate the channels in a 3-D image, we know exactly where to section to find a specific melt channel.

Question 2: You mentioned the melt prefers to dissolve pyroxene as it migrates. Does the melt composition affect whether or not pyroxene is consumed by the melt, or does all melt regardless of composition deplete pyroxene when migrating upward?

The basic petrological observation is that melt dissolves more pyroxene at low pressure than at high pressure. So, melt composition is determined by the mineralogy of the mantle. It all works quite predictably.

Question 1: Why does the melt go from being channelized to forming large magma chambers? What changes the behavior of the melt?

The melt needs ultimately to get through the (rigid) lithosphere, which is relatively cold and would cause the melt to solidify. By ponding in a magma chamber, the larger volume of melt will stay molten until the pressure builds up enough to fracture the lithosphere, allowing the melt to escape.

Question 2: Why is pyroxene so essential to the melt as it ascends? Why wouldn't the melt require another mineral?

It is a question related to mantle mineralogy. Given the minerals that are present ... largely olivine, orthopyroxene, clinopyroxene, spinel ... petrologist (using appropriate phase diagrams based on their experiments) tell us that melt forms when three or four of these phases hit the right P,T conditions. As P decreases as the melt rises toward the surface, the melt is capable of holding more pyroxene.

Question 1: With the melt having the capability to move through the rocks themselves, does that increase their flow rate if a large quantity of the rocks melt also?

Yes. A rock containing a few percent melt is much weaker (~ factor of 10) than a melt-free rock.

Question 2: How does a hot spot come into existence and what is the relationship it shares with lava flow on earth's surface?

The dominant (though not only) thought is that hot spots originate near the core-mantle boundary. It's an idea introduced by Jason Morgan. However, Don Anderson thought differently. It's a great story in the history of science that you might enjoy investigating.

Question 1: The mechanical-stress driven melt separation model could explain what is happening beneath the surface at mid-ocean ridges, but how does the melt form those channels in areas where there is a “hot spot” like Hawaii; does the lack of mechanical stress in those kinds of areas mean that the processes are only chemically driven?

Even beneath Hawaii, there will be mechanical stresses that could lead to channelization. However, I don't think that there is any field evidence to test this possibility. Certainly, chemistry plays a big role in such areas.

Question 2: Does the “positive feedback loop” (where the melt begins to localize at the area of lowest pressure, and therefore produce more melt while abandoning other forming channels) help to explain how one of the three branches in a continental rift essentially “dies off” during the formation, or is that a different process?

It is not obvious to me that melt channelization plays a role. It's not a topic that I know much about, but, if I had to guess, it's a larger scale constraint that governs the behavior of the continental rift system.

Question 1: What pressures do you simulate for channeled flow?

We use rather modest pressures of 300 MPa. In these experiments, the goal is to understand the physics and chemistry involved in channelization without replicating precise mantle conditions.

Question 2: Why do you twist samples as well as push down?

Twisting allows us to reach very large strains, approaching those experience deep in the mantle.

Question 1: Will understanding the migration of the melt give a better indication of how and when eruptions might occur?

Indeed, that is one of our important goals. We hope to understand, for example, how fast melt can be delivered from a depth of 100 km to Earth's surface to feed a magma chamber.

Question 2: Is there a difference in migration patterns in relation to geographic location?

The basic patterns are remarkably similar in ophiolites through out the world.

Question 1: I have always wanted to ask this question of someone who studies the mid ocean ridge. I understand that the mid-ocean ridge is a pull apart zone, that is being pulled apart by the mantle convection? Right? Ok, but when I think of the mantle pushing to the surface at the ridge I envision the mid-ocean ridge to be rising higher and higher over time, but every picture I have seen has it drawn that its the lowest point is the mid-ocean ridge. Why is it slowly not growing like a volcano slowly builds?

Mantle convection is ultimately the driver. However, the plates are being pulled apart primarily by pull of the subducting plates. You are right, because there is hot (magmatic) material beneath a mid-ocean ridge, thermal expansion produces a long-wavelength (10s of km) topography that is high as you approach the ridge axis. It short-wavelength (1 km) topography, however, maybe low from extraction of magma.

Question 2: In the experiments that you have done, does the chemical composition effect the “finger's” route to the surface? Do the fingers ever hit a wall and solidify as a dike? if so is it harder for the melt to remelt itsself or find a new path to the surface? Like if you did your experiment once then did the same after it soolidifies, would the melt try to go up the old paths or create new ones?

In the experiments, the furnace keeps the entire sample assembly hot, so the melt does not solidify when it contacts the wall between the sample and the Ni capsule. If we cooled and then reheated a sample, melt would continue to migrate along the same paths upon reheating.

