X Marks the Spot: Seismic Signals of Silica and Hidden Hawaiian Heterogeneities

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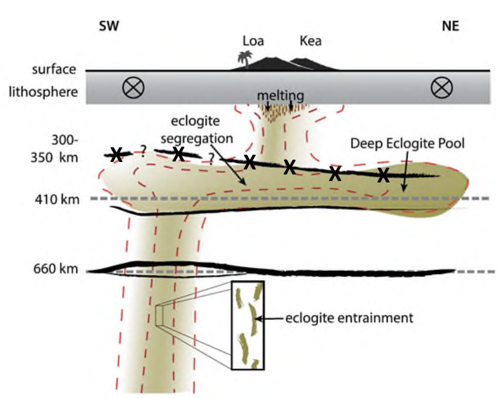
Abstract

The Hawaiian Island chain in the middle of the Pacific Ocean is a well-studied example of hotspot volcanism caused by an underlying upwelling mantle plume. However, the thermal and compositional nature of the plume is still uncertain. The depth and amplitude of seismic discontinuities can show how the plume effects phase transitions in mantle minerals, providing insights into the plume's thermo-chemical properties. This study utilises >5000 high quality receiver functions from Hawaiian island stations to detect P-to-s converted phases. These receiver functions are stacked in a variety of ways in order to image seismic discontinuities between 200 to 800 km depth. In the mantle transition zone, we find that to the southwest of the Big Island the 660 discontinuity is split. This is inferred to represent the position of the hot plume at depth, with the upper discontinuity caused by an olivine phase transition and the lower by a garnet phase transition. In the upper mantle, the so-called X-discontinuity, which has an enigmatic origin, is found across the region at depths varying between 290 to 350 km. To the east of the Big Island the X-discontinuity lies around 336 km and is particularly strong in amplitude, to such an extent that the discontinuity around 410 km disappears. Synthetic modelling reveals that such observations can be explained by a silica phase transition from coesite to stishovite. This suggests there is widespread ponding of silica-saturated material (such as eclogite, which is silica-rich relative to pyrolite) spreading out from the plume to the east, a hypothesis which is consistent with dynamical models. We suggest that this seemingly thermochemical plume could be sampling recycled basalt, now in the form of eclogite, from lower in the mantle. Therefore these results support the presence of a significant garnet and eclogite component within the Hawaiian mantle plume. We will briefly highlight further work comparing Hawaii with other hotspot locations around the world to consider whether this is also occurring in other plumes and what heterogeneous plumes may imply about the recycling of material in the mantle.

X Marks the Spot:

Seismic Signals of Silica and Hidden Hawaiian Heterogeneities



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AGU Fall Meeting 2020

Based on: Kemp et al. (2019) - X-discontinuity and transition zone structure beneath Hawaii suggests a heterogeneous plume - EPSL

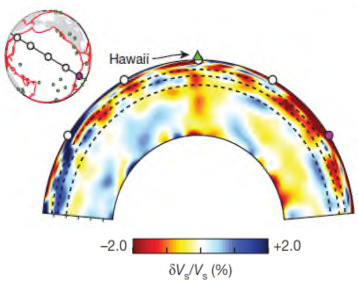
To watch a video of this presentation, follow this link: https://youtu.be/ZgS5Gabk-_E

Hello, everyone. Today I'm going to take you on a journey deep underneath the Hawaiian Islands of the Pacific Ocean. In search of the mysterious X-discontinuity. I'm going to use seismic waves to uncover a treasure trove of silica that lies down there, which has implications for the heterogeneous nature of mantle plumes, and the recycling of material in the mantle. My name is Matthew Kemp. I'm a PhD student at the University of Oxford in the UK. And this talk is based on the work that I did when I used to study and work at the University of Cambridge also in the UK. I worked alongside my supervisors Jennifer Jenkins, and Sanne Cottaar, our geochemical correspondent John MacLennan, and also I'll be showing some work of Steven Pugh, who's a current PhD student there who has been carrying on this work, so I've got a bit of a hint of what he does. So without further ado, here is "X Marks the Spot: Seismic Signals of Silica and Hidden Hawaiian Heterogeneities”.

