Student questions: Marcia Bjornerud colloquium on "Reading the Record of Ancient Earthquakes at Three Levels in the Crust: Insights from Greenschist-, Amphibolite- and Eclogite-facies Pseudotachylytes"

4/17/19

Question 1: Could we ever use what we know of pseudotachylytes to create a system that can predict future earthquakes?

Not directly *predict* earthquakes but understand better the mechanisms by which earthquakes happen in particular tectonic settings.

Question 2: Is there a critical point where having to much fluid could be a sign of a great earthquake about to occur?

Yes, the capacity of elevated pore fluid pressure to cause brittle failure of rocks -- and sometimes earthquakes -- is well known (it was even the plot of a bad 1980s James Bond film)! We've done this unintentionally through the disposal of wastewater from hydrofracking in Oklahoma. But this is separate from the phenomenon of thermal pressurization, which happens once seismic slip begins.

Question 1: Are you able to say anything about the magnitude of these ancient earthquakes from the pseudotachylytes?

Approximately, yes, through the equation in my 9^{th} slide, relating the thickness of the pseudotachylyte melt along a fault surface to the coseismic stress drop. If coseisimic displacement can also be estimated (from offset markers), earthquake magnitude may be estimated from scaling laws from modern earthquakes

Question 2: Will this research affect how we prepare for future earthquakes?

Yes, to the extent that understand velocity weakening mechanisms in particular settings allows us to better anticipate the maximum possible size of earthquakes.

Question 1: Are we able to determine when an earthquake happened by studying Pseudotachylytes?

If pseudotachylytes are relatively young and unaltered (still glassy), they can be dated directly via 40Ar/39Ar dating. The New Zealand pseudotachylyte I talked about has been dated this way (I should have mentioned that). In other cases, the age must be constrained indirectly by relating the pseudotachylyte to metamorphic minerals and fabrics that have been dated isotopically (this was the case in the Wisconsin and Norwegian examples).

Question 2: Are we able to determine how much Q was released just by studying Pseudotachylytes if we don't know all the variables of the equation?

No. But the only things you need to observe in the field or lab are the thickness of the melt layer and the % of unmelted clasts in the pseudotachylyte. The values of other variables can be found from databases for different mineral and rock compositions.

Question 1: Has eclogite been found associated with earthquakes in areas other than Norway?

Yes, I know of occurrences in Corsica and Zambia, and there may be others – but ours were the first to be described!

Question 2: How dry is dry enough, in order to cause an earthquake at extreme depths?

In the Norwegian case, the rocks were really, really dry – no hydrous minerals at all; Loss on ignition values <0.1%

Question 1: Where could one find a modern analog of a wet pseudotachylite?

Probably in a subduction zone

Question 2: What can pre-existing pseudotachylites deform into?

Almost any other fault rock type – cataclasite or mylonite.

Question 1: If you assume the 1 [m/s] slip rate needed to create enough heat to melt, is it possible to back out the total timing of the earthquake recorded in the rock record?

To some extent. People have calculated how long the pseudotachylyte is likely to remain liquid at particular depths (only minutes in the upper crust) and how far it might flow in that time, which depends also on the composition, which dictates viscosity.

Question 2: It's very interesting to see that the amount of heat generated in an earthquake is so high. Do you have any thoughts on the speed at which the heat energy is dissipated?

Very quickly (minutes)– this is the reason that pseudotachylyte is considered diagnostic of ancient earthquakes. At subseismic slip rates (<1m/s), the heat is carried (conducted or advected) away faster than it's generated.

Question 1: Have pseydotachylytes been observed in low grade metamorphic facies such as zeolites or prehnite-pumpellyites?

I know that there are some cases where paleo-depths are surprisingly shallow (ca. 5 km) – Coast Ranges in British Columbia and the Nojima fault zone in Japan.

Question 2: Would there be a linear relationship between pseydotachylyte thickness and water content in hydrous rocks?

Not necessarily. Hydrous minerals could facilitate melting by lowering the melting temperature, but on the other hand as I indicated in the talk, presence of a separate fluid phase could suppress melting through thermal pressurization.

Question 1: You mentioned that you hope to change other's minds in the fields on the melting process, have you garnered much pushback from this stance?

Actually the view I (and a few others) have been trying to change is the idea that pseudotachylyte is the only recognizable record of ancient seismic slip. As I showed in the NZ case, I think there are certain criteria that can allow us to recognize evidence for thermal pressurization – e.g., fine fault rock injected into the host rock.

Question 2: How long does it take water to run out during the eclogitizing process?

We did some modeling of the process and think that the eclogitization reactions probably happened quite fast, geologically (because the granulites were so metastable – they should have converted at much lower pressures) – on the timescale of 1000s of years, and that would probably be the timescale for the consumption of the introduced fluids.

Question 1: According to my petrology class, introducing fluids and hydrous minerals to a melting environment, such as at subduction zones, shifts the melting curve towards lower temperatures. Is this not applicable to a frictional melting environment?

(As stated in a previous answer): Hydrous minerals could facilitate melting by lowering the melting temperature, but on the other hand as I indicated in the talk, presence of a separate fluid phase could suppress melting through thermal pressurization.