Question 1: What sort of overall impact does the characterization of melt structures tell us? Does it give us a timescale of a volcanos or something of that nature?

It tells us a lot about how quickly melt can escape from the mantle. This timing is important because the composition of the melt provides insight into the composition of the mantle. However, chemical exchange between melt and the rocks through which it migrates is dictated by the time available. If the melt moves quickly, it will not be able to equilibrate with the surrounding rock. If it moves slowly, equilibration will occur. Thus velocity controls the chemistry and thus the interpretation of the observed chemical signals.

Question 2: Are these melt structures also observed on other celestial bodies such as the Moon, Mars, or Titan?

My bet is that the answer is yes. The same physics applies. However, verification will not come quickly.

Question 1: What controls the extent of partial melting between 1 and 10 percent?

In Earth, it is the mantle chemistry/mineralogy combined with P and T. In the lab, we make samples and design experiments to study the underlying physics, so we control how much melt is in each sample as a way of studying, for example, the effect of melt fraction on rock viscosity.

Question 2: Do you think that technological advances would better enable you to change pressure and induce various chemical reactions at the same time?

Some breakthroughs in technology are needed to extend our experiments in this area. The primary need is for sensors (chemical and mechanical) that operate at high temperatures and high pressures. Most instrumentation gets crushed or burned up under out P,T conditions.

Question 1: Could the properties we see in Earth melt segregation be applied to other planetary bodies so that we could understand how their cores form and how their layers interact?

Yes. The governing physics is the same, independent of planetary body. We understand in some detail the influence of properties such as the acceleration due to gravity and chemistry, so application to other planets should not be too difficult. A lot remains to be determined about how different layers (core – mantle, for example) interact. It's an area of active research.

Question 2: Could radioactive material in the Earth's crust that is naturally occurring and the material deposited by humans have some sort of effect on the angles produced or the melt segregation?

I doubt it. These perturbations occur too late in the eruption process.

Question 1: Are there other tools to analyze the melts *in situ*?

The main tool is x-ray tomography using a synchrotron x-ray source. Synchrotrons produce an extremely high flux of x-rays. Some folks are using this technique to study samples after they are removed from high P,T conditions. However, the potential is there for observing melt migration *in situ* at Argonne National Labs or Brookhaven National Labs.

Question 2: Have you seen or found different processes of melt segregation under different conditions?

We have explored such a small range of parameters, up to this point. Each experiment requires weeks of preparation and analysis, so progress is slow. Our goal is to broaden the range of conditions to see if there are physical processes operating that we have not yet identified.

Question 1: Is it possible to form a melt-enriched channel outside of a shear zone?

Yes, we do it by not imposing a stress such that channelization is controlled totally by chemistry.

Question 2: Does water play an important role or is it not needed during melt channelization?

To first-order, water enhances the kinetics but doesn't change in fundamental way the mechanisms (thermodynamics).

Question 1: At what depth does partial melting commonly begin?

Melting beneath a mid-ocean ridge commences at a depth of ~100 km.

Question 2: You discussed spontaneous stress-induced melt segregation. What are some other factors that could cause melt segregation?

The primary factor is a pressure gradient. In Earth, the pressure gradient arises due to buoyancy forces, as melt is less dense than rock. Differential stresses are also important, both in Earth and in the lab.

Question 1: In the diagram example referred to in the lecture this afternoon, the rocks which experienced the melting were composed of olivine and pyroxene, with increasing silica levels as the magma chamber grew and subsequently escaped through fractures. What potential types of rocks would we see if we were looking at those fractures or dikes from the surface?

The primary rock would be a solidified basalt or a gabbro.

Question 2: Are the geophysical processes that produce the melting you simulate in the lab (such as torsion) the same geophysical processes that would metamorphose sedimentary rocks into gneiss?

At some scale, yes. The key players are pressure and temperature in both cases. Tectonic stresses also play a critical part in both cases.

Question 1: What other processes besides plastic deformation and melt-solid reactions play important roles during melt channelization?

These are the key players.

Question 2: In the melts being examined what processes are responsible for such high olivine content?

One could start with a phase diagram from a mantle mineralogy. Maybe one way to think about this problem is to note that olivine is the primary mantle mineral with lesser amounts of pyroxene. Also, the melting points of clinopyroxene and orthopyroxene are significantly lower than that of olivine.

Question 1: What is the purpose of twisting around experiment in the lab?

It's fun and permits us to make cool microstructures. In addition, rocks in Earth often experience high strains, similar to those produced in our torsion experiments.

