Student questions: Carmala Garzione colloquium on “The Tectonic Evolution of the Central Andean Plateau and Geodynamic Implications for the Growth of Plateaus”

8/30/17

Question 1: During your discussion, you mentioned leaf wax. Is this leaf wax obtained from fossils or current foliage?

The leaf wax is derives from organic-rich sedimentary rocks and is extracted as specific molecular biomarkers (n-alkanes).

Question 2: There was a plot in your talk that had “VSMOW” for units. What does that stand for?

“Vienna Standard Mean Ocean Water” is the agreed upon ratio of mean seawater defined by the International Atomic Energy Agency in Vienna. It is the standard reference frame used in the denominator of the delta18O and deltaD equation for water samples.

Question 1: Why does crustal thickening in this mountain range propagate from the south towards the north?

We still do not know why the surface uplift of the Altiplano began in the south, mainly because we don’t know what geodynmanic process caused the rise of the southern Altiplano. Ingnimbrite eruptions began in the southern Altiplano and Puna plateaus at ~15 Ma, and so we can speculate a lower crustal and/or mantle process is responsible.

Question 2: Is there anywhere else in the world that has mountain belts growing/uplifting in pulses?

Both pulsed surface uplift and propagation of surface uplift has been hypothesized for the North American Cordillera based on paleoaltimetry estimates. Recent paleolatimetry studies in the southern Tibetan plateau have also identified a potential pulse of surface uplift in the Oligocene; however more work needs to be done there.

Question 1: How does the transformation of olivine to eclogite relate to the peeling off of the mantle lithosphere as the Nazca plate subducts?

It is the transformation of basaltic crust to eclogite that forms the highest density mineral assemblages. Lower crustal eclogite is more dense than mantle lithosphere, and so the ultra high density would promote sinking and ultimate removal of lower crust and mantle lithosphere.

Question 2: Did you see a change in volcanism during this period? Did the thinner crust cause more frequent mafic eruptions?

Yes. Basaltic and shoshonitic eruptions follow the surface uplift events in the Altiplano. These are small volume eruptions, possibly because the still thick and relatively hot crustal column causes contamination of mantle and/or eglogite partial melts.

Question 1: Are there examples of lower crust removal in other intermontane plateaus? If so, do you see similar uplift timelines (i.e rapid pulses of uplift)?

Yes. This process has also been argued for the North American Cordillera, the Sierra Nevada, and the southern Tibetan Plateau.

Question 2: Could differential uplift of the Eastern and Western Cordillera have created climate conditions that would make it difficult to use paleoaltimetry to judge uplift rates?

Great question, and the answer is “yes.” The Altiplano records of surface uplift in the late Miocene are “noisy” records likely because this region was in the rainshadow of the central Eastern Cordillera. Despite the noisy signal we have multiple proxies for temperature, isotopic composition of rainfall, and aridity that support the magnitude of surface uplift that we infer. The temperature and aridity records are particularly important because they respond differently to a rainshadow than the isotopic evolution of a vapor mass.

Question 1: I didn't follow when you said that complex wind patterns affect these 'methods', which is why the atmospheric conditions in the field site need to be well understood. If the 'methods' refer to delta-O-18/carbonate clumped isotope thermometry, why would complex wind patterns affect the isotopic record of sediment?

To accurately apply stable isotope methods to reconstruct paleoelevation, the isotopic evolution of a vapor mass must follow a Rayleigh distillation path that results in systematic depletion in delta18O with altitude. Competing airmasses, especially those that are far-traveled or have traversed arid regions, may show much more complicated patterns of stable isotope evolution that do not correpond with elevation.

Question 2: You showed a few graphics depicting results from a multitude of datasets in the region. Are you able to draw conclusions about the validity or biases of the different methods (paleobotony, delta-O-18/clumped isotopes, etc)?

Yes. This is some of what I covered in the technical seminar. Every method has uncertainties and systematic biases, and there are additional data and observations that help identify systematic biases in each method.

Question 1: Is there any petrologic evidence supporting lithosphere underthrust peeling eclogite formation, or is this material simply too deep to sample?

