nature portfolio

Peer Review File

Quasi-Love wave scattering reveals tectonic history of Australia and its margins reflected by mantle anisotropy

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10th Mar 21

Dear Dr Eakin,

Your manuscript titled "The Deep Roots of Geology: Tectonic History of Australia Preserved as Mantle Anisotropy" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these concerns.

In the revised version, please make sure to:
1) Discuss and quantify the uncertainties involved in the interpretation of the scatters, in terms of location, depth and magnitude;
2) Provide a robust and compelling case for a statistically significant correlation between the scatterers you observe and tectonic features (lithospheric boundaries and the continental margins) including quantification of the uncertainties involved.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript.

However, please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Joao Duarte, PhD
Communications Earth & Environment
orcid.org/0000-0001-7505-3690

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review of "The Deep Roots of Geology: Tectonic History of Australia Preserved as Mantle Anisotropy" submitted to Communications Earth & Environment by Caroline Eakin

This manuscript reports scattering of surface seismic waves at just over three hundred locations in and around the Australian continent. About one-third of the scattering events are located within 1º of continental margins, and just over a quarter are located within 1º of known crustal boundaries within the Australian continent. The location of scatterers is investigated with respect to seafloor ages, free-air gravity anomalies, tectonic provinces, and seismic tomography. The main conclusions of the manuscript are that the location of scatterers suggests "deep mantle roots" (l. 13) to continental margins and to major crustal boundaries. For the continental interiors, the results "imply pervasive fossilized lithospheric anisotropy, on a scale that mirrors the crustal geology at the surface, and a strong lithosphere that preserves this signal over billions of years." (l.14-16). For the continental margins, the results "indicate either the edge of the thick continental lithosphere or small-scale dynamic processes in the asthenosphere, such as edge-drive convection" (l. 16-18).

I found the article interested and well presented. The identification of QL scatterers represents a significant amount of work and will be of interest to the solid Earth Science community. I was less convinced by the interpretation of the results (see below). It seems problematic that the title and abstract are largely focused on scatterers near major continental tectonic boundaries that represent ~27% of the dataset. It is also unclear that the relationship between these scatterers and tectonic boundaries is statistically significant. Finally, the depth of the scatterers seems to be largely unconstrained so it is unclear how deep the "deep roots" of geology might be.

Main comments:

The presentation of results does not include any uncertainties. Is this because the identification of QL scattering events is largely visual and picked manually? Nevertheless, it should be possible to estimate an uncertainty about the location, depth, and magnitude of scattering events? This seems important since the location of scattering events is key to the interpretation of the results.

l. 67-69: "In total, 83 scatterers lie within 1° of a known major crustal boundary in Australia (dotted yellow lines)." How significant is this result? It seems that most of continental Australia is within 1º of the dotted yellow lines on Fig. 3b. (see also Fig. S7). Statistical tests (see for example Figure 4 of Hoggard et al., 2020) could be carried out to demonstrate that the relationship is better than random. This could also be done for the oceans. At the very least, scatterers should be shown on a map (in the main text) showing zones within 1º of relevant boundaries. What proportion of continental scatterers and oceanic scatterers is away from tectonic boundaries or continental margins, respectively? If I understand correctly, a link to amplitude is not expected; it would be nice to clarify this.

The discussion about the depth uncertainty is helpful, in particular l. 91-97 and Fig. 3b. Is the depth necessarily greater than 100 km (l. 118-119) or could some scatterers be shallower? Given the uncertainty, it would be better to give a range (i.e. predominantly between 100 km and 200 km depth) in the abstract, rather than a single depth (~150 km, l.8).

Edge-driven convection (EDC) is mentioned as a potential mechanism to generate scatterers. This mechanism seems plausible for the trailing edge of the plate (Farrington et al., 2010), including the Newer Volcanics Province in SE Australia (l. 111-112). However, EDC is in my view a less likely mechanism along the eastern continental margin of Australia (contrary to the conclusion on l. 132-133): the gradient in lithospheric thickness is not as steep there, and EDC would be largely suppressed by the largely north-south pressure gradient due to the motion of the plate.

Given the spatial distribution of scatterers, I suggest discussing the potential link to topography gradients, with gradients in gravitational potential energy (e.g. Ghosh et al., 2009) as a potential driver. Note that a quick search did not return results for a detailed study of Australian gravitational potential energy. Incidentally, it is well known that a significant fraction of earthquakes within continental Australia are on the continental margins (e.g. http://www.quakes.uq.edu.au/quakeinfo.html).

Mentioning the Australian Stress Map (e.g. Rajabi et al., 2017) might also be helpful, in particular with respect to shallow/asthenospheric scatterers.

Regarding fossil anisotropy and the complexity of SKS splitting in the Australian continental lithosphere: could this be linked to a layer subcontinental lithosphere (e.g. Yuan and Romanowicz, 2010)? This reference or a similar one seems relevant to the discussion l. 119-122.

Minor comments:

What is the implication of a cluster of scatterers away from mapped boundaries in the Northern Territory? This is interesting as the Kimberley Block may present an Archean root (Graham et al., 1999; and perhaps also Betts et al., 2002).

The location of scatterers is analysed with respect to free-air gravity anomaly (Fig. 3c), which is better constrained than Bouguer gravity anomaly. I wonder if a spatial relationship could be established with the Bouguer anomaly - this could be interesting since the scatterers are deep.

On Figure 1, I suggest highlighting the QL wave graphically, for instance by adding a thick line in the background.