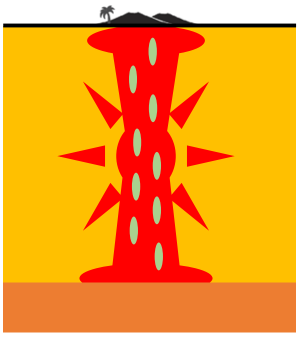
Hawaiian Hotspot and Mantle Plumes

Tomographic models show a mantle plume beneath Hawaii:

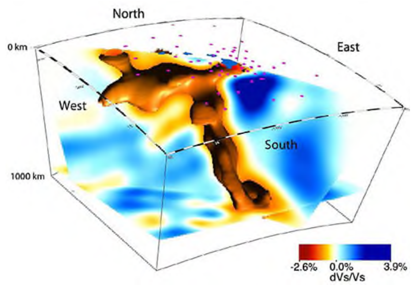
Global



Adapted French and Romanowicz (2015)



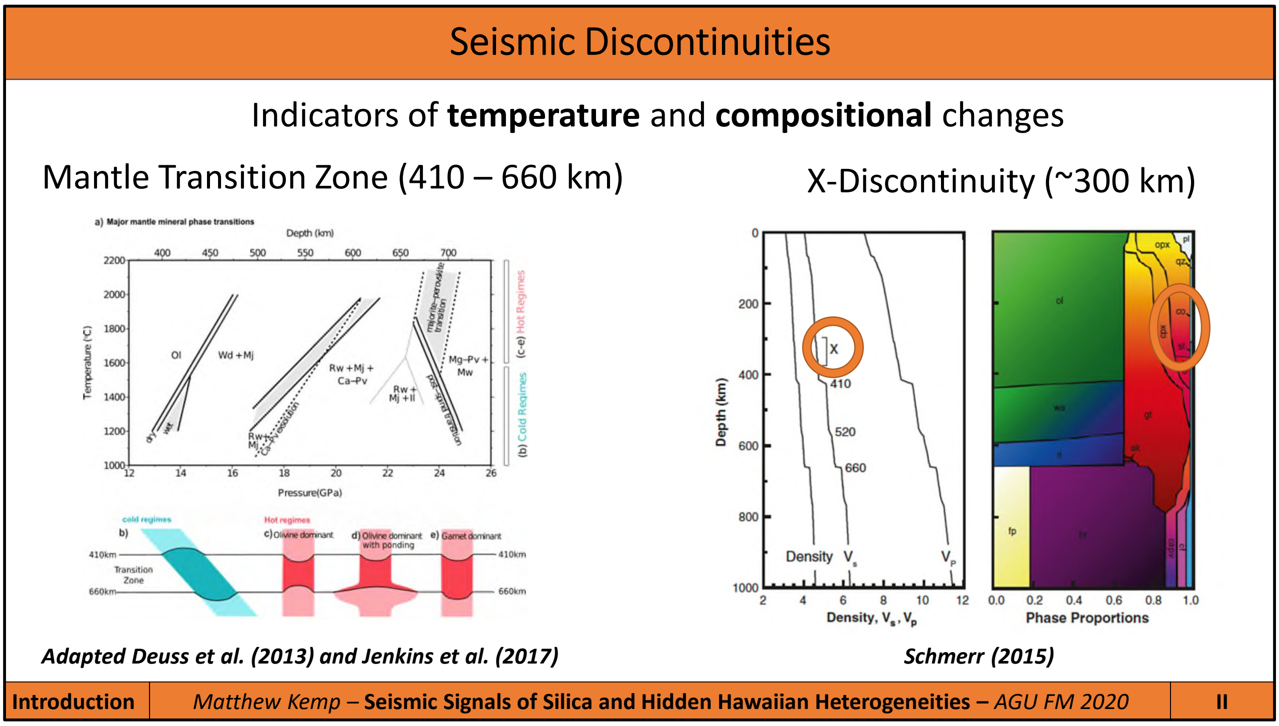
Regional



Cheng et al. (2015)

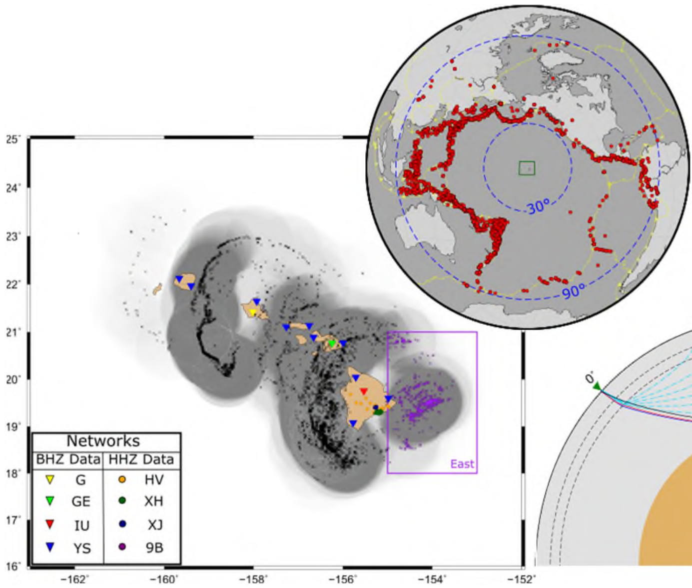
Temperature *or* **Composition** *or* **Both**