Yes. Some of the mafic volcanics in the Lake Titicaca area have trace element compositions consistent with partial melting of eclogite. These partial melts are presumably generated as the lower crust sinks and heats.

Question 2: Does the process of lithospheric underthrust peeling affect the downangle trajectory of the subducting slab underneath it, or vice versa, and how?

Based on both the magmatic arc history and surface uplift history, we know that the pulses of surface uplift are not occuring during flat slab subduction. Observations from the distribution of magmatic arc volcanism suggest that slab angle steepens before the lower crustal/mantle processes that result in surface uplift occur.

Question 1: Are there models that predict future elevation changes in the Altiplano as a result of modern geodynamic processes, and is there any consensus between these models?

Yes. For example, geophysical observations in the Andes of Argentina show a basin region that is sitting relatively low beneath relatively flat-slab subduction that still has eclogitic lower crust and mantle lithosphere attached (Gilbert et al., 2006 – Geophys J Intl). Presumably future slat roll back in this region would allow for lower lithpshere removal and surface uplift of this region. Also the Central Altiplano sits at ~3600 meters and still has some high velocity material attached (based on tomography studies). Both young mafic volcanism and geophysical imaging in the Titicaca area suggest possible ongloing removal of lower lithosphere in this region.

Question 2: Is this process only observed in the Andes, or are there similar examples of plateau growth elsewhere?

Yes. This process has also been argued for the North American Cordillera, the Sierra Nevada, and the southern Tibetan Plateau.

Question 1: Out of the two main models for removal of lithosphere, is the base detachment (more brittle) or the dripping (less brittle) more likely in the Altiplano area?

I think you are asking about delamination versus convective removal of lowere lithosphere? Models for these processes both require plastic behavior of the lower lithosphere (not elastic/brittle), but the convective removal process allows for much higher rates of deformation of the lower lithosphere during dripping.

Question 2: Volumetrically in the Altiplano, how is the relationship between acid and mafic volcanism? Is it characterized by major acid eruptions and minor mafic eruptions like in the Puna Plateau?

Like the Puna, the Altiplano is characterized by major felsic/intermediate eruptions and very minor mafic eruptions.

Question 1: How is the 'bend' of the Brazilian plate formed if the model shows the eclogite bed dropping into the lower crust-upper mantle instead of bending?

Sorry, but I don't understand this question. Do you mean the bend in Andes?

Question 2: With respect to the Brazilian Plate 'bending' and following the subduction of the Nazca Plate, wouldn't we expect some sort of partial melt and/or plume arising below the lower crust-upper mantle from partial melting of the two plates as they subduct?

Generally, subducting oceanic plates (like Nazca) do not undergo partial melting within the subduction zone. However, they do lose volatiles and incompatible elements that are dragged down the subduction zone (for example, from subducted marine sediments). These volatiles and incompatible elements lower the melting temperature of the mantle wedge, and that "hot" partial melt is what ulimately moves upward and causes partial melting of the crustal lithosphere.

Question 1: What other processes affect oxygen isotopes, and what are their magnitudes and uncertainties relative to the elevation/temperature effect?

I talked about this in detail the technical talk. The largest errors are associated with the T of carbonate precipitation and scatter in the d18O versus altitude relationship. In the thermodynamic model of Rayleigh distillation, the starting T before vapor mass ascent is the largest source of uncertainty. The largest source of systematic bias is evaporation from surface waters and rainfall.

Question 2: What causes slabs to subduct along a flat trajectory as oppesed to a steeper trajectories?

My understanding is that mantle flow processes are responsible for steeping and shallowing of the slab, but I do not know this literature.

Question 1: I must admit alot of this talk went over my head with the technical aspects and content. I just wanted to know why certain processes were able to be used in the altiplano/andean area and not used elsewhere in the world? (Dr Garzione mentioned that the/some proesses could not be used in other regions)

Oxygen isotopes cannot be used to estimate paleoelevation in the northern Tibetan Plateau because vapor mass isotopic evolution does not follow a Rayleigh distallation process. The other processes fractionating water isotopes are so large that they destroy the isotope-elevation relationship.