I was surprised by the absence of references on l. 20-25.

Zealandia (l. 10, l. 62, l. 79, and elsewhere): I suggest using the culturally inclusive name Te Riu-a-Māui/Zealandia (e.g. Bischoff et al., 2020).

References - these are mostly pointers and I do not expect them to be cited in a revision; which references are appropriate is up to the author.

Betts, P.G., Giles, D., Lister, G.S. and Frick, L.R., 2002. Evolution of the Australian lithosphere. Australian Journal of Earth Sciences, 49(4), pp.661-695.

Bischoff, A., Barrier, A., Beggs, M., Nicol, A., Cole, J. and Sahoo, T., 2020. Volcanoes buried in Te Riu-a-Māui/Zealandia sedimentary basins. New Zealand Journal of Geology and Geophysics, 63(4), pp.378-401.

Ghosh, A., Holt, W.E. and Flesch, L.M., 2009. Contribution of gravitational potential energy differences to the global stress field. Geophysical Journal International, 179(2), pp.787-812.

Graham, S., Lambert, D.D., Shee, S.R., Smith, C.B. and Reeves, S., 1999. Re-Os isotopic evidence for Archean lithospheric mantle beneath the Kimberley block, Western Australia. Geology, 27(5), pp.431-434.

Rajabi, M., Tingay, M., Heidbach, O., Hillis, R. and Reynolds, S., 2017. The present-day stress field of Australia. Earth-Science Reviews, 168, pp.165-189.

Yuan, H. and Romanowicz, B., 2010. Lithospheric layering in the North American craton. Nature, 466(7310), pp.1063-1068.

Nicolas Flament, Wollongong, 16 February 2021

Reviewer #2 (Remarks to the Author):

see the attached file

Reviewer #3 (Remarks to the Author):

see attached PDF

Review of the paper "The Deep Roots of Geology: Tectonic History of Australia Preserved as Mantle Anisotropy" by C. Eakin.

The basic idea to use quasi-Love (QL) anisotropic data to make structural geology is really good, provided that the interpretation is correct. The author collected an impressive dataset of QL data in Australia, and I have no doubt on the data processing. But my main concern is the interpretation of data in terms of scatterers.
I will try to explain why this interpretation is partly wrong or at least incomplete. I read: (line 36) that "quasi-Love wave travels with the slower velocity (than fundamental Love G1) of the fundamental Rayleigh wave mode R1".
This statement or hypothesis (also read in Park & Yu, 1993, Yu et al., 1995, …Chen & Park, Tectonophysics, 2013, many other papers from the same group, and more recently in Servali et al., Tectonophys. 2020) does not catch the whole complexity of anisotropic causes and origins giving rise to quasi-Love (QL) waves. The whole interpretation of the observed delay times δt between G1 and QL is based on this statement. I understand that it is very convenient and easy to use the formula (3) to derive the location of the scatterer, but it is an oversimplification of the generation of QL, and I will explain why the location of scatterers using this formula is not accurate. A discussion of the limitation of this hypothesis is never provided.

To my knowledge, there are two different theoretical approaches for generating QL waves, the propagation of plane waves in multi-layered medium (since Crampin, 1975 and then Maupin, 1989, Tanimoto, 2004) and the normal mode approach (see papers by Park and Yu, 1992, Yu and Park, 1993 and many other papers from the same group) with first-order perturbation theory.
When toroidal and spheroidal modes are strongly coupled, in particular through strong anisotropy gradient, energy is transferred from toroidal modes to spheroidal modes and QL propagates at the Rayleigh wave velocity. In the benchmark experiment of Chen and Park (Tectonophysics, 2013), the azimuthal anisotropy is only located in an equatorial band of ~900km width, but the rest of the medium all around is isotropic. In this particular case, the scatterer is correctly located.

In the approach investigating Love wave propagation in a plane multi-layered medium (see old papers by Crampin, 1975, Maupin, 1989 and more recently of Tanimoto, GJI, 2004), when a Love wave enters an anisotropic medium, it was shown that the polarizations of both Love (T) and Rayleigh waves (R, Z) rotate, giving rise to quasi-Love waves on T, Z and R components and quasi-Rayleigh waves (on R, Z, T components) and the velocity of quasi-surface waves QL and QR is quite complicated (see for example Tanimoto, 2004). But, in a homogeneous anisotropic medium, the velocity of quasi-Love waves on T and R, Z is the same on the three components. The calculation of Tanimoto (2004) is only valid for the fundamental modes, but since the author claims that she gets rid of overtones, it should be a good approximation. However, when the quasi-Love comes out the anisotropic region (in particular the strong anisotropy gradient) and entering another region (isotropic or anisotropic), with lateral variations of properties, quasi-Love waves propagate at the Rayleigh wave phase velocity. So the delay time between G1 and QL might be due to lateral variations of azimuthal anisotropy, not only to the anisotropy gradient.
In the real Earth, Love waves propagate from the source to the receiver station in several anisotropic regions with different orientations and amplitude, adding complexity to the incoming Love wave train. As mentioned by Kobayashi (GJI, 1998), lateral variations in azimuthal anisotropy are necessary to generate QL-waves and the location of the scatterer is

quite difficult to determine. Even Kobayashi & Nakanishi (GRL, 1998) found that the conversion point is frequency dependent and sometimes QL waves arrive faster than Love waves. So, the hypothesis that the conversion for Love waves is a point is very questionable. It means that the uncertainties associated with the scatterer location can be very large. There is no attempt in the present paper to estimate such uncertainties.