The Hawaiian island chain in the middle of the Pacific Ocean is a well studied example of hotspot volcanism caused by an underlying upwelling mantle plume. This mantle plume has been viewed in various tomographic models, both on a global and a regional scale. But there are many questions about this plume, whether it's just hotter than its surroundings, it's got a higher temperature, whether it has got a different composition to its surroundings or whether is a bit of both.

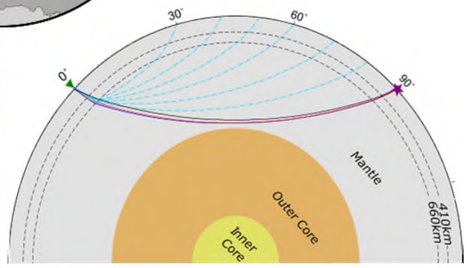


To find out about the variable temperature and composition of plumes, we can use seismic discontinuities. These are sudden changes in seismic wave speed, which are caused by phase transitions in minerals in the mantle. They can be indicators of temperature and compositional changes. We can see some seismic discontinuities across the whole world such as those at the mantle transition zone, at 410 and 660 kilometres depth. These are thought to be due to the olivine phase transitions, which of course is a very plentiful mineral in the mantle. Because of the thermodynamic properties of these phase transitions, if a hot plume goes through the mantle transition zone, the 410 will go down the 660 will go up and therefore you will have a thin mantle transition zone. So if you spot this thinning, then perhaps that is the position of the plume at depth. However, there is actually a garnet phase transition that also happens around 660 kilometres. And this has a different thermodynamic property and it goes down in hot regions. So if you spot it going down as well as up, perhaps there is an increase in garnet in that area. There are other seismic discontinuities that are only seen in patches around the world such as the X-discontinuity, which is found at about 300 to 350 kilometres depth. There are various reasons why this could occur. One of them is that it's a phase transition from coesite to stishovite, which is a form of silica. So perhaps if you see the X-discontinuity, it could mean that there is an increase in silica in that region.

Events and Seismic Stations



- Over 70 seismic stations
- Downloaded over 10000 traces
- Years 1990-2017
- Magnitude from 5.5-8
- Teleseismic distances (30°-90°)

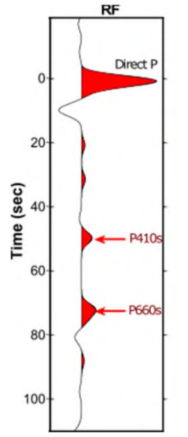


Kemp et al. (2019)

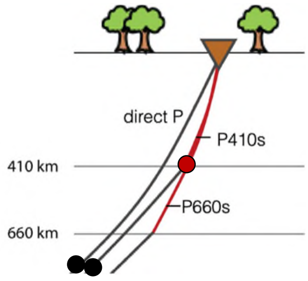
To measure these seismic discontinuities, we're going to need some seismic waves. And to detect these we used over 70 seismic stations across the Hawaiian Islands. We then downloaded over 10,000 traces of earthquakes over the last 30 years of a high magnitude, and they were all within teleseismic distances from those Hawaiian Island stations.

Receiver Functions

Detect conversions of **P waves** to **S waves** at discontinuities



Kemp et al. (2019)



- Produce Receiver Functions (RFs)
- Quality check removes 90%
- Data-set: ~5000 high quality RFs
- Convert from **time** to **depth**