Question 2: As some of the results of the study showed differences in crustal thickness compared to what was expected, how can this help us predict future processes of crustla ”thickness” and its correlation to climate change as mentioned during the talk.

If the crust is thicker than balanced cross sections predict, then some of that crust has to be removed by lower lithosphere detachment or by lower crustal flow and visa versa.

Question 1: On the slide explaining along-strike variations in paleotopography, you explained that lower elevation in the middle of CAP is observed in central CAP, but not in southern CAP. You pointed out it might be because of the lack of data, but what would be the other possible hypothesis of explaining the difference between southern CAP and central CAP?

This is a tough question because we are less certain about what might have caused the Southern Altiplano to rise earlier than the Central Altiplano. The southern Altiplano does not show excess crust thickness or missing crustal thickness based on balances cross sections, and so it is permissable that surface uplift might simply track crustal shortening.

Question 2: You mentioned that by using crustal thickening modeling, you can compare it with actual crustal thickness, which then implies how much crusts were removed by convective removal of the lower lithosphere. What would be the limitations of the current crustal thickening model and possible direction for future research (e.g., incorporating other factors contributing to crustal thickness or the removal of crusts)?

The crustal thickening model is based on balance cross section reconstructions that have uncertaities associated with them. Additional reflection seismic data (that is expensive and logistically challenging to collect) would be helpful to resolve some of the remaining uncertainties in the balance cross sections.

Question 1: How does the mantle lithosphere separate from the upper crust and curl backwards with the subducting plate and how are these methods/mechanisms tested?

I think your are referring to the ablative subduction model. The following two references describe this process. The way that we have attempted to test for this process is to determine whether the "gradual" crustal shortening history is accompanies by a concomitant "gradual" surface uplift. If surface uplift tracks crustal shortening then the mantle lithosphere would need to be removed continuously.

Tao WC, O'Connell, RJ 1992. Ablative subduction: A two-sided alternative to the conventional subduction model. *J. Geophy. Res. Solid Earth* 97 (B6): 8877–8904.

Pope DC, Willett SD. 1998. Thermal-mechanical model for crustal thickening in the central Andes driven by ablative subduction. *Geology* 26 (6):511–514.

Question 2: Is the isotope/ temperature information stored in plant wax diminished or corrupted over time?

No. The preservation of the leaf waxes ensures the record is uncorrupted. The record can be lost if the leaf waxes are altered.

Question 1: How are the elevation cross-section profile plots for the non-modern data developed?

Through various paleoelevation estimates from climate proxies in the plateau itself, combined with surface uplift estimates from river incision histories/stream profile analysis on the eastern and western flanks of the mountain belt.

Question 2: What measuring or simulation techniques were used to obtain the modern elevation cross section plots?

This comes purely from digital elevation models based on satellite data.

Question 1: How prevalent are the geophysical conditions displayed in the Altiplano around the world?

Any oceanic-continent convergent setting that is analogous to the Andes (i.e, shows significant crustal shortening) should reflect similar geophysical conditions. Continent-continent convergent settings also include similar geomorphic characteristics, such as broad high plateaus associated with very thick crustal lithosphere.

Question 2: What new tools can be developed to actually measure the flow of the lithosphere and whether or not it is being removed?

The integrated tools that I described in the colloquium are some of the newest approaches. However, new geodetic approaches may have the potential to be able to resolve patterns of crustal deformation that are occuring in association with crustal flow and lower lithosphere removal.

Question 1: Near the beginning of your presentation, you went over some of the paleoelevation qualification techniques used, such as examining the oxygen isotope content in sedimentary deposits. You mentioned that this Altiplano Basin was a great location for such techniques due to the lack of variation in air masses. I was curious if you had other locations in mind that would be suitable for this type of research utilizing that particular technique?

Yes, the Himalaya and southern Tibet are also ideal locations because the air mass trjectories from ocean to plateau are simple and the dominant fractionation process in atmospheric water is Rayleigh distillation. Any mountain range that reaches elevations of >3000 m with single airmass influence that traverses 1 elevation gradient should be a good region for methods based on water isotope fractionation.

