报告人：Brian L.N. Kennett | 整理：唐清雅，蒋梦凡，塔力哈尔·哈帕尔，孙伟家（地球与行星物理院重点实验室）

Good morning! I know how difficult it is to understand lectures in a foreign language. So I have made an experiment today preparing by my ph.D students in Canberra, this slides translating in Chinese. And I will speak in English. I hope it is useful. And you will be able to follow this slides, if you do not follow my English.

Lithosphere is the shell part of the earth, moves with the plate tectonics, oceanic lithosphere recycle, continental lithosphere conserve pretty much, but consequence of that system is the continental lithosphere carries with it, much of history. If we look at the seismic reflection profile results, we can see the distinct ancient traces in the tectonic process. When you move to the mantle lithosphere, the scales are bigger, and high reflection frequencies very little is seen in terms of the energy return. But as I hope to demonstrate this story, the complexity we see in crust.

So I illustrate here, the reflection profile is across the South Australia. It is the 5000 kilometers or 6000 kilometers line from the West Australian Craton to the South Australian Craton. Here the craton is of three parts overlaps. This is the structure of the craton. This one is crossing the south part between that we see the steep line and here, representing different tectonic pieces. I believe that if you were able to look at the right scale in the mantle where we will see something similar.

The basic definition of the lithosphere as a part of the tectonics moves has a lot logical definitions. We cannot access that geology directly. Many contrast of the definition about lithosphere based on different properties. We are talking about the mechanical lithosphere associated a number of right lines. That is about half of the seismic lithosphere described by the seismic wave velocity. On the define transition from conduction and transition, and the variation of the petrology lithosphere includes two parts – mantle parts and positions variation. The base of the lithosphere is sharp and that makes it difficult in many cases to get the best possible definition of the lithosphere.

The property we have from seismology are the variation of the seismic wave attenuation with that. The relative or absolute seismic wave speeds from body wave studies and surface wave studies. From body wave tomography, the energy coming up below with the degree of vertical smearing, associated with that. The surface wave traveling far miles. We can also look at the gradient of seismic waves, and for example the relationship with the temperature. We do not really know the propagation quality, in many cases, to do the mass of the seismic wave. Another quantity we know there is， but we do not understand fully is the seismic anisotropy, not be talking too much about azimuth anisotropy today, but more about radial anisotropy, and the distinction between velocity of horizontal travelling and vertical travelling. Receiver functions studies is coming to and the favorite of approach is to use the S wave incident because the P wave coming before the S waves, so do not interfere the multiple waves in shallow intersections. And another technique I believe is using the auto correlation of the seismic waves, to get the P wave reflectivity below the stations.

Much of the work I have done to get to the understanding I am trying to share with you has come from the studying of Australian continent, but the result study through smoothly, for Australia we have large scale information from surface wave tomography, which can sustain lateral resolution of 200 kilometers. We have evidence particularly from delay time tomography of details studies from southeastern Australia. The smaller scale and the resolution is down to the fifty kilometers, and we believe the similar structure exist another part of the continent. On top are the large scale variation or the medium scale variation. In the craton we have strong evidence for the present fine scale structure, some of the evidences comes from horizontally propagating phases, such as Pn and Sn. And in other places we have information from the auto-correlation of the P waves, it gives necessary P wave reflectivity and shows complex information. And if we want to understand the lithosphere as a whole. We have to recognize all of these scales of present, they all interact to give you the actual structure.

So to introduce you the broad scale of the Australia structure, and why this is a good place to look at these, Australia has a very old craton of old pacific comes from here, Proterozoic in the middle, Phanerozoic in the east, so we have old age range from ration across the area of boundary of the china and the population is about 25 million. So populated very empty. We have well determined property on shear wave on 21S and 31S. And you can see that here they extend from a couple of 300 kilometers.

In the southeast of the Australia, we have been able to do research many years with small property or small number digital in the beginning. A picture of the Australia stations, this is many years experimentation, becoming the 12 hundred station. From that delay time tomography, it is able to make this image, we are seeking the result of the different experiment, so only the short away structure or the longer structure supply the AuSEEM preference model, the point we see is at the across of the craton here to Phanerozoic here, which been affected by setting of the new Zealand IN this area. The look point variation is also 50 kilometer, since there are cratonic and Proterozoic region, we believe that the supply is more general across the country.