Question 2: Are there any other events besides earthquakes that produce enough friction to form pseudotachylytes, and if so, is there a way to distinguish them from those caused by earthquakes?

Meteorite impacts can generate pseudotachylyte but leave other diagnostic signature as well. Small amounts of frictional melt can also form at the base of large landslides.

Question 1: In order to produce an earthquake, you said the rocks around the fault must be strong to create tension but collapse though velocity weakening. Is pseudotachylyte a rock that follows these guidelines or is it just a product the frictional heating?

The latter; Pseudotachylyte is the product of frictional heating once seismic slip has begun.

Question 2: You may have already answered this, but on one of your last slides you said dry pseudotachylytes only form early in fault zone history, why is that?

Because once a fault zone has failed in a major sesmic event, it will have been opened up to fluids (which are pretty ubiquitous in the crust). So from that point, thermal pressurization may prevail, though maybe, if the fault zone permeability structure is just right, it could start producing 'wet' pseudtachylyte.

Question 1: What are we hoping to achieve from real-time seismic hazard assessment?

Understanding in detail the rock physics of earthquakes, which can help with probabilistic models of seismic risk and inform building codes etc.

Question 2: What led to the recognition that Pseudotachylytes are potential indicators of ancient earthquakes?

They're such unusual, distinctive-looking rocks, and the fact that they're glassy, but could not possibly be volcanic (since many occur in rocks from great depth), was a key observation.

Question 1: Is there anyone else that you know of who has found evidence of frictional melting in the presence of water?

After I starting working on the NZ case, I discovered that researchers studying an ancient accretionary prism (shallow subduction complex) in Japan had found similar features.

Question 2: How realistic is it that we will see these types of observations contributing to seismic analysis on a regular basis?

I think we will see more of these sorts of studies. As I mentioned in the talk, this is an exciting time in which it is becoming possible to link features structural geologists have been observing with real-time phenomena that were previously the domain of seismology.

Question 1: I may have not understood properly but finding Pseudotachylyte in an area is an indication that an earthquake had occurred once in the past?
Yes.

Question 2: If I understand correctly, Pseudotachylyte can be found on the surface but it contains information of different crust layers?

Yes, many rocks that occur as outcrops at the surface today were at great depth in the geologic past and have been 'exhumed' by tectonics and/or erosion, allowing us to see what happens at inaccesible depths in the crust.

Question 1: How do we know that the earthquakes that caused the eclogite happened at such deep depth considering how old the rocks are?

The key observation is that the pseudotachylyte has tiny crystals of minerals diagnostic of eclogite conditions – kyanite, and garnet of a particular composition – and whose shapes indicate rapid growth from a melt. So that links the pseudtach formation with the eclogite P-T conditions.

Question 2: How did the eclogite lose all its water?

The *granulite* (rock from which eclogite formed) lost its water through an earlier metamorphic event (Grenville Orogeny). Water was introduced locally along fractures, probably during earthquakes, in the Caledonian Orogeny and was consumed by the eclogite-forming reactions.

Question 1: Are there any specifically unusual places in the world where you find pseudotachylytes?

The Norwegian case I talked about is pretty unusual because the rocks were at such great depth. At the other extreme, there can be small amounts of frictional melt formed at the base of large landslides.

Question 2: Are there any other ways to interpret real-time seismic records thus far?

Some people are looking for ways to recognize localized frictional heating (in the absence of frictional melts) in shallow fault zones using organic chemistry – i.e. looking for hydrocarbons along fault zones that record higher temperatures than the host rock.

Question 1: What are the typical thermal sensitivities of dating pseudotachylytes?

Not sure if I understand the question – but the melting process resets the K/Ar isotope system (in rocks of appropriate composition) and if pseudotachylytes are fresh, they can be dated directly with the 40Ar/39Ar method.

Question 2: How are seismic slips connected back to mylonites and quartz-hornblende veins?

In the Wisconsin example, it appears that seismic failure and fracture (which allowed silica-bearing fluids to enter) was occurring in alternation with slow, plastic deformation (mylonitization) and metamorphic crystal growth. This is interesting since it suggests complex hybrid rock behavior right at the brittle-plastic transition in the crust.

Question 1: You mentioned a hypothesis for the limitedness of the distribution of pseudotachylytes, but have there been any hypotheses regarding the actual geographic distribution?

There's no reason to think they don't occur around the world in tectonically active (or once-acive) areas. The known geographic distribution is just an artefact of where people have looked and recognized them.

Question 2: Between methods like SIMS, EPMA, etc., what's best for your work on pseudotachylytes?

Microprobe and especially SEM BSE analyses are very useful. These are such fine-grained (to glassy) rocks, it is difficult to identify mineral phases, but elemental distribution patterns can be revealing (e.g. to test whether the melt was generated by the adjacent rocks or might have flowed some distance).

Question 1: Can psudotachylytes form in other ways like in a volcanic eruption?

Not volcanic eruptions (or if there were frictional melting, it might be difficult to distinguish from magmatic melts in a volcanic setting) - but meteorite impacts can generate pseudotachylyte. And small amounts of frictional melt can also form at the base of large landslides.