All paths given on figure 2 cross oceanic areas (Pacific or Indian oceans) which are well known to be strongly anisotropic. It means along their paths, Love waves cross regions with different anisotropic parameters, and have time to generate quasi-Love waves and to accumulate delay time between G1 and QL. It makes the interpretation of the delay time δt between G1 and QL problematic. What happens to QL generated before it crosses anisotropy gradients?

When a quasi-Love wave is generated, there is as well a quasi-Rayleigh wave, which should be visible on figure S1. Why is QR waves not visible? Since the traces are normalized, may be, the selected Rayleigh waves have a smaller amplitude than the amplitude of Love waves. For Rayleigh waves in the radiation node, the observation of quasi-Rayleigh waves is very difficult since they have a very small amplitude. This point should be clarified. Does the author only look for Rayleigh wave data in their radiation node?

Higher modes/overtones issue: It is mentioned that data are low-passed filtered at 100s to suppress overtones. I am not convinced that data are really devoided of overtones. The overtones, even for shallow earthquakes, can have a significant amplitude. In the plane layered medium approach, the coupling between the fundamental modes of Love and Rayleigh (G1 and R1) is usually small and it is necessary to consider the coupling between Love waves G1 and Rayleigh higher modes to generate QL.
By the way, the depth of events is never mentioned in figures S1, S3, S4, not mentioned in the table provided in the supplementary information. It should be very easy to check whether Rayleigh overtones have a small amplitude by computing synthetic seismograms with widely available normal mode codes. If overtones are not negligible, there is a strong coupling between fundamental Love mode and Rayleigh higher modes, since they have similar group velocities. And this might significantly bias the measurement of δt.
There is no discussion of the error bars of the location of scatterers (strong anisotropic gradients).
I do not want to say that the whole interpretation is wrong, but that the location of scatterers is not necessarily accurate. And the estimate of the uncertainties on the location of scatterers should be welcome.

When looking at the distribution of scattering points (figure 3), it looks like a random distribution, and I confess that a lot of imagination is necessary to see the correlation with the complex geology of Australia. When looking at the maps displayed in Figures 3c,d the probability for finding a scatterer close to a geological structure (within 1°) is probably not negligible. Some scatterers do not seem to be correlated with geological features. Figure 4c displays the long wavelength distribution of azimuthal anisotropy but is it useful? I did not read any attempt to try to find correlations or relationships between the distribution and amplitude of scatterers and azimuthal anisotropy.

In conclusion, even though it is an interesting paper, with original data, the methodology based on the interpretation of QL waves is not really innovative and even not robust, so the location of scatterers is unsettled. The originality stems from the investigation of the

Australian continent. The same approach of using QL was also followed in other groups in other parts of the Earth, since the use of QL waves is a new way to make "geology". So, the work is not really original except that the approach is applied to the first extensive study of the Australian continent. But I am not convinced by the reliability of the results. Some modeling of results should be important to support the observations. I do not recommend the publication of this paper as it is.

Technical points:

Figure 4b,c: why does the author plot the model of Schaeffer & Lebedev for velocities and the model of Debayle et al. for azimuthal anisotropy? and why not the regional models of Debayle et al. (2005) or Simmons et al. (2002) who obtained consistent models of S-wave velocities and azimuthal anisotropy.

Figures S4 and S5: these figures display scatterers for a specific event. I do not understand why very close stations provide completely different locations of scatterers, for example, the two stations in south-west Australia or other close stations in south-east Australia. Some stations are almost aligned along the ray path and should provide the same location for scatterers.

Not quoted references:

Crampin, GJRAS, 40, 177-186, 1975.

Kobayashi & Nakanishi, Geophys. Res. Lett., 25, 1067-1070, 1998.

Maupin, G.J.I., 98, 553-563, 1989.

Simons et al., G.J.I., 151, 738-754, 2002.

Tanimoto, G.J.I., 156, 73-78, 2004.

Comments to Editor

The manuscript investigates the geographical correlation between the scattering of surface waves and geological margins in the lithosphere around Australia. The location of scatterers displays similarities with these margins. Based on this evidence, the author concludes and hypothesizes new insights. To find the scatterer locations Quasi-Love waves have been used that representing the location of lateral gradients or sudden changes in seismic anisotropy.

I recommend the manuscript to be published in Communications Earth & Environment after **a minor revision**. The manuscript is scientifically well written. Arguments and conclusions are clear and convincing and based on conclusive evidence. Methodology is clearly explained.

Comments to Authors

Main Comments

- Line 148, you use a back-projected distance to find the location of scatterers assuming the great-circle path. How much lateral velocity variations can change the path from the great circle? This can affect the location of scatterers and therefore probably your conclusions. How to answer this concern. Explain it.

- Fig 4b, we know that in the mentioned period, surface waves are mostly sensitive to the depth range of 100-200 km. However, they are affected by other depths. Although Fig 4b is informative, but depicting scatterers only between 100-200 km could be misleading. I mean scatterers could originate from other depths, and showing them only between 100-200 km may not be appropriate.

- Fig 4c, it is an interesting figure showing the azimuthal anisotropy and velocity. Is it possible to make a figure with scatterer location and background color of directional variations of the azimuthal anisotropy? This means that sudden changes of the azimuthal anisotropy could correlate with the location of scatterers. Refer to my previous comment, it is possible to check this correlation at other depths and may find some clues about the depth of scatterers.