Question 2: On the same note as above, I was also curious if there were other mountain formations, those that don't necessarily meet the kind of conditions suitable for the data-collecting techniques you utilized at the Andean Plateau, that you'd like to investigate, and if you have determined what other techniques could be used in those locations instead?

Stable isotopes in hydrated glass associated with intermediate and felsic volcanism have shown promise, although there is still some debate about how these samples need to be prepared to ensure that the early history of glass hydration (just after eruption) is isolated. Generally magmatic arc regions do not preserve the types of climate proxies that I discussed, and so these methods have the potential to be applied to a wide range of volcanically active regions.

Question 1: With the plate that is hitting South America, it was said it is colliding at two points on either side of the curve on the West mountain range. Is it possible the eastern Cordillera is missing eclogite because it is pushed into the alitplano, where there is excess, allowing it to be the high elevation plateau that it is?

Good question. In the Annual Reviews paper cited in the talk, we discuss the possibility that some of the loss of crustal lithosphere in the Eastern Cordillera may have flowed into the Altiplano region. As for the large step in the Moho observed in the Eastern Cordillera, I don't think we can rule out that some of the lower crust may have been moved westward. A classic paper by Bryan Isacks (citation below) discusses deformation of the lower crust during subduction of foreland lithosphere, and we acknowledge this process in the paper.

Isacks BL. 1988. Uplift of the Central Andean Plateau and bending of the Bolivian orocline. J. Geophys. Res. 93:3211–31

Question 2: When measuring the delta O-18 and delta-D on the altiplano plateau, can deeper levels be researched to see the sediment buildup beneath the top layer, or is this a more 'recent' process that only measures the top layer?

We are collecting temporal records that rely on deeper (older) deposits as well as the overlying sedimentary and paleoclimate records. All of our sections have been deformed and are therefore exposed at the surface today.

Question 1: In your talk you referred to predictions about along strike paleotopography. Is this in reference to a particular orientation in regards to the modern morphology?

Yes. This refers the N-S orientation of the modern relief of the Andes.

Question 2: For a Petrology class, I studied a sample of Sanbagawav eclogite that was found in a lens of mafic rock in an exposed subduction zone. I'm curious if this is part of the process you described of lower lithosphere delamination that may have been interrupted and entrained into the accretionary prism.

I suspect that the eclogite that you studied formed within the subducting oceanic slab and was entrained in the subduction zone and ultimately incorporated into the accretionary prism. That type of eclogite forms in oceanic lithosphere that has be transported to depth during subduction. The eclogite transformation that I was discussing occurs in mafic lower crust in the overiding plate (South America), rather that the subducting oceanic plate (Nazca). This "continental" eclogite would reach the depths/pressure needed for metamorphism simply through crustal shortening and thickening.

Question 1: What chemical compositions enable the high density of eclogite to drive lithospheric subduction into the mantle?

The main mineral assemblage includes garnet with a density of ~4 gm/cm^3 and pyroxene with a density of ~ 3.3 gm/cm^3. The abundance of garnet in eclogite results in a higher average density than mantle mineralogy at the same depths/pressures.

Question 2: In a broader sense, how does our understanding of paleotopography of the Andes, for example, help us in practical terms? In other words, why is paleotopography relevant?

In the broad field of geology and tectonics the fundamental geodynamic processes that produce high topopgraphy and broad/flat plateau regions are still highly debated. The rates of the different proposed processes are different by an order of magnitude! Beyond tectonics, mountain belts play a significant role in the evolution of regional and global climate, as well as biological evolution. The understanding of processes and rates of surface uplift of the Andes, Tibet, and other mountain belts is providing crucial information for understanding long-term climate evolution, speciation rates, and mechanisms of speciation and development of high biodiversity in these regions.

Question 1: What causes the loss of crustal material?

During lower lithosphere removal, the key ingredients are the high density of the lower crust, as well as the material properties of the lower crust. Lower crustal eclogite is more dense than mantle lithosphere, and crustal thickening would promote heating of the lower crust that would enable this material to deform and flow downward.

Question 2: How do we know during which time period the surface uplift events took place?