1 – Depth Stacks
Detect possible conversions

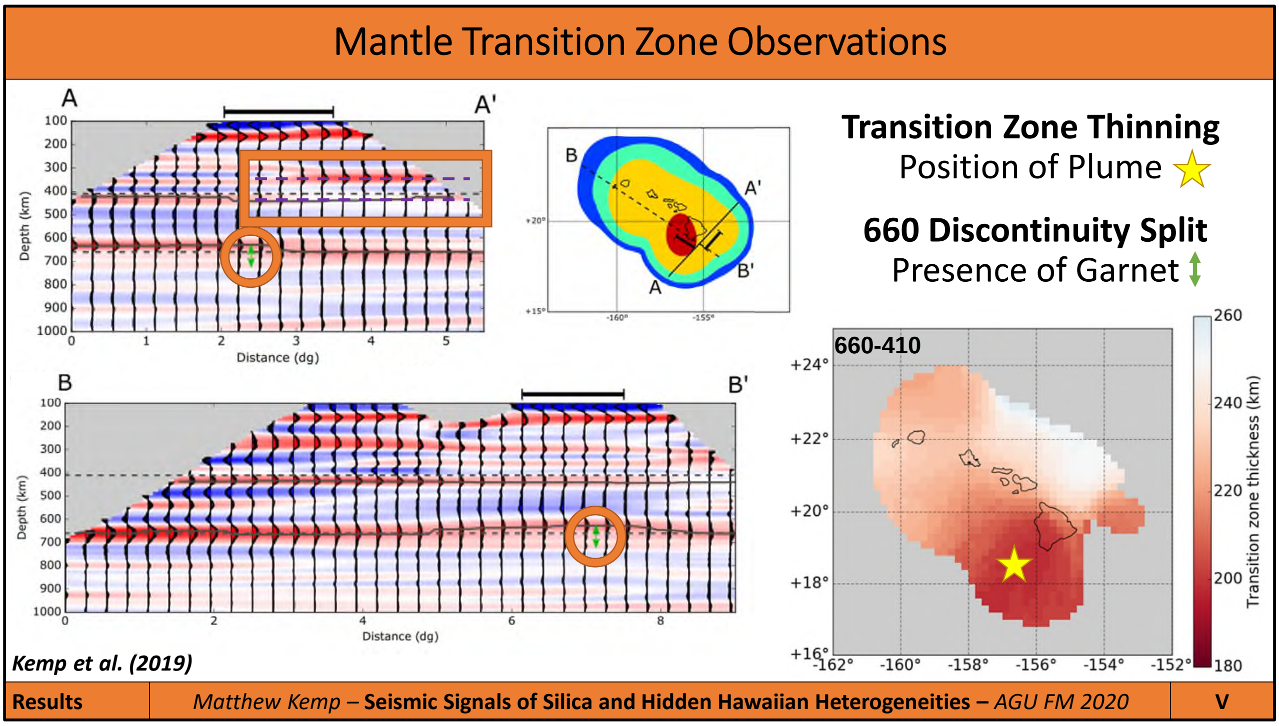
2 – Slowness Stacks
Check whether signals are conversions

3 – Synthetic Stacks
Link observations to geochemistry

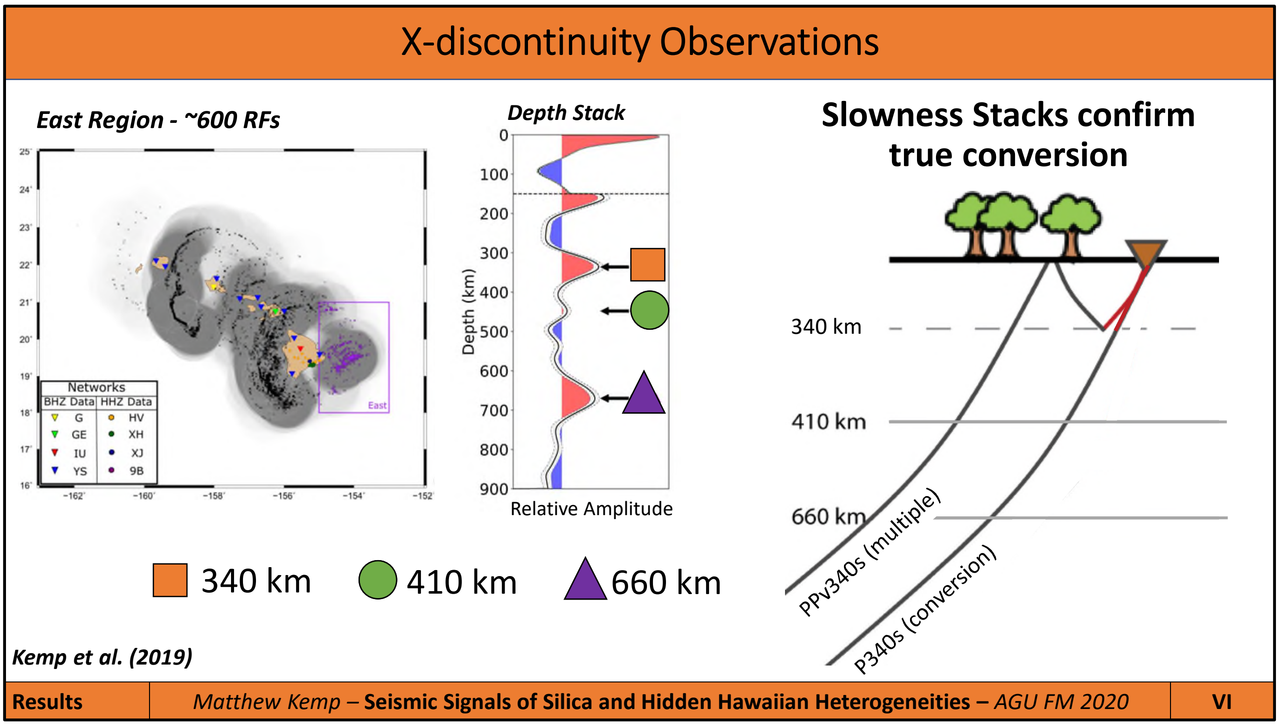
4 – Geodynamic Interpretation
Implications for mantle recycling