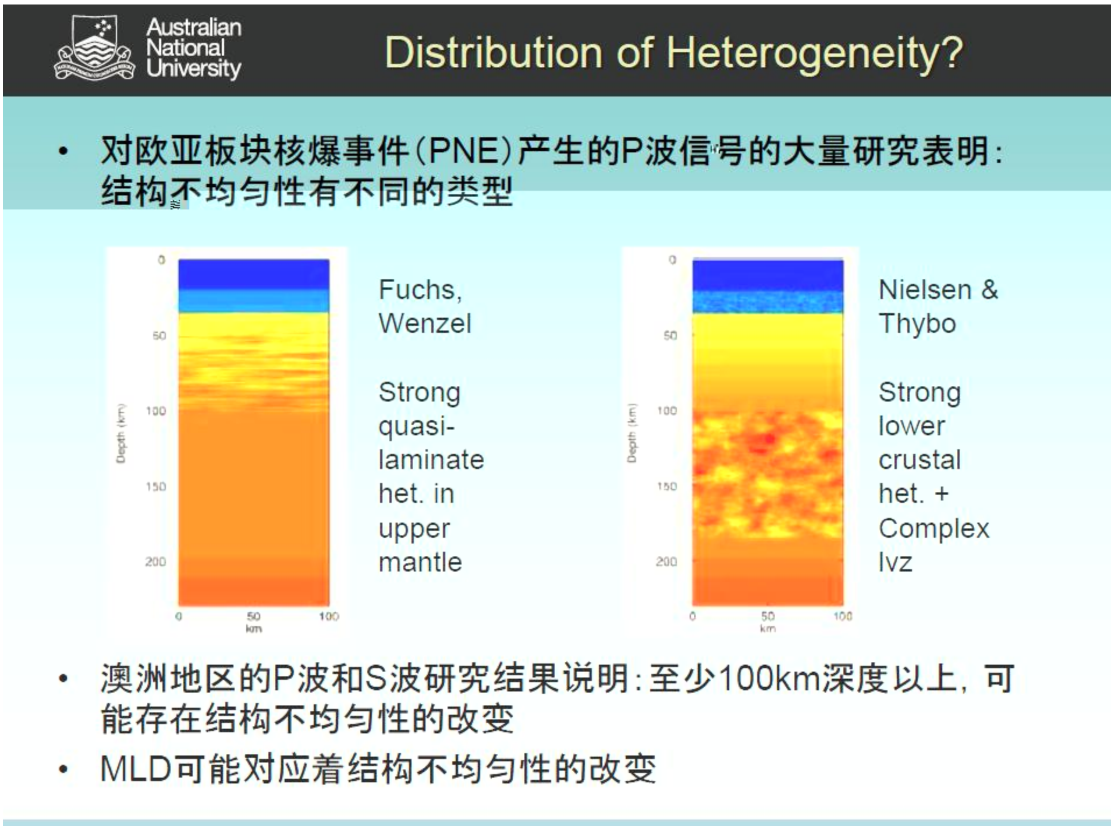
So when we look at the lithosphere, and try to understand the properties, as I mentioned before, it is not sharp at the base of lithosphere. But that cannot consistently hit across the continent. That is to try to display the transition between the lithosphere and asthenosphere. On the using of approximate, and that defines lower bound at the shallow bounds from the transition negative velocity gradient as a function of depths. And the bottom is clearly S wave velocity defined, so we take the three dimensional velocity distribution. Look at the vertically profile through it, And each point define a shallow and deep bound on the transition. These are more generous than the true position of the base of lithosphere, we can do the consistent treatment across the whole continent. Where the lithosphere is thin, the shallow bound usually have correspond point closely to the actual base of the lithosphere. But where the lithosphere is thick, the deep bound is more grown.

So to illustrate, we will see the cross section again at 21 and 31 South, showing here the seismic wave stays, and the radial anisotropy has the square of velocity, the horizontal shear velocity and the vertical shear velocity. Why do we use the square, because the ratio of the actual modeling define that one? So the lithosphere-asthenosphere transition, I'm showing here is the dashed lines and that can affect velocity variations. This point is we come across here, coming across the craton onto the transition, and that is very sharp change in that transition. One another thing I would like to note is that the velocity behave with the high velocities above the shallow transition reflectivity. We see frequently large the anisotropy in the neighborhood in the deep bound. The anisotropy and the velocity are not behaving the same way.