The sections that I discussed have volcanic deposits that are well-dated. Many of the sections also have been by dated by magnetistratigraphy using the volcanic ages as a tieline to the geomagnetic polarity time scale.

Question 1: Was the formation of eclogites a cause for stripping of the mantle lithosphere or was that what caused convection to strip the mantle lithosphere?

The growing consensus is that the high density of eclogite is a critical component that leads to the removal of the lower crust and mantle lithosphere. Some of the argument for this comes from modeling studies that can simulate lower lithosphere removal if high density eclogite is incorporated into the model. Additional evidence comes from the paleoelevation records that I discussed. All of the regions where we have captured a rapid pulse of surface uplift had achieved crustal thicknesses necessary to form eclogite in the lower crust.

Question 2: How much have you looked into the high velocity AA anomaly and other anomalies in the area and how useful is the data for determining the cause of the uplift seen in the Altiplano?

The University of Arizona geophysics group, with whom I've been collaborating, has looked at the distribution of the AA and has noted in several published papers that this region of high velocity material corresponds with lower elevations in the Altiplano. This suggests that a portion of attached high density material is holding or pulling these regions down by a few hundred meters (the scale of the elevation difference with other parts of the Altiplano where there is no AA anomaly).

Question 1: Can you tell whether the climate change event shown from measurements was caused by the uplift of the Altiplano or by some other event?

Yes. In the published papers of these climate records and their application to estimating surface uplift magnitudes, we have used various methods to tease out surface uplift from other influences. The approach varies for each region depending on the proxies and local climate. For example, in the southern Altiplano, we collected a low elevation record of temperature change over time and used the difference between low and high altitude records to calculate the paleoelevation. Our more recent studies (since 2013) also used T lapse rates and isotope-elevation gradients that have been corrected for the effects of surface uplift. We have also compared the magnitude of global climate change over time to the magnitude of climate changes observed in the Andes. The signal of climate change in the Andes is much larger and occurs at different times compared to the record of global cooling.

Question 2: What could cause the northern, central, and southern parts of the mountains to look so different?

One major factor may be the magnitude of crustal shortening. The central and southern Altiplano and Eastern Cordillera have seen similar amounts of shortening, with the central region showing the largest % percent shortening. The northern plateau region shows much less shortening than the central and southern parts of the plateau. It therefore makes sense that the central Plateau, with highest percent shortening, shows the first pulse of surface uplift at ~24 to 17 Ma in the Eastern Cordillera, because crustal thicknesses were greatest there. The southern Altiplano rose in the middle Miocene, 16 – 13 Ma. The northern Altiplano, with its smaller magnitude of crustal thickness did not rise until late Miocene – Pliocene time.

Question 1: Even though weathering takes away a good amount of isotopes on the leeward side of the mountains, can't core samples or drill samples get the materials needed?

Sorry, but I don't understand this question.

Question 2: You showed a graph on the past height and shape of the Andes Mountains. Have similar results about the past shape of large mountain ranges been found?

As far as I know, the Andes is the only mountain range where we have enough information about the elevation history of the interior (based on climate proxies) and the flanks (based on river incision histories) to be able to carry out these types of reconstructions.

Question 1: How would the weathering of oceanic movement, rainfall, or earthquakes affect the steadiness pulsed uplifts?

Sorry, but I don't understand the question.

Question 2: When the surface uplifts, how does the cloud cycle affect the environment ecosystem of the uplift, is there any evidence that there is any abundance or lack of elements that can harm or support the process of the subduction zone?

Again, I don't quite understand the question. There is a paper by Lamb and Davis (2003) – Nature that discusses the potential role of climate in raising the Andes. This paper is focused on the role of the arid Western Slope in promoting sediment starved conditions in the trench that the authors argue contributed to the surface uplift of the Central Andes.

Question 1: What mechanism is sparking and stopping the surface uplift regions?

Based on the timing and high rates of surface uplift, along with the other geologic indicators that I discussed, we believe that removal of dense lower crust/mantle lithpshere, as well as lower crustal flow are responsible. Surface uplift would slow/stop when regions affected by these processes reach isostatic balance and/or low gradients in gravitational potential energy (applicable to regions of crustal flow).