Method | *Matthew Kemp* – **Seismic Signals of Silica and Hidden Hawaiian Heterogeneities** – *AGU FM 2020* | **IV**

We use this data to generate receiver functions, which can pick out conversions of P waves to S wave at discontinuities. For example, a direct P wave which is a P wave throughout all of its journey, will arrive first at a station. And then a bit later, there will be a P to S converted phase because it will start as a P, hit the discontinuity and turn into an S wave and the S wave travels a bit slower, so it will arrive a bit later. And these phases are very small in amplitude, so we need to stack lots of them together to be able to detect them. We therefore produced all these receiver functions from all the traces. We did a big quality check which removes over 90% of them. So we're left with a dataset of about 5000 very high quality receiver functions. We then convert them from time to depth using a variety of seismic velocity models. And that means that if you see a little red peak at a certain depth, that could mean that there is a conversion happening at that depth and therefore a seismic discontinuity at that depth. We took all of these receiver functions and stacked them in a variety of ways making depth stacks to detect those conversions. We use some slowness stacking to check whether they were true conversions, or whether they were multiples that came in at a similar time. We then use synthetics stacks to try and work out what the geochemical signals are in the deep. And then we finally did a geodynamic interpretation of what was going on, and what this could mean for the recycling of material in the mantle.



Let's start in the mantle transition zone, at the deepest part of our observational area. We can look at the transition zone thickness over the Hawaiian region. And you can see here the redder parts show the transition zone when it's thinnest. And the thinnest part is to the southwest of the big Hawaiian island, which we've marked with a yellow star. We think that this is the position of the plume because the thinnest part of a transition zone is usually where the hottest region is. If we then look at these cross sectional depth stacks, so you can see depth on the y axis then a cut across the Hawaiian region. And the red peaks are showing possible points of conversion and therefore possible seismic discontinuities. The green arrows show that where the thinnest mantle transition zone is the 660 also splits. You have the upper one, which we think is the olivine-controlled one, which is higher because it's hotter, but you also have a slightly weaker lower signal which descends a bit in this hotter region. We think this could be because of the presence of a Garnet composition, which will give that different phase transition. We also see in the upper bit of the mantle, especially to the East region, you can see a very strong signal at around 340 kilometres depth and a weaker signal at around 410 kilometres depth.



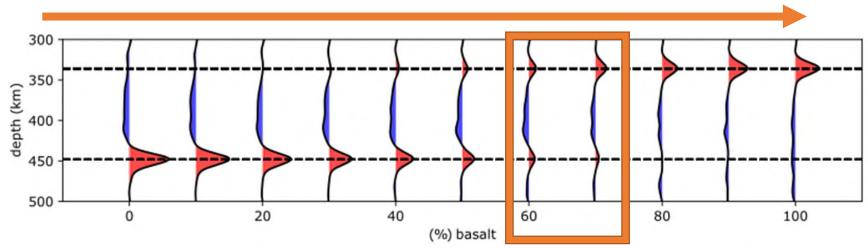
This strong signal at around 340 kilometres depth is seen throughout the whole region. And it's particularly strong as I said, in the east of the region, we made a depth sack of around 600 of the receiver functions in that area. As you can see here, the depth on the y axis and the relative amplitude, relative to P (the direct P wave) at the top here on the x axis. You see that strong 340 signal and then the weaker 410 and then the strong 660 at the base of the mantle transition zone. Therefore, the 340 kilometre signal is possibly the X-discontinuity as it is very similar to those seen in other studies. But to confirm this, we used a slowness stack. The slowness stack showed the required slowness for the 340 converted wave, but it also showed one of a multiple that bounced off the surface back down to the 340 discontinuity and then bounced back up to the surface as an S wave. So we think from both of these sightings, that this is a true conversion, and that this is the X-discontinuity.