Minor Comments

- Line 59, replace blue circles with cyan circles

- Line 68, to be consistent with Line 60, say how much percentile is 80 scatterers.

- Line 74-76, use the same abbreviations as Fig 3 caption in the text.

- Fig 3b, what is the meaning of dark and light gray colors in Australia and Zealandia?

Summary of Major Changes

I thank the three reviewers for their constructive comments, which have overall strengthened the conclusions presented within this manuscript. In particular the addition of statistical tests have now demonstrated the significance of the spatial correlation of the scatterers with the continental margins and geological provinces. In addition a more detailed consideration of the uncertainties involved in QL wave interpretation finds that the expected error on the location of the scatterers is on the order of 100 km, consistent with the conclusions drawn from the results. A considerable effort has been made to fully address the requests and concerns from each of the three reviewers, which can be found in the detailed responses to the line-by-line comments. Further details of the two major improvements to the manuscript, and where to find them in the revised text, are outlined below.

Uncertainties in the Interpretation of Quasi-Love wave scattering:

A new sub-section dedicated to this topic, titled "*Errors and uncertainties on the interpretation of Quasi-Love waves*", has been added to the Methods. This outlines in detail the uncertainties associated with the interpretation of the Quasi-Love scatterers including the mechanism, amplitude, depth, and location. An additional sub-section is now provided at the start of the Discussion to summarise the most important points for the reader, with a link to further details provided in the Methods.

Demonstration of statistical significant correlation between scatterers and tectonic features:

Following helpful suggestions from Reviewer 1 (Nicolas Flament), the spatial correlation has now been quantified and demonstrated, bolstering the arguments presented within the manuscript. The new Figure 4 shows the cumulative distribution function (CDF) of the scatterers relative to the ocean-continent boundary (continental margins) and the major geological provinces of Australia (internal continental structure). Both distributions show that the Quasi-Love scatterers lie closer to these features than expected compared to randomly located points. Using a two-sample Kolmogorov–Smirnov test the statistical significance for the continental margins is calculated as 4% (p-value = 0.04), and 0.06% for the geological provinces (p-value = 0.0006). This quantitative analysis is outlined in two new paragraphs added to the Results section. This lends convincing support to the presented argument that both the continental margins, and the internal geological boundaries of Australia, are locations where Quasi-Love waves are preferentially generated.

Reviewer #1

Review of "The Deep Roots of Geology: Tectonic History of Australia Preserved as Mantle Anisotropy" submitted to Communications Earth & Environment by Caroline Eakin

This manuscript reports scattering of surface seismic waves at just over three hundred locations in and around the Australian continent. About one-third of the scattering events are located within 1º of continental margins, and just over a quarter are located within 1º of known crustal boundaries within the Australian continent. The location of scatterers is investigated with respect to seafloor ages, free-air gravity anomalies, tectonic provinces, and seismic tomography. The main conclusions of the manuscript are that the location of scatterers suggests "deep mantle roots" (l. 13) to continental margins and to major crustal boundaries. For the continental interiors, the results "imply pervasive fossilized lithospheric anisotropy, on a scale that mirrors the crustal geology at the surface, and a strong lithosphere that preserves this signal over billions of years." (l.14-16). For the continental margins, the results "indicate either the edge of the thick continental lithosphere or small-scale dynamic processes in the asthenosphere, such as edge-drive convection" (l. 16-18).

I found the article interested and well presented. The identification of QL scatterers represents a significant amount of work and will be of interest to the solid Earth Science community. I was less convinced by the interpretation of the results (see below). It seems problematic that the title and abstract are largely focused on scatterers near major continental tectonic boundaries that represent ~27% of the dataset. It is also unclear that the relationship between these scatterers and tectonic boundaries is statistically significant. Finally, the depth of the scatterers seems to be largely unconstrained so it is unclear how deep the "deep roots" of geology might be.

I wish to thank the reviewer for their insightful comments and suggestions, which have been most helpful in improving the robustness of the interpretations and conclusions. The relationship between the scatterers and tectonic boundaries has now been shown to be statistically significant following the suggested analyses. This is described in greater detail below in the response to the main comments.

For the title, to me tectonic history reflects both the continental internal boundaries and the rifted passive margins. To better reflect this I've modified the title to: "The Deep Roots of Geology: Tectonic History of Australia **and its Margins expressed by** Mantle Anisotropy"

I've changed the opening line of the abstract to make it clear that "deep roots" refer to depths within the mantle, i.e. below the crust:
"The Australian continental crust preserves a rich geological history, but it is unclear to what extent this history is expressed deeper within the mantle"

Main comments:

The presentation of results does not include any uncertainties. Is this because the identification of QL scattering events is largely visual and picked manually? Nevertheless, it should be possible to estimate an uncertainty about the location, depth, and magnitude of scattering events? This seems important since the location of scattering events is key to the interpretation of the results.

In order to improve clarification around the uncertainties involved, new text has been added to the Discussion and Methods sections, both under the sub-heading "*Errors and uncertainties on the interpretation of Quasi-Love waves*". After considering multiple factors a typical error in location is estimated to be on the order of 100 km, which is consistent with the current interpretation of the results.
Below is the written summary of the uncertainties involved in terms of mechanism, amplitude, depth and location that are provided on lines 195-238 in the Discussion. A full detailed description of each is provided in the new sub-section under Methods (line 449 onwards).