Question 2: You talked about the different elevations levels in different regions in the same plane, however they look quite different as to when the surface uplift regions start/stop. Why didn't the event that made one region elevate affect the other if they're in the same plane?

The lithosphere behaves elastically to a certain depth. The regional extend of surface uplift is define by the magnitude and locus of surface uplift, as well as the elastic thickness of the lithosphere. The magnitude of surface uplift is defined by isostasy (bouyancy) of the crustal lithosphere. This magnitude of uplift diminishes away from the locus of uplift over ~50 to ~200 km depending on the elastic thickness, with smaller elastic thicknesses associate with shorter wavelengths of deflection. The crustal lithosphere in the Central Andean Plateau is relatively hot and has a thin elastic thickness, which is why surface uplift events are more localized around the regions of lower lithosphere removal and lower crustal flow.

Question 1: When predicting paleo topographies, it appears the main tools used are your deep knowledge of uplift, deformation, and erosion. Are there other factors that play a significant role in recreating these ancient landscapes?

Sorry, but I don't understand the question.

Question 2: It was mentioned that limitations and other constraints would be presented during your more technical talk. Can you briefly describe the uncertainities involved in recreating paleo topographies?

I talked about this in detail the technical talk. The largest errors are associated with the T of carbonate precipitation and scatter in the d18O versus altitude relationship. In the thermodynamic model of Rayleigh distillation, the starting T before vapor mass ascent is the largest source of uncertainty. The largest source of systematic bias is evaporation from surface waters and rainfall.

Question 1: Hello, You mentioned the air mass flow projection to come from the equator and move east to west. How confident are you that pattern was consistant over the time period of interest for your isotope data?

Numerous climate modeling experiments predict the same pattern of flow under different climate conditions and different paleogeography. The fact the South America has remained at essentially at the same latitude over the time period that we are studying means that the northern and central Andes have always resided in the path of easternly flow (i.e., from the Atlantic).

Question 2: You stated that there is an abundance of basin fill within the alteplano. You also stated that the eastern ridge in the central, central Andes is more defined and at a higher elevation earlier in history. Does the sediment in the bath-tub confirm higher volumes of sediment from the eastern ridge opposed to the southern Andes where you state the eastern ridge took longer to reach elevation?

Yes. There are are sedimentary provenance studies that show that the Eastern Cordillera has provided the main source of sediment to the central and eastern Altiplano since at least late Oligocene time.

Question 1: How are oxygen isotopes inherent to material differentiated from those contributed by rainfall? Is there an elevation at which the compositions of the two sources of isotopes are indistinguishable?

It is well established that oxygen isotopes in bicarbonate and water are equilibrated in modern soils. Because the O in bicarbonate is insignificant compared to the amount of O in the water in which it is dissolved, the meteoric water composition dominates the O isotope composition of carbonate that precipitates from meteoric water. If a soil formed in a carbonate substrate, then there may be a problem. However, paleosols that form discrete carbonate horizons are usually leached of carbonate in the upper part of the B horizan and carbonate accumulates in the lower B horizon. This is true for the paleosols that were sampled in the Altiplano.

Question 2: What are the parameters used in the climate correction factor used to derive the temperature-altitude relationship?

The difference in surface T and the delta18O of rainfall under lower elevation scenarios are used to apply a correction to both the T-altitude relationship and the delta18O-altitude relationship.

Question 1: What other regions of the world demonstrate rapid pulses of surface uplift?

Both pulsed surface uplift and propagation of surface uplift has been hypothesized for the North American Cordillera based on paleoaltimetry estimates. Recent paleolatimetry studies in the southern Tibetan plateau has also identified a potential pulse of surface uplift in the Oligocene; however more work needs to be done there.

Question 2: Did the uplifting of the Andes mountains cause the aridification of the western coast of South America as well?

Most climate modeling experiments indicate that the west coast of South America was arid, and possibly even hyperarid, without the presence of the Andes.

Question 1: What was the event 10-6 Mya that caused the uplift of the Altiplano?