The Cratonic lithosphere, in the sense of study of the Eurasian using this kind of huge explosions with very dense instrumentation. They show high frequency P waves travel to very far distance, with complex behavior. We see something quite similar in the propagation of earthquake from the Indonesia subduction zones into north Australia. Apparent P and S wave with one of our rare, used to be rare, earthquakes in the central Australia. In the first 20 year my residence in Australia we have no earthquake there, then now recently we have quite a lot this region. There are recently five earthquake here, but the radiations they have been seven in this region. So just like the central China, the responsibility of large continental earthquake, so this is the Ernabella earthquake in 2012, recording the west station of the West Country, they are the cratonic parts, fast arrivals relatively associated with long trail fine frequencies. But if we look to the east, particularly into the group of the frequencies. We see a bit long trail, but they are the lower frequencies, and particularly in the high frequencies.

This is the example from Indoneasia suduction zones, and showing the very clear low frequencies followed by here nearly two minutes of high frequencies arrivals. This is crossing the oceanic and continental lithosphere. And then for S, very strong trail infect is so strong that you can see the very high frequencies are riding on the surface wave. These are frequencies time blocks, they are sustain high frequencies, and rate of the decay factory slow. When you recognize this is two minutes also, it decays very slow, it means S wave Qs are more than one thousand, and that is very high. We have been able to play a couple of movies because we have some compatibilities about the using computer. We simulated the properties of these waves coming from subduction zone into the mantle.

And then we get seismic graph and we have structure like this, and crustal, and couple of lines heterogeneity, and fine-scale heterogeneity. We are able to produce a seismograms like this, and reproduces many of the properties of this sort of arrivals. What we get is the waves come up the subduction zone, but link into the oceanic lithosphere, and then propagate horizontally with complex interaction. The precise detail of the behavior to where the subduction zone, and hence how much oceanic lithosphere present.



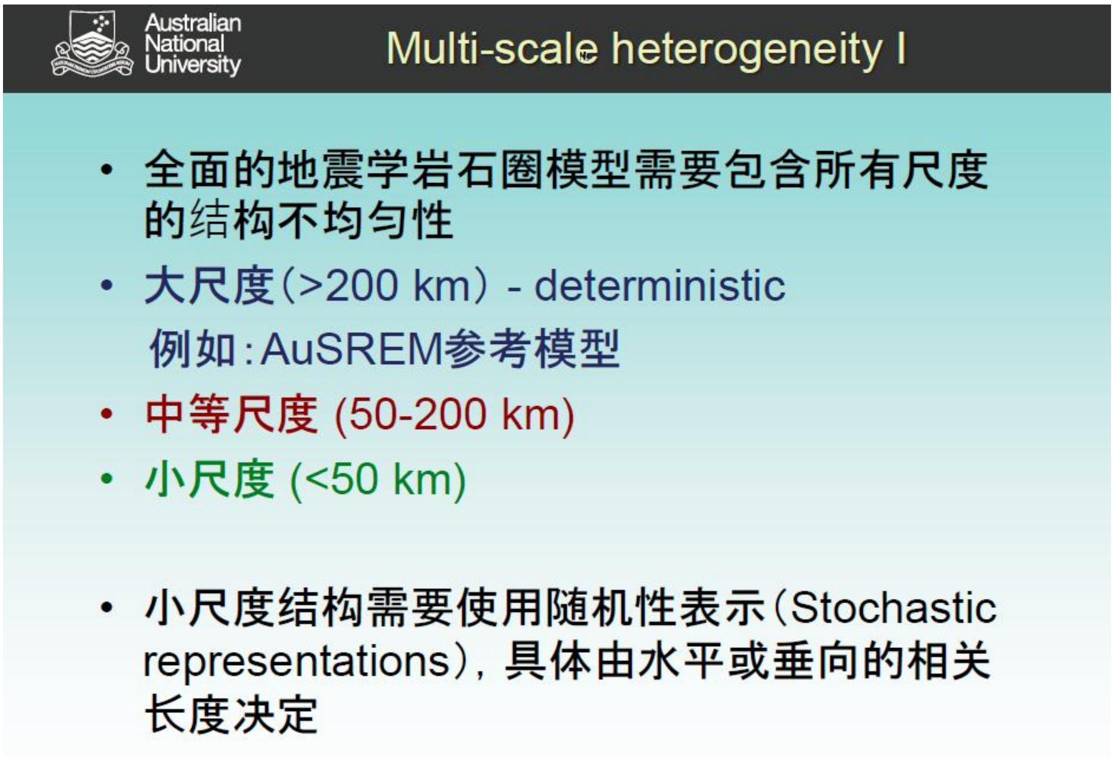
So studies of these explosion records, as to the nature to the heterogeneity that explain the behavior. Fuchs and Wenzel group, come up with the idea that the strong quasi-laminate heterogeneity in the upper mantel. Or the Nielsen&Thybo group that concentrated on the presence of strong heterogeneity of base crust and then complex heterogeneity in low velocity in the transition from the lithosphere to asthenosphere. In the previous picture, I showed you the quasi-laminate simulation of the works quite well, but we can gain more information, we have come to recognize the best representation of the Australia is actually take both of pictures and merge. We have to link heterogeneity in this region down to about hundred kilometers. But we have to gain up together, we do not need strong quasi-laminate heterogeneity, what we actually need is the medium heterogeneity sending to lithosphere. And if we take account of large scale variation, we can actually reproduce amount of fine scale. So for Australia, we need both of these variations. Change the style, as you go into the lithosphere-Asthenosphere transition zone. And lots of author think that the big lithosphere discontinuity has some association with the changed heterogeneity.