"Errors and uncertainties on the interpretation of Quasi-Love waves

It is important to first consider the uncertainties associated with the analysis of QL waves before making any physical interpretations. A brief summary is provided here in terms of the mechanism, magnitude, depth, and location (for a more detailed description please see Methods). Numerous studies have demonstrated that QL waves are most efficiently generated by lateral gradients in seismic anisotropy (i.e. changes in either the strength or orientation of seismic anisotropy), and are difficult to reproduce with purely isotropic velocity changes [36–39]. Higher mode Rayleigh waves with velocities faster than the fundamental mode may potential interfere within the selected time window, but shallow earthquakes (<50 km) should preferentially excite the fundamental mode rather than higher modes [40]. In addition all QL wave detections are visually inspected to ensure similarity in waveform shape with the Love wave (G1).

The magnitude of the QL wave (i.e. size of the symbols in Fig. 3), is expressed as the relative amplitude between QL and G1. This magnitude is a function of both the strength of the lateral anisotropic gradient and the propagation azimuth relative to the anisotropic geometry. If the propagation direction is parallel or perpendicular to the symmetry axis then the amplitude will be zero. A particularly large QL amplitude is therefore indicative of the presence of a strong gradient but a small amplitude, or even absence of a QL wave entirely, is not conclusive evidence of a weak or non-existent gradient. It is therefore not possible to directly interpret the amplitudes of the observations.

Depth sensitivity kernels calculated for a QL wave with a dominant frequency of 0.01 Hz (100 s) suggest a broad range of sensitivity throughout the upper mantle, with a peak around 100-200 km depth (refer to Fig. S1 of Levin et al. (2007), Fig. 9 of Chen and Park (2013)). While potential contributions from shallower or deeper depths cannot be entirely ruled out, the source of the QL waves most likely resides within the upper mantle, and not within the crust.

The location of the QL scattering source is found by back-projection along the great-circle path (Figs. 1, S2, S5). Potential location errors are estimated to be on the order of 100 km, considering the typical wavelength of 100s surface waves, the results of numerical experiments[18], potential deviations from the great-circle path, and assumptions made the uniformity of the average Rayleigh and Love phase velocities between source and receiver (refer to Methods for details). This is consistent with the spatial distribution of results found relative to certain tectonic and geological features (Figs. 3-4, S9)."

l. 67-69: "In total, 83 scatterers lie within 1° of a known major crustal boundary in Australia (dotted yellow lines)." How significant is this result? It seems that most of continental Australia is within 1° of the dotted yellow lines on Fig. 3b. (see also Fig. S7). Statistical tests (see for example Figure 4 of Hoggard et al., 2020) could be carried out to demonstrate that the relationship is better than random. This could also be done for the oceans. At the very least, scatterers should be shown on a map (in the main text) showing zones within 1º of relevant boundaries. What proportion of continental scatterers and oceanic scatterers is away from tectonic boundaries or continental margins, respectively? If I understand correctly, a link to amplitude is not expected; it would be nice to clarify this.

Thank you for drawing to my attention the statistical tests from Hoggard et al., (2020) which proved to be most helpful and relevant for demonstrating spatial correlations within the present dataset. After speaking to the lead author of the aforementioned study, who has since joined RSES/ANU, I implemented similar cumulative distribution functions (CDFs) showing the distribution of the scatterers relative to tectonic features (see new Figure 4). When compared to the average properties (mean and standard deviation) of 100 distributions of the same sample size but with points randomly located, it is shown that the scatterers are preferentially located closer to the continental margins and boundaries of major geological provinces than random. In both cases the result is shown to be statistically significant, with rejection of the null hypothesis (that the CDF for the scatterers cannot be distinguished from random) at the 4% and 0.06% significance level for the continental margins and the geological provinces respectively. Further details with regards to these CDFs plots and results are described in two new paragraphs on lines 116-148.

As correctly inferred by the reviewer, after further inspection it was found that most of continental Australia falls within 1° of the known crustal boundaries (Korsch & Doublier, 2016), which meant it would be physically impossible to distinguish a true relationship from that which is random. To overcome this, the crustal boundaries dataset was swapped for the major geological provinces at 1:5M scale as defined by Geoscience Australia (Raymond et al., 2018). These represent the "*spatial extents of the fundamental geological elements of the Australian continent*". As this dataset only focuses on the largest scale, the most fundamental geological boundaries, they are more spaced out, and allow for the possibility of statistical significance to be determined (figure 4).

Figure 4 also now includes maps showing zones of distance from the tectonic boundaries (continental margins & geological province boundaries) as requested.

The reviewer is correct that a link to amplitude is not expected. The reasoning behind this in included in the response to the comment above on uncertainties. On line 225 it is explicitly stated "*It is therefore not possible to directly interpret the amplitudes of the observations*".

The discussion about the depth uncertainty is helpful, in particular l. 91-97 and Fig. 3b. Is the depth necessarily greater than 100 km (l. 118-119) or could some scatterers be shallower? Given the uncertainty, it would be better to give a range (i.e. predominantly between 100 km and 200 km depth) in the abstract, rather than a single depth (~150 km, l.8).

The abstract has been changed to "*Scattering of surface waves predominantly between 100-200 km depth*" as suggested. The restriction of ">100 km" has also been removed from the discussion, and replaced with the modified statement: "*Furthermore this implies that* *geological boundaries are preserved over billions of years not only in the crust but also at deeper depths as anisotropic gradients in the lithospheric mantle*."

A summary of the depth sensitivity is included in the response to the previous comment on uncertainties (including depth).