Synthetic Stacks and Geochemistry

X-discontinuity observed

Cause: Coesite-Stishovite Transition?

Silica component – Basalt/Eclogite



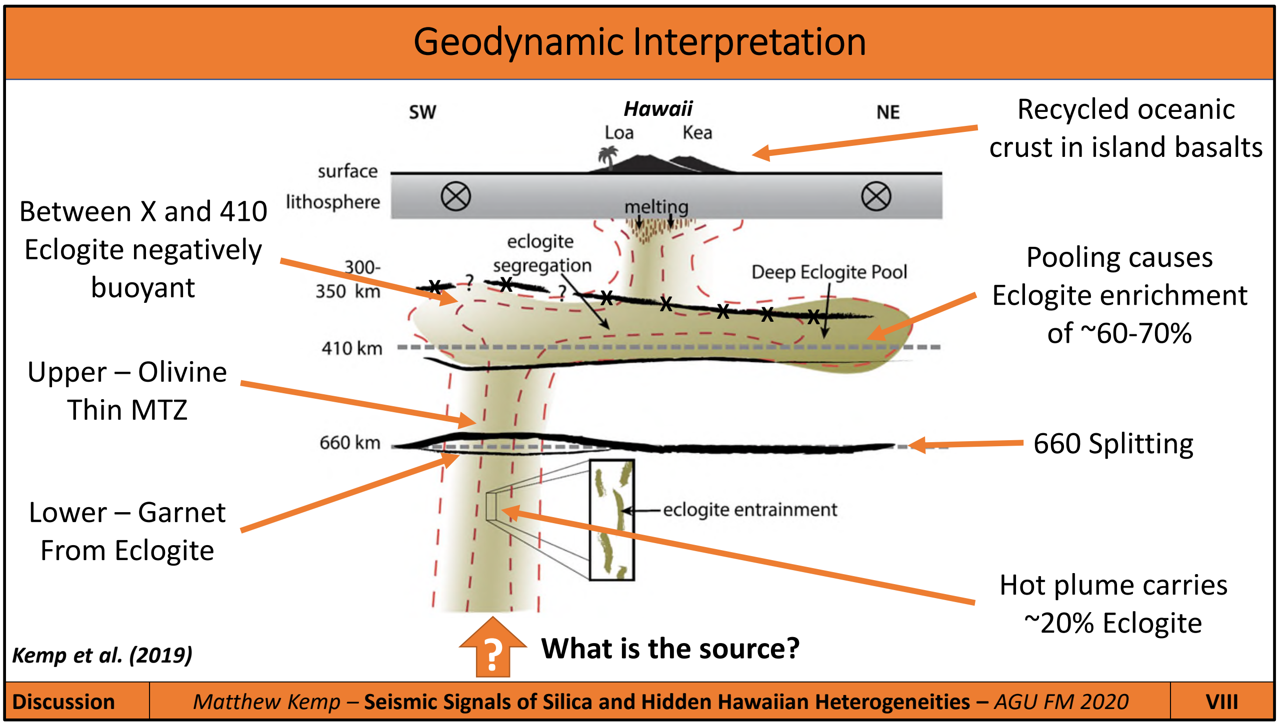
Increase Basalt fraction

Observing X and not 410
needs basalt fraction ~60-70%

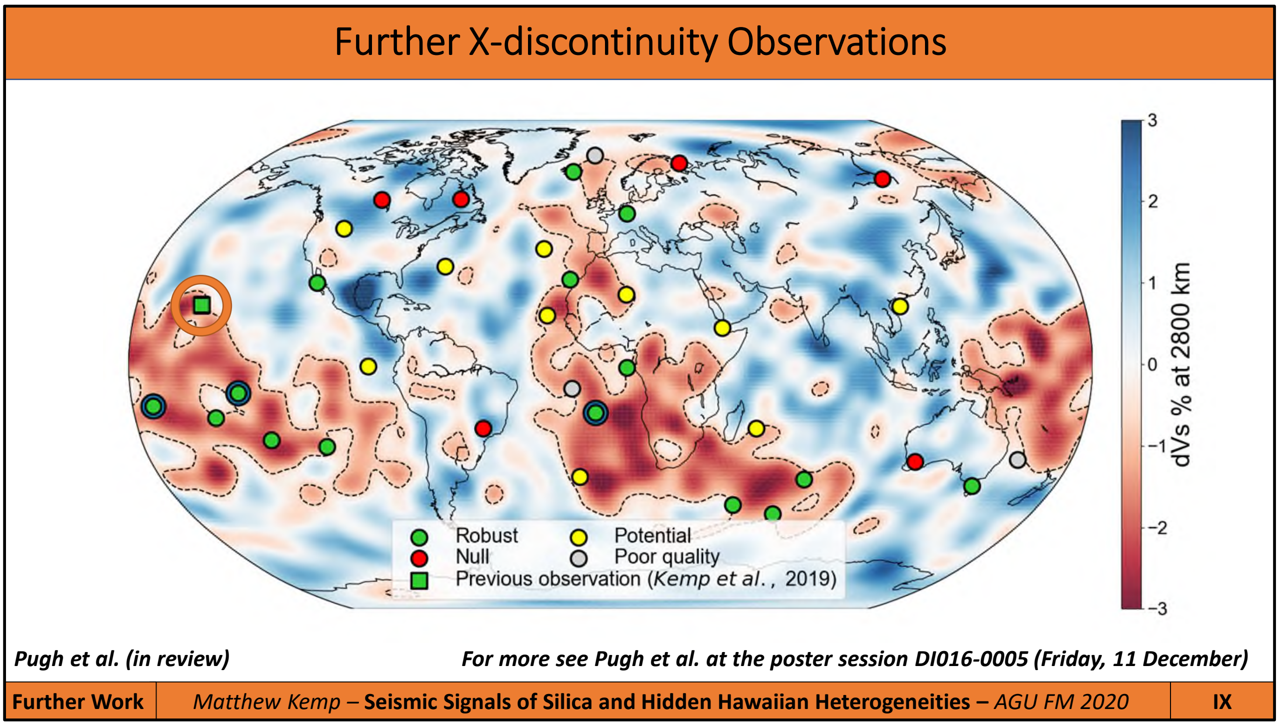
Plumes can only hold 20%?

Kemp et al. (2019)

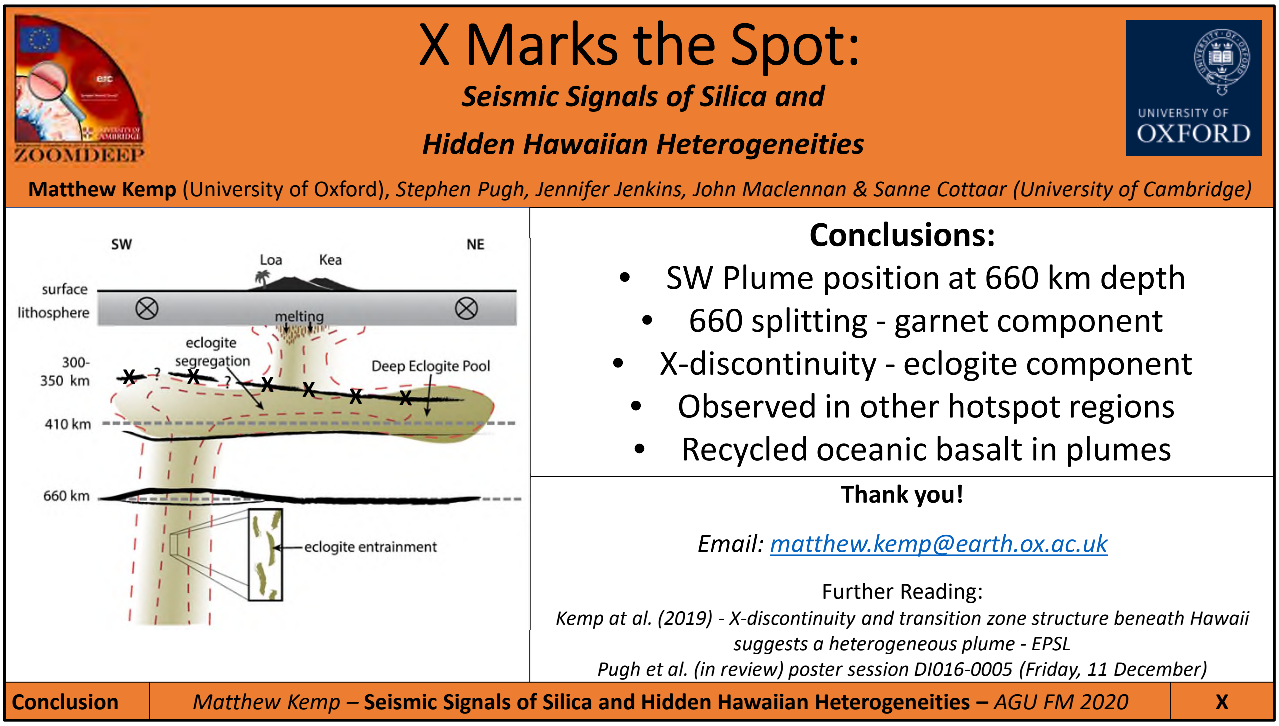
We found the X-discontinuity, but what does that mean? Well, the X-discontinuity is thought to occur because of a phase transition from coesite to stishovite. This is quite a big jump in seismic wave speed, so you don't need that much silica to make it happen. But normal pyrolitic mantle composition doesn't have any of this free silica. So perhaps there is another component in the plume, something like basalt, or at that depth, it would be called eclogite. To test this out, we made some synthetic stacks. So we made the same depth and slowness stacks that I've shown before, but this time using various computational models and changing the amount of basalt in the system compared to pyrolite. So we increase the vessel fraction from left to right, this is again as a depth stack with depth on the y axis. And as you can see, as the basalt fraction increases, the 410 kilometre discontinuity which is in the eastern region, which this is specifically from is around 450 kilometres. It gets weaker and weaker as the basalt fraction increases, while as the 340 kilometre discontinuity gets bigger and bigger. We think that to have this very weak 410, and the observation of the X-discontinuity, we need a basalt fraction of around 60 to 70%, which is quite a lot and geodynamic models to show that plumes can only hold about 20% fraction of basalt. So what's going on? Let's look at the geodynamics.