The regional evidence for fine-scale heterogeneity came from the study horizontally traveling waves. And then you look at the properties of the considerable distance. The more direct evidence comes from, in fact, looking at the properties, beneath the stations. And the technique we have been using to there is that of the using the auto-correlation from the seismic arrivals to get that P waves reflectivity. This can be done with the continual waveforms, also with major coda of P waves, or anyway principle coda S waves. The source plane is inner arrow coda beneath the receiver. And in this case, we are not relying on conversion. Unlike the receiver function, we not look at P to S or S to P wave conversion. This means more subtle pictures of the velocity variations can be imaged for this detected, but we do not need too large change.

So the first example I show is the P wave reflectivity along the profile through the northern Australia. It is the roughly the same place before I projected everything onto 20 south. And this crosses from Archean, in the Western Australia to the Proterozonic in central Australia, and finally come up the Phanerozoic Australia here. Now if you look at this image, you will see considerable difference in the properties of the stations here, they are noisier and that noise the properties of local scatter. If the medium vary horizontally get into energy return, besides all coming to time. So it is hard to unravel the detail with the scattering. And in Archean we have relatively simple behavior at the Heterogeneity. And it may be difficult to say that the little area here, it represent the estimated depth of the MLD from the S to P wave receiver function. They correspond to changes in P wave reflectivity in each case. But it is difficult to immediately these criteria for recognizing the MLD. I should point out the red blue bars here, correspond to the estimates of the thickness of the lithosphere-asthenosphere transition. And the substation, this is what we do see a change of reflectivity as we come into this lithosphere-asthenosphere transition.

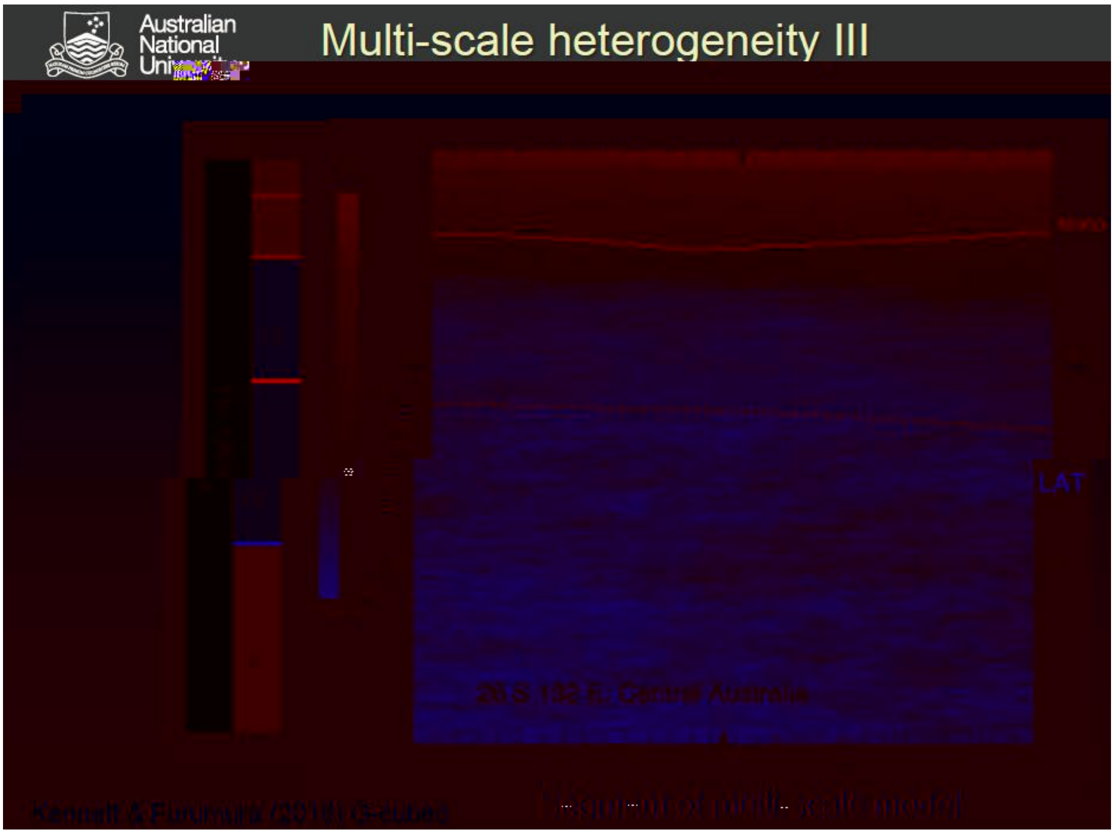
The alternative way of looking at the auto-correlation properties is to work with the coda of the earthquakes and samples taken from the sanatown for Western Australia. They use based years of approach to stack many hundreds of arriving phases to get an estimated P reflectivity. This approach does not fit so strongly by local structure, so it is clearer record. And they find apply automatic gain control, the control give some help in recognizing changes in P reflectivity. And therefore picking up lithosphere discontinuity, instantaneous frequency can also help. So there are indications here over presents, over a couple of different discontinuities, a shallow one, a slightly deep one, but it is closed to the point where you get into this lithosphere-asthenosphere transition. I think this is an important point we took often of the lithosphere discontinuity as evidenced comes from many different places around the world and there may be many different types of such sequent discontinuity.