Edge-driven convection (EDC) is mentioned as a potential mechanism to generate scatterers. This mechanism seems plausible for the trailing edge of the plate (Farrington et al., 2010), including the Newer Volcanics Province in SE Australia (l. 111-112). However, EDC is in my view a less likely mechanism along the eastern continental margin of Australia (contrary to the conclusion on l. 132-133): the gradient in lithospheric thickness is not as steep there, and EDC would be largely suppressed by the largely north-south pressure gradient due to the motion of the plate.

The reference of Farrington et al., 2010 is indeed pertinent and has been added on line 262: "For the southern Australian margin, geodynamical models have suggested the formation of broad upwellings in the region behind the trailing edge of the continent due to EDC (Farrington et al., 2010)"

Thomas Duvernay (RSES, ANU) has been studying EDC for different geometries during his PhD, supervised by Rhodri Davies. Below I've copied a figure from his most recent pre-print that shows EDC can still occur when the continental boundary is parallel to the plate motion direction, in the models it is neither enhanced nor suppressed, unlike when the boundary is normal to the background flow.

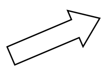


Figure 9c from Duvernay et al.,G-cubed (http://www.essoar.org/doi/10.1002/essoar.10504315.1), showing 3-D representation of the velocity field around a continent, highlighting the dynamical instabilities that form at the edges of thick lithosphere (blue colours), in the presence of a prescribed background flow (large arrow).

Secondly, below is a cross-section from the work of Rawlinson et al., (GRL, 2017) through SE Australia. The area outlined by the blue rectangle suggests that even relatively small undulations in the LAB can modify the mantle flow below. Dashed black lines show the primary zone of interest for QL waves (i.e. 100-200km).

Figure 4a from Rawlinson, Davies, & Pilia (GRL, 2017).

In order to convey this reasoning the following has been added to the text on the discussion of EDC:

"Recent modeling work (Duvernay et al., 2021) suggests that even when the edge of the continent is parallel with the background mantle flow direction (as is thought to be the case for eastern Australia) dynamical instabilities in mantle flow can still be found at the edges of thick continental lithosphere, and may be enhanced where there are undulations or notches in the geometry of the boundary. It remains to be seen however whether the same effect could be generated beneath eastern Australia with only small changes in lithospheric thickness and/or viscosity."

The corresponding statement in the conclusions has been clarified as follows:

"Based on the newly acquired results, it is speculated that at the continental margins small-scale convective processes, such as EDC, or localized disruptions to the mantle flow field, may be occurring where the lithosphere transitions from continental to oceanic. Alternatively QL scattering may be explained by the difference between fossil anisotropy in old thick continental lithosphere and active flow in the oceanic asthenosphere. However, this is harder to justify where the continental lithosphere is younger and thinner on either side of the Tasman Sea."

Given the spatial distribution of scatterers, I suggest discussing the potential link to topography gradients, with gradients in gravitational potential energy (e.g. Ghosh et al., 2009) as a potential driver. Note that a quick search did not return results for a detailed study of Australian gravitational potential energy. Incidentally, it is well known that a significant fraction of earthquakes within continental Australia are on the continental margins (e.g. http://www.quakes.uq.edu.au/quakeinfo.html).

Figure 1 from Ghosh et al., (2009) copied below, shows that the gravitational potential energy (GPE) is relatively low across Australia and its margins. There is a small difference between the continent and ocean, along the northwestern and southern margins, but little difference along the eastern margin. Perhaps this contributes in some way to stresses within the lithosphere at the margins, helping to generate the seismicity? However I'm not aware of any publications that directly make such a claim, and I can't find much in the literature for Australian earthquakes that mention GPE. Even if this is the case, there isn't a clear connection as to how this would influence anisotropy development in the underlying asthenosphere, which is the most likely depth region being sampled by the Quasi-Love waves where the lithosphere is thin at the continental margins.

Mentioning the Australian Stress Map (e.g. Rajabi et al., 2017) might also be helpful, in particular with respect to shallow/asthenospheric scatterers.

Below is figure 9b from Rajabi et al., (2017) showing the Australian stress map. The continental scale pattern doesn't suggest drastic changes associated with the continental margins, or geological terranes.

The present-day crustal stress field, as shown above, does however vary regionally across Australia, and continental deformation certainly does occur in the form of occasional intra-plate earthquakes, the location of which are often guided by past tectonic boundaries and zones of pre-existing weakness within the continent (e.g. Sykes, 1978). However, the overall level of seismicity and present-day strain-rates within the continent are low, with no significant deformation of the continent discernable from GPS (Tregoning, 2003). Such low strain rates are highly unlikely to induce dislocation creep and generate new anisotropy within the lithosphere. Instead fossilised anisotropy frozen-in during the last major deformational episode, e.g. during past orogenesis and suturing events, seems much more plausible in order to generate the level of deformation needed to alter the lithospheric anisotropy.

References

- Tregoning, P. (2003). Is the Australian Plate deforming? A space geodetic perspective. *SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA*, 41-48. http://rses.anu.edu.au/geodynamics/gps/papers/ausplate01.pdf
- Sykes, L. R. (1978), Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation, *Rev. Geophys.*, 16(4), 621– 688, doi:10.1029/RG016i004p00621.

Regarding fossil anisotropy and the complexity of SKS splitting in the Australian continental lithosphere: could this be linked to a layer subcontinental lithosphere (e.g. Yuan and Romanowicz, 2010)? This reference or a similar one seems relevant to the discussion l. 119-122.