Question 2: Do you expect psudotachylytes to form from the japan earthquake since it happened closer to the surface?

It's possible, though the rupture is thought to have reached such shallow depth due to thermal pressurization, which generally supresses pseudotach formation.

Question 1: How much can you expect to gain by finding pseudotachylyte?

A better understanding of the detailed physics of earthquakes.

Question 2: How do we know what depth the pseudotachylyte formed?

By linking the metamorphic minerals and textures in the host rock to the pseudotachylyte. For example, in the Norwegian case, the key observation is that the pseudotachylyte has tiny crystals of minerals diagnostic of eclogite conditions – kyanite and garnet of a particular composition – and whose shapes indicate rapid growth from a melt. So that links the pseudtach formation directly with the eclogite P-T conditions.

Question 1: Can the pseudotachylite deposits be used to determine recurring quakes?

Yes, in a general way, if there is evidence of multiple overprinting events. But we probably wouldn't be able to determine recurrence interval since any dating methods would not have the appropriate resolution.

Question 2: Can the grain orientation in the pseudotachylites be used to determine the direction, duration, and velocity of orogenic events?

The 'fabric' in pseudotahylytes often does indicate that the melt flowed during the short time it was liquid. But this would record transient pressure gradients in the fault zone, which is interesting, but not related to larger tectonic patterns.

Question 1: What work must be done to further validate these findings?

Experimental work on the behavior of thermally pressurized fault rocks would be wonderful but very challenging to set up.

Question 2: Does this change how we look at ancient earthquake mechanisms or how we might look at modern earthquakes?

I think so! As I said, my key point was that the events we call earthquakes are really a widely varying range of physical phenomena. Understanding what happens at their sources can only help us make better risk assessments.

Question 1: Are we aware of the presence of pseudotachylytes on extraterrestrial bodies? For example from seismic activities on the moon or Mars?

I don't think anyone has found any fault-related pseudotachylyte on the Moon or Mars (impact melts have certainly been found in moon rocks). If they were found, it would be interesting not only because of what they would reveal about seismic activity, but also because such rocks would have had to be brought up from depth by some process.

Question 2: Is there significant difference between pseudotachylytes formed in deep crust dry conditions to those formed from seismic activities in the shallow crust in arid climates?

Even the shallowest pseudotach (other than in landslides) is not formed at depth less than about 5 km, so the climate doesn't really affect the hydration state of the crust.

Question 1: What causes injection veins in rocks?

The overpressure caused by volumetric expansion when the rock on the fault zone melts.

Question 2: How do you distinguish between cataclasite rocks from Pseudotachylyte rocks?

Cataclasite is granular – still particulate -- fault rock, usually recognizable in thin section. But it can be tricky if the cataclasite is really fine grained. Then SEM or XRD analyses may be necessary.

Question 1: Does pseudotachylyte form at shallower depths than the greenschist-facies?

Only rarely – 5 km is about the shallowest on actual faults. But as mentioned in previous answers, large landslides sometimes have thin frictional melts at their bases.

Question 2: Do pseudotachylytes only form in certain rock types or can they form in any rock type?

At a given site, they will preferentially form from lower-melting temperature rocks/minerals, but have been found in almost all rock types.

Question 1: When analyzing a rock unit or individual sample, what other characteristics are indicative of ancient earthquakes besides the presence of pseudotachylytes?

As I argued in the NZ example, injected cataclasites may record co-seismic thermal pressurization.

Question 2: How does the history of a pseudotachylyte sample being formed through classically dry processes versus wet ones affect the conclusions of previous seismic activity?

Dry pseudotachylytes probably form only early on, since once a fault zone has failed in a major sesmic event, it will have been opened up to fluids. After that, thermal pressurization may prevail, unless the fault zone permeability structure is just right, allowing fluids to drain during earthquakes. Then the zone could start producing 'wet' pseudtachylyte over several earthquake cycles until the fault permeability falls and fluids get trapped.

Question 1: What is the minimum temperature for the pseudotachylytes to form?

The melting temperature of the host rock (depends on composition)

Question 2: What are the requirements for a rock to be "eclogited"?

About 1 GPa pressure (at least 35-40 km depth) and 650-700° C. Also, as shown in the Norwegian case, the metamorphic reactions can't occur without H_2O.

Question 1: How can the study of these pseudotachylites be used to understand current seismic activity?

(Copied from previous answer) My key point was that the events we call earthquakes are really a widely varying range of physical phenomena. Understanding what happens at their sources can only help us make better risk assessments.

Question 2: Are pseudotachylites also used to study the history of impacts and other high heat, high pressure events?

Pseudotachylyte-like melt rock can be generated in meteorite impacts too and is used to understanding the physics of shock wave propagation.

Question 1: How can this research help us predict earthquakes?

Not directly *predict* earthquakes but understand better the mechanisms by which earthquakes happen in particular tectonic settings.

Question 2: Can we found similar patterns in Antarctica ice?

Hm… sudden basal slip of glacial ice does generate melt (and can destabilize ice sheets) but I don't know whether we can observe the results of that directly.