So the middle lithosphere discontinuity (MLD) is difficult to describe, because I think different people will be looking different things and producing different definitions. Aneczetic and one of the ways we made some progress based by looking at the properties of the P waves. Where a lot of the work is being underestimated by inversions. Reasonable description is a modest amount of the quasi-laminar heterogeneity that is the elongated features on the horizontal direction, they are merging into the structure as shorter correlation within the lithosphere-asthenosphere transition, we can make the correlation somewhat shorter, this change is probably associated with processes occurring in the lithosphere from the low, changing the character of the structure and the lithosphere-asthenosphere transition playing an important role here.



Now if we want to try to produce a model bringing together all of things we know about the lithosphere, we have to take account more scales. And I will show you some results and some illustration of properties from multi-scale behavior. So the largest scale behavior regiment 200km, we can be represented to deterministic behalf the estimates of velocity structure, for example the reference model and we can use them. For the medium scale and the fine scale, we know they are presents, what we do not expect the part of continent as any details for the medium scale. Yes, we could produce small pattern for central Australia, and what we can use random stochastic representations of structure. So we make random processes and produce all of these behaviors. But we do not know in details of these.

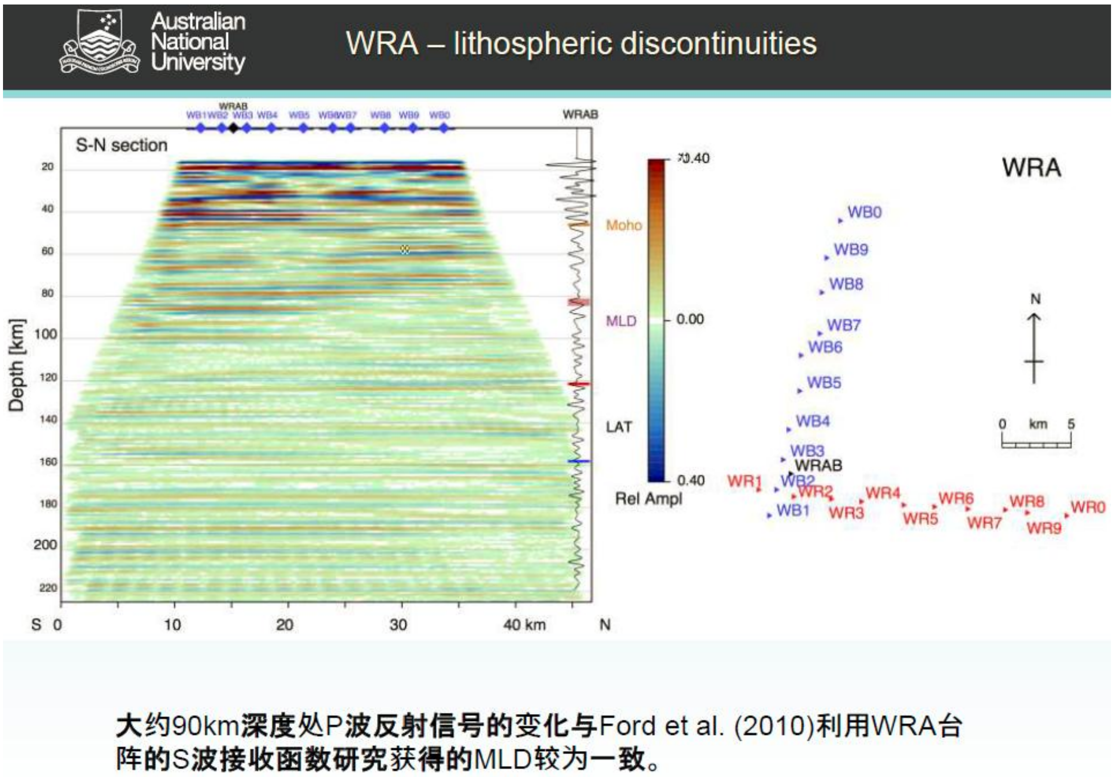
So, the structure, this is the full representation of the structure, it involves horizontal scale of base structure from surface wave tomography. Then the Medium-scale, heterogeneity regimes the rms het is about 1%, horizontal correlation is about 100km, vertical correlation is about 24km. The range of fine-scale is emphasizing with strong heterogeneity in the crust and weakening heterogeneity and in the regime heterogeneity there in the lithosphere Asthenosphere transition, and looking at that table is terribly informative.