A statement on the potential for multiple layers to exist within cratonic lithosphere, including the above reference, has been added at the requested location in the discussion. As far as I'm aware however studies of the Australian continent have yet to characterise or even detect multiple layers of lithospheric anisotropy, or even any kind anisotropic discontinuity present within the Australian lithosphere. Hence, some of the significance of the present study.

Minor comments:

What is the implication of a cluster of scatterers away from mapped boundaries in the Northern Territory? This is interesting as the Kimberley Block may present an Archean root (Graham et al., 1999; and perhaps also Betts et al., 2002).

Thanks for bringing this reference to my attention. The following has been added to line 157:

"Interestingly, there are several large scatterers associated with the Kimberley (K) region of northwestern Australia, which has been argued to be a small cratonic block underlain by an Archean mantle root (Betts et al., 2002; Graham et al., 1999)"

The location of scatterers is analysed with respect to free-air gravity anomaly (Fig. 3c), which is better constrained than Bouguer gravity anomaly. I wonder if a spatial relationship could be established with the Bouguer anomaly - this could be interesting since the scatterers are deep.

I want to avoid over-interpreting the gravity but rather illustrate to the reader where the most significant gravity anomalies are, and what this implies about deformation of the crust and potentially also the lithosphere. I've now added a dashed white circle to highlight the

region of central Australia with the prominent E-W trending gravity anomalies, and the presence of scatterers located there.
From my understanding, the Bouguer and Free-Air gravity anomalies are quite similar for Australia, given the relatively low-lying topography of the continent. They both typically reflect similar sub-surface structure, so I don't see that there would be much added benefit to include such a figure.

On Figure 1, I suggest highlighting the QL wave graphically, for instance by adding a thick line in the background.
I've made it slightly thicker but I prefer to keep the QL propagation path as a thin line. It serves the purpose to illustrate that it is a portion of the Love wave energy (thicker line) that has been converted.

I was surprised by the absence of references on l. 20-25.
Appropriate references have been added to the opening statements of the introduction.

Zealandia (l. 10, l. 62, l. 79, and elsewhere): I suggest using the culturally inclusive name Te Riu-a-Māui/Zealandia (e.g. Bischoff et al., 2020).
Thanks for suggesting this. I've replaced Zealandia with Te Riu-a-Māui/Zealandia in the text.

References - these are mostly pointers and I do not expect them to be cited in a revision; which references are appropriate is up to the author.
Thank-you for helpfully providing references. Most of these have been included in the revision.

Betts, P.G., Giles, D., Lister, G.S. and Frick, L.R., 2002. Evolution of the Australian lithosphere. Australian Journal of Earth Sciences, 49(4), pp.661-695.

Bischoff, A., Barrier, A., Beggs, M., Nicol, A., Cole, J. and Sahoo, T., 2020. Volcanoes buried in Te Riu-a-Māui/Zealandia sedimentary basins. New Zealand Journal of Geology and Geophysics, 63(4), pp.378-401.

Ghosh, A., Holt, W.E. and Flesch, L.M., 2009. Contribution of gravitational potential energy differences to the global stress field. Geophysical Journal International, 179(2), pp.787-812.

Graham, S., Lambert, D.D., Shee, S.R., Smith, C.B. and Reeves, S., 1999. Re-Os isotopic evidence for Archean lithospheric mantle beneath the Kimberley block, Western Australia. Geology, 27(5), pp.431-434.

Rajabi, M., Tingay, M., Heidbach, O., Hillis, R. and Reynolds, S., 2017. The present-day stress field of Australia. Earth-Science Reviews, 168, pp.165-189.

Yuan, H. and Romanowicz, B., 2010. Lithospheric layering in the North American craton. Nature, 466(7310), pp.1063-1068.

Nicolas Flament, Wollongong, 16 February 2021

Reviewer #2

Review of the paper "The Deep Roots of Geology: Tectonic History of Australia Preserved as Mantle Anisotropy" by C. Eakin.

The basic idea to use quasi-Love (QL) anisotropic data to make structural geology is really good, provided that the interpretation is correct. The author collected an impressive dataset of QL data in Australia, and I have no doubt on the data processing.

Thank-you to the reviewer for these comments, and for indicating that they consider the collection of the QL dataset, the primary purpose of this observational manuscript, to be valid and "impressive".

But my main concern is the interpretation of data in terms of scatterers.
I will try to explain why this interpretation is partly wrong or at least incomplete. I read: (line 36) that "quasi-Love wave travels with the slower velocity (than fundamental Love G1) of the fundamental Rayleigh wave mode R1". This statement or hypothesis (also read in Park & Yu, 1993, Yu et al., 1995, ...Chen & Park, Tectonophysics, 2013, many other papers from the same group, and more recently in Servali et al., Tectonophys. 2020) does not catch the whole complexity of anisotropic causes and origins giving rise to quasi-Love (QL) waves. The whole interpretation of the observed delay times dt between G1 and QL is based on this statement. I understand that it is very convenient and easy to use the formula (3) to derive the location of the scatterer, but it is an oversimplification of the generation of QL, and I will explain why the location of scatterers using this formula is not accurate. A discussion of the limitation of this hypothesis is never provided.

I appreciate the reviewer sharing their concerns with regards to the interpretation of the QL dataset. This has helpfully brought to my attention some key points and limitations which have benefited from further attention in the manuscript. This has also provided an opportunity to clarify some statements that appear to be a potential source of misinterpretation.