Question 2: What is the uncertainty in the lab? Since most of the observations can only make in the lab, how do you know for sure it will have the same condition as the earth in term of the amount of pressure and heat etc.?

P and T are relatively easy to control in our lab experiments, and we know the P-T conditions quite well for Earth. We don't try to specifically reproduce mantle P-T conditions but rather focus on designing experiments that will allow us to investigate the physical and chemical processes so that we can understand the physical and chemical laws that permit scaling from lab to Earth conditions. At the moment, our biggest uncertainty is in the reaction kinetics ... exactly how fast does the melt dissolve pyroxene.

Question 1: Are the channels already pre-formed from chemical reactions, does a catalyst come in, once the melt is present, for creating the channels, or both?

The channels form spontaneously during deformation and stochastically by chemical reaction. There is not catalyst required.

Question 2: What are the other variables in permeability and what are the limiting cases to the permeability (infinite permeability, zero permeability, other)?

You can certainly produce zero permeability by starting with a rock that contains no melt. In that case, the permeability structure evolves as melt penetrates into the sample, driven by surface tension or buoyancy. The maximum permeability is limited removing all of the solid, leaving a system composed of 100% melt.

Question 1: Are those fingers unique to MOR's, or are they present in other volcanic systems (hot spots, subduction zones)?

They have been studied in detail at MORs but are likely present in other zones of melting.

Question 2: Are the melt fingers the same scale as they would be in the crust? if not, what size would the fingers be there?

The key factor is grain size. In our experimental samples, the grain size is about 10 microns. In Earth, it is about 1 mm. In the permeability equation, you will recall that permeability increases as the square of the grain size. If you pursue this type of scaling relationship, the prediction is that melt channels in Earth should be one the order of 100 times larger than in experiments. Of course, our sample sizes (a few 10s of mm) place a major constraint on the channel size in our experiments.

Question 1: Are there earthquakes associated with the melt channels or do they occur too deep and less brittle?

The channels probably do not result in earthquakes. As you note, P and T are too high.

Question 2: Can the melt channels be observed in seismic tomography?

I don't think that tomography has sufficient resolution, yet. However, they are 'observed' by sharp decreases in S-wave velocity near the mantle solidus temperature, as shown in the paper by Kawakasu et al. in *Nature*.

Question 1: I have almost zero geological background. What is “melt” (i.e., how does it differ from, say, magma), and what are the important motivations for studying it?

Melt = magma = lava, in our experiments. The composition of melt tells us a lot about deep mantle processes and thus help us understand the geodynamic and geochemical evolution of the terrestrial planets.

Question 2: I note from your presentation that you perform small-scale tests in your lab. How well do these lab tests scale up to realistic geological length- and time-scales?

Actually, they scale up surprisingly well. One of the fun aspects of our research is collaboration with a group at Oxford where they use models of two-phase (melt-solid) flow to describe large-scale geological processes. They use the same equations to model our experiments. The fact that they can reproduce our results with computer models lends support to the use of these models for studying Earth.

Question 1: Do the melt flows follow the same fluid dynamics as other gaseous/liquid flows?

Yes, as long as the gases and liquids are obeying laminar flow (which would be a bit unusual for gases). Our flows and those in the mantle are laminar, not turbulent.

Question 2: Are the samples for the structural experiments taken from the field or created using similar conditions?

We usually start with natural samples but then pulverize them to produce fine-grain powders that we then make back into a rock. The small grain size allows us to study these phenomenon in relatively small lab samples. We then apply the physical and chemical relationships needed to scale to mantle length and time scales.

Question 1: In the melt pocket alignment image you showed, it is noted (with red circles) that many pockets are at a 45 degree angle, but without those markings I wouldn't be able to tell that there was any trend because so many pockets are at different angles. How does one go about noticing trends in pocket orientation?

We use image analysis methods. We ‘train’ the computer to recognize melt pockets based on gray scale. Melt pockets are generally lighter than the solid grains. Once the computer identifies the melt pockets, there are software programs that will fit each melt pocket with an ellipse. Once we have an ellipse for each melt pocket, we can find its long axis and thus its orientation.

Question 2: Your study focused mostly on olivine and pyroxene and I'm curious if these minerals represent a significant majority of the minerals which comprise “melts”, or if rather they simply represent a more significant factor in the physical dynamics of melt paths and hence that was the focus?

These minerals are a simplification to the full mantle mineralogy, which would include olivine plus two pyroxenes plus spinel at more shallow depths and garnet at greater depths. The goal is to capture the physics and chemistry that control channel formation. Once we understand the scaling laws, good computer models can apply our results to the length and time scales appropriate for Earth's deep interior.