So here is illustration of water segment model action looks like. This is from a two dimensional simulation of Central Australia. This is looking at the 300 kilometers structure vertically and horizontally. We have a crustal heterogeneity which shallow stronger as we get the Moho. The modest heterogeneity for this region is fine scale, a distinct change in neighborhood associated with the surface wave. And then we have short scales here, you can see a patch is on the short horizontal distance. That's the segment of the multi-scale model.

And that crust model produces, in the same way the simple model I have shown in the Indonisia subduction zone, and realistic representation of horizontal propagation. This profile here, is taken at the mid-point, just a representative sample. You can see all the fine scale variation depths translates into the producing strong scattering here. You can see the wave trails, the red place representing scatter energy continues spreads out for hundred kilometers behind waveform. That is what we gave the long extending coda. The energy in three dimentions actually can tell from ray trace studies travels approximately along the great circle. It is being generated along the part and travel along the part rather than wide scatter from sides. The example tht□x 1 - 1 0 □

waves, the coherence is very good of the full departure of the array that is not the transverse component that is only smaller than scatter energy. here is the S, and surprise is how weakly correlated S is across the ###(地名). Even for the transition component. The later arrival is this, tend to be smartly better correlated than the beginning. if we have a successful of model heterogeneity, we have to explain my P waves, well correlated than S wave, and one of the reasons is so simple that the white lengths of S wave is smaller than interact more strongly than structure.



So to see whether the multi-scale model actually reproduce this behavior, undertaken simulation on 2d, and 3d simulation is too grand to present time to make it, it is just practical but not to do many tests. So this simulation over propagation distance is 1300 kilometers into a line stations. We got the P wave radial component, geologically history. The profile we looking at extending from the Southern Australia craton, upper to the northern Australian craton follows the one major road through the central continent, and it passes two component seismic arrays, ASAR, NAC, which is both primary stations in the network. So what we are looking at are the properties of the wave field along this line, we look at the receiver function at CCP stacking on the station correlation and also at the properties of auto-correlations for P waves and reduce the common reflection point stank.

We're taking this case Moho from the AuSREM model, and LAT from the results of Yoshizawa. And we attempt to estimate potential of local lithosphere discontinuity based on combination of the visual property and variation frequencies.

If I pull down all the different estimates on background of such seismic velocity or radial anisotropy. What we found are probably to find elsewhere is the properties of radial anisotropy, appeared more regularly to the position where S estimated directly the lithosphere discontinuity, directly along the seismic wave. The LAT is here, here is a line of approximately along the significant major gradient.

We have two seismic arrays and at these arrays we have relatively long rounds, so here we have projective all the results that we have on the array onto a north-south profile. If you used a migration procedure introduced by litto in JAPAN in which we take individual records and we spread out, in that we will get behavior like this, and then some old different migration, this gives us crude estimate of the behavior like that. What we see here is the very consistent behavior through crust, the bounding, the double lift of the Moho. The Moho in this region is somewhat transitional, and so we do not expect very short Moho. Then we have another relatively consistent behavior terminating the 90 km, we can associate the big lithosphere discontinuity. And then greater that, what we see are features that take 50km. we are beginning to see the pictures of scales, studies using horizontally propagating waves. So this is a beginning of total image of the structure. If we look at the array of the north this is a big different configuration. Here are stronger variations with looking at the larger horizontally distance. We see again relatively consistent crustal structure and WRA seismic station here. In this neighborhood, this is record of the FF station, this is the estimate of the lithosphere discontinuity from S to P conversion. So in both of these velocities, we see evidence for the existence of this structure that can lack out skills no more than 10-20 km. many of you may be familiar with the common conversion stacking surface waves. The study which seek out the profile showing the very distinct Moho, and it was picking up the jumps in the crustal pignosphere.

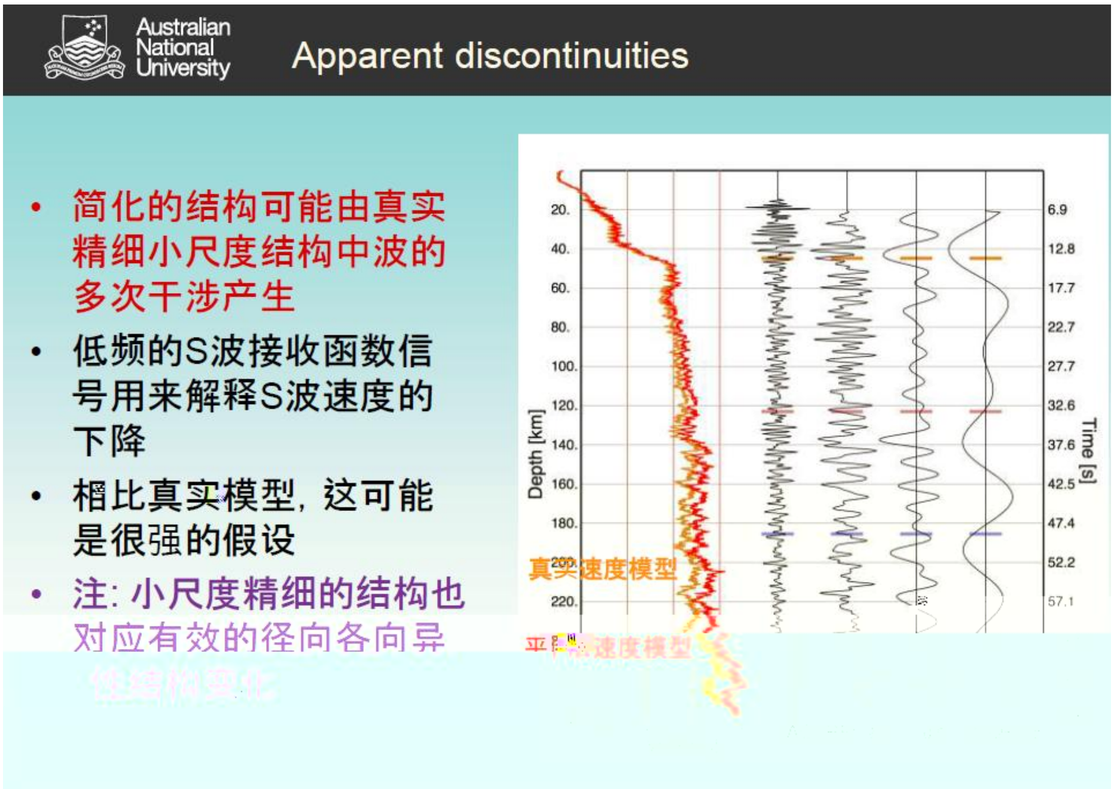
It looks closely here, we can see a brown balls from original Moho models match. The Moho model of Moho surface through our country is smooth, and we can pick up jumps. Below the Moho, we can see the complex structure, and this is the P to S receiver function, and in that case, it could be contaminated by crustal mountains. Here fortunately, the Moho is weak, and so the crust is not much a problem. And nobody think that is a problem. The middle part here is coming reflection points stacking, using earthquake arrival auto-correlation. Dashed line is the transfer from the Moho from receiver function under the relatively component, the common receiver point stacking, in the similar way of reflection point study, this kind of study will give you. If you look at the places where the reflection occurred, along trajectory of incoming P wave. So we met each of these arrival with that great slowness in the velocity model with the 35-40 km, it gives a complex picture. But if we look at it in more details here, we see a very distinct arrivals here, this is interesting surface can be detective conversion point here. We believe this is an image of detection surface in central Australia, accommodating changes craton. I put on the dashed line in purple for the lithosphere discontinuity. The frequencies used to produce the image, we are not seeing any very distinct arrivals associated with lithosphere discontinuity, some of that changed in that neighborhood.

This is a very complicated region and we actually have no very continuous lithosphere discontinuity to image.

What might we expect, if we look at the simulations, so I come back to the multi-scale model and now I'm going to look at one deep profile at this white marked one, we can expect that if we looking at this earthquake with some station that means relatively shallow model, down here what we are doing is horizontal average? On the right, the red is velocity profile using calculations, and the orange is the regional true structure. This is the auto-correlation transition energy, which gives us give direct estimate of the P wave reflectivity. Next, I hope the rest of the S to P receiver function. This is what if you were able to get from S wave. The feature of auto-correlation directly presents these, and it is a good time between correlation and receiver function. S wave receiver function generally consider the frequency, and next case is that we get apparently simple signal came from this complicated model, when we get character simple trace, they do not necessarily find the existences of the simple structure the path simple signal can represent a model.

So, when we get a simple apparently traces that they do not necessarily find existence simple structure, this ethnic is very important in the contact of the S wave receiver function. The character of the S to P receiver function is a change function of frequency. Change function of frequency is a characteristic of deviation for more complex structure. The more complement gives you a message. So, the fact we can head emphasize the ground, and the fact people devise five label model representation of structures. This is not the fine work, we have to be careful, has to using all the different transitional evidence we have.

Is it possible to get any more information about the natural structure? This is a simulation using a group of stations, thirty stations on three km part, and along the top model here, back to the same migration procedure I illustrate early. If we pick up the Moho very well and if we actually look at features interactive actually reflect well structure present in the original problem. And the grate of that here, we are getting more horizontal smearing in the true model. A striking feature is what happens if we reduce the frequency. Here we get to see the fine scale structure, what we now see some of the transition structure associated with the large scale features, for example, this distinctive array. So one model has both limit, fine scale and large scale features, reflecting different wise in the interpreting properties.



The last topic I would like to talk about is extending to Seismic-Geochemical heterogeneity, in 2003 down along this line put there, in the mantle xenoliths results, or profile from South Australia here on the craton zone. On the background here I show you all of the seismic stations. What we have done is to take auto-correlation result from all of these stations, and stack the mark in the immediate neighborhood of each of these to get into the estimate of the P wave reflectivity below those stations. The majority of the stations are coherent, so we can get relatively high frequencies.

So here I have plotted stack case reflectivity against the results from the all arriving different study, which should be our arrays in term of mineral composition. So to get this image, we got conversion of geochemical results from pressure to depth with time. We take account for the uncertain depths of time translation to the seismic wave and the geochemical results. I think you will find the kind of remarkable things. For example, the estimate of the geochemical lithosphere and craton here corresponds with the position of the mechanic, so there is a base of LAT. Each of the major change of the composition will check out some composition. What they think indicate is that they find a scale variations in the seismic properties, reflects geochemical influences. There is a good deal to learn from those as to the nature of what he's going on. Over here's the estimate of the top of lithosphere-asthenosphere transition. The petrological lithosphere is somewhat lower, but it doesn’t mean the bounds. So this is interesting example because general corresponds indicate in the path. And it is to be made between geochemical heterogeneity and seismological heterogeneity.

So in conclusion, I just like to indicate that we've been able to decipher some properties of seismological lithosphere, all reflect the nature of what we actually have recognized. We need to recognize all range scale in the heterogeneity. The large scale is for the whole, the medium-scale probably find details, medium scales probably reflect the detail processes, the fine-scale is been arrived in which different aspects to link most closely to geodynamic and geochemical processes. When we look this lithosphere, it is important to recognize a simplicity, actually comes from the complexity. Many complex systems have simple outcomes, the lithosphere at least raise our path. We cannot directly image the finer scales that indicate our ways which we can get some information of indirect image close to the stage of being able to get the structure. We need a very fine scale supplying field to produce that, which is something smelling, large experiment, thousands of seismic experiments have been deployed, most of the directors of Charles structure, but we have to know of the information.

The mid-lithospheric discontinuity, here's the time recently well to changes in the style of heterogeneity. The class of behavior they want to see seems to tie to extent to search michsizemmis occurring and inter traction in the base. So the transition from lithosphere and asthenosphere is dominated I believe what is happening below the shadow part of lithosphere.

I just like to acknowledge many people’s work helping me make this study! Thank you!