As the reviewer highlighted, the interpretation used here, to convert the time delay between G1 and the Quasi-Love wave to distance, and back-project the location of the scatterer, has been used in countless previous studies published by several groups. I list additional references below from other groups, to add to the examples provided by the reviewer. It is clear that the approach I have followed is standard practise within the published literature. Instead it appears to me that the source of the issue is the term '*Quasi-Love wave*', which appears to have multiple potential meanings in the literature. I thank the reviewer for the opportunity to clarify this. Please see further details in the response to the comment immediately following this.

<u>Example additional references following the same QL delay time conversion to distance</u>:

Cheng, W., Hu, X.G., Liu, L.T., 2021. Anisotropy Gradients in the Middle of the Ross Sea Embayment, West Antarctica: Evidence From QL Scattered Surface Waves. Geophys. Res. Lett. 48, e2020GL091232. doi:10.1029/2020GL091232

Kobayashi, R., 2002. Polarization anomalies of Love waves observed in and around Japan. Earth, Planets Sp. 54, 357–365. doi:10.1186/BF03352425

Kobayashi, R., Nakanishi, I., 1998. Location of Love-to-Rayleigh conversion due to lateral heterogeneity or azimuthal anisotropy in the upper mantle. Geophys. Res. Lett. 25, 1067–1070. doi:10.1029/98GL00651

Kobayashi, R., Nakanishi, I., Tsuboi, S., 1997. Polarization anomalies of surface waves recorded by a broadband seismometer network in Hokkaido, Japan. J. Phys. Earth 45, 383–396. doi:10.4294/jpe1952.45.383
Levin, V., Park, J., Lucente, F.P., Margheriti, L., Pondrelli, S., 2007. End of subduction in northern Apennines confirmed by observations of quasi-Love waves from the great 2004 Sumatra-Andaman earthquake. Geophys. Res. Lett. 34, 1–5. doi:10.1029/2006GL028860
Margheriti, L., Lucente, F.P., Park, J., Pondrelli, S., Levin, V., Steckler, M.S., Baccheschi, P., Salimbeni, S., 2014. Large-scale coherent anisotropy of upper mantle beneath the Italian peninsula comparing quasi-Love waves and SKS splitting. J. Geodyn. 82, 26–38. doi:10.1016/j.jog.2014.07.007
Oda, H., Onishi, S., 2001. The effect of regional variation of lattice preferred orientation on surface waveforms. Geophys. J. Int. 144, 247–258. doi:10.1046/j.0956-540X.2000.01329.x

I agree that assumptions made about the hypothesis of back-projection and errors on the scatterer location are important factors to consider. Please see two new sections of text added to the Discussion and Methods sections titled "*Errors and uncertainties on the interpretation of Quasi-Love waves*", in response to comments from the reviewers. This new text provides an overview of such considerations for the reader.

Fundamentally, however, I maintain that the basic principle of converting the QL time delay to distance and back-projecting is appropriate and has been demonstrated to be valid on numerous occasions by the aforementioned studies. If this formula were an "oversimplification" and "not accurate" then we would not expect to see the spatial correlations that we do, in particular in repeatedly mapping these scatterers to plate boundaries (Chen and Park, 2013; Kobayashi, 2002; Kobayashi et al., 1997; Levin et al., 2007; Rieger and Park, 2010; Yu et al., 1995), locations that make physical sense, places where we expect to find strong lateral gradients in upper mantle anisotropy. Even for this study alone, the statistical significance demonstrated in Figure 4, suggests that the formula used is sufficiently accurate to produce consistent results.

To my knowledge, there are two different theoretical approaches for generating QL waves, the propagation of plane waves in multi-layered medium (since Crampin, 1975 and then Maupin, 1989, Tanimoto, 2004) and the normal mode approach (see papers by Park and Yu, 1992, Yu and Park, 1993 and many other papers from the same group) with first-order perturbation theory.

I thank the reviewer for bringing such papers to my attention. From my reading around the literature on this topic, it appears that unfortunately the term '*quasi-love wave'* is being used in multiple contexts to refer to different physical phenomena. I think the issue is best summarised by Maupin & Park (2015) (copied below) on page 285 of their chapter on seismic anisotropy from 'Treatise on Geophysics' (https://doi.org/10.1016/B978-0-444-53802-4.00007-5):

"*Surface waves with polarization anomalies related to anisotropy have been called **'quasi-Love'** waves or 'quasi-Rayleigh' waves in the literature, **but the terms have been used slightly differently in the contexts of polarization–distortion or of scattering**. **In the context of polarization–distortion**, the usage is similar to that of quasi-P and quasi-S body waves: A 'quasi- Rayleigh' wave is mainly P-to-SV-polarized with some transverse motion (Crampin, 1970), and **a 'quasi-Love' wave is mainly transverse-polarized with some P-to-SV motion**. **For surface- wave scattering, the term 'quasi-Love' applies to the anomalous P-to-SV-polarized wave that scatters from the main Love wave**. Conversely, the 'quasi-Rayleigh' term applies to the anomalous transverse-polarized wave that scatters from the main Rayleigh wave**. The quasi-Love wave is a Rayleigh-polarized wave whose energy propagates with Love-wave phase velocity before scattering and with Rayleigh-wave velocity***

after scattering, observed as a distinct wave that requires a name*. If scattering occurs close to the station, the quasi-Love wave arrives as an apparent precursor to the Love wave, hence its name. Similarly, the 'quasi-Rayleigh' wave is a Love-polarized wave that trails the