Here is a schematic diagram of what we think is going on underneath Hawaii. Let's start at the base. So we see the plume coming up with eclogite entrained within it and because it's very hot, it's able to carry about 20% of it as eclogite. It then hits the bottom of the mantle transition zone, and we see this splitting of the 660 kilometre discontinuity. The lower one is thought to be because of garnet and in fact, if you have an eclogite component, then there's probably going to be more garnet in that, which is another reason why we think that there's eclogite in here. And then the upper one is because of that olivine, the normal pyrolitic mantle compositional mineral, which gives you that thin mantle transition zone, pointing us towards the southwest of the region being the position of the plume. We then travel up through the 410 kilometre discontinuity out of the mantle transition zone and into the upper mantle. At this point eclogite is going to become negatively buoyant and start to pool downwards. And we think that this means some of the eclogite is segregated and forms a deep eclogite pool out to the east. And this pooling would increase the amount of eclogite up to percentages of 60 to 70%, giving us those observations that we see of the strong x discontinuity and the 410 disappearing. The plume then continues its journey up to the surface melting as it goes. And when it gets up to the surface produces various basalts and lavas. One question is, where is all of this coming from, what is the source of this eclogite? One hint may be that the island basalts that we see at the surface, some of them have some recycled oceanic crust component in it, perhaps it's from there.



Finally, we come to Steven Pugh's work, who has searched across the whole of the world for the X-discontinuity in various different places. And he has found it! You can see on the left with this green square, the Hawaiian observation that I made. And then you can also see lots of robust signals of the X-discontinuity in green. These are mostly at hotspot locations, and therefore possibly linked to mantle plumes. You also see some null observations, those in red, which are underneath cratonic regions. So we think that the X-discontinuity is often associated with these hotspots, and therefore mantle plumes. And they also seem to be associated in some way with the large low velocity provinces, so those big red blobs around this map. And this suggests that all of these plumes are sampling some source of recycled oceanic basalt perhaps brought down by subducted slabs, and bringing it back to the surface. And this is in some way related to these LLVPs. You can read more about the Stephens work at his poster on Friday.



And so we come to the end of our journey underneath Hawaii, and what have we found? Well, we've seen that to the southwest of the Big Island, there's the position of the plume at 660 kilometres depth. We see that because of the thinning mantle transition zone. We see that the 660 discontinuity splits suggesting some kind of garnet component in the system, which could be part of a bigger eclogite component, which is further backed up by the finding of the X-discontinuity, which is possibly caused by a silica phase transition. This X-discontinuity is observed in other hotspot regions around the world, and suggests that these plumes are sampling some source of recycled basalt, perhaps oceanic crustal basalt. And this is in some way linked to large low velocity provinces. Thanks very much for listening. I hope you've enjoyed it. If you have any questions, please email me. I'll come along to the session where I'll be having a short talk on this. And if you want to read a bit further, you can look at the paper we published last year. Or you can look at the further work that Steven Pugh has been doing in his poster session on Friday. Thanks very much.