In the talk and Annual Review paper that I mentioned, we deduce that both removal of lower lithosphere and lower crustal flow are responsible for the surface uplift of the central and northern Altiplano over this time frame.

Question 2: What's the cause in the difference in uplift of the southern, central, and northern Central Andean Plateau?

One major factor may be the magnitude of crustal shortening. The central and southern Altiplano and Eastern Cordillera have seen similar amounts of shortening, with the central region showing the largest % percent shortening. The northern plateau region shows much less shortening than the central and southern parts of the plateau. It therefore makes sense that the central Plateau, with highest percent shortening, shows the first pulse of surface uplift at ~24 to 17 Ma in the Eastern Cordillera, because crustal thicknesses were greatest there. The southern Altiplano rose in the middle Miocene, 16 – 13 Ma. The northern Altiplano, with its smaller magnitude of crustal thickness did not rise until late Miocene – Pliocene time.

Question 1: With weathering bringing sediments into the central Altiplano, what are some of the challenges related to differentiating between authigenic and detrital sediments used in the geochemical analyses?

Detrital carbonates are dissolved within paleosol profiles associated with pedogenesis. It is more difficult to isolate the potential influence of detrital carbonates in lake deposits, but we did not use lake carbonates for any of the paleoclimate reconstructions that I discussed because closed lake systems do not provide a clear record of local rainfall compositions.

Question 2: Two major pulses of uplift were metioned in the formation of the Andean orogen, does these relate, and if so how, to the lower lithosphere anomaly seen in the seismic data?

The seimic data, especially receiver functions that define the depth of the Moho, point to a region of lower crustal removal. The mantle tomography shows that the mantle lithosphere is missing beneath the Eastern Cordillera and much of the Altiplano. This provides insights into the most recent (late Miocene – Pliocene) surface uplift events. The seismic data, however, cannot be used to infer anything about the late Oligocene - early Miocene surface uplift pulse because these data only tell us about the modern state of the lithosphere.

Question 1: Was geophysics or seismology used to map the shallow slab subduction of the Pacific Plate?

Yes. Cahill and Isacks (1992) JGR Solid Earth provided the first well-resolved image of the transition from dipping slap to flat slap in Peru. Recent updates come frome the PERUSE seismic experiment.

Question 2: Is the shallow slab subduction the main reason for the high subduction rate or is it due to the density of material or a combination of both?

Sorry, but I don't understand the question.

Question 1: I'm an astrophysicist so my questions are more methodology-based rather than theory. I'm very curious how it is that you use the vegetation to do historical analyses of the rock formations. I believe you called this paleobotany. How does this method work? What exactly are you testing in the plantlife and what do you infer from that?

I don't use these methods in my own research, but the methods are based on use of the modern leaf characteristics as they relate to modern climate to reconstruct paleoclimate, in particular paleotemperature. For example the size of leaves and the shape of the the leaf margin changes under different climate conditions.

Question 2: I was fascinated by the contour mapping over elevation and relative velocities of mass pockets in the crust and mantle near the end of your presentation. How is this data collected?

This data is collected through the deployment of a passive seismic experiment. Seismometers are strategically placed over a region of interest to capture natural earthquake events. Usually seismometers are deployed for 18 to 24 months to collect enough events (that travel through the region of interest) to resolve crustal and lithospheric structure. New methods rely on the same seismic data, but use ambient nose (such as weather events, human generated noise, or waves breaking on the coastline to image the crustal lithosphere. In general, these methods rely on the change in seismic wave properties that result from major discontinuities associated with changes in the composition or density of the crustal and mantle listhosphere. You can think about this as a planetary scale ultrasound.

Question 1: Will there be further research conducted to determine if there are sources of the eclogite from other geographical regions that may share a similar geologic history to the Atacama?

I think you mean Altiplano? If so, the answer is yes. The is similar ongoing research in the North American Cordillera, Alpine-Himalayan system, and the Tibetan Plateau.

Question 2: Do you have any plans to expand your research area beyond the Central Andean Plateau?

I also work in the Tibetan Plateau. Some of the research is focused on resolving the surface uplift of Tibet, and some of it is focused on understanding how the growth of the Tibetan Plateau has influenced regional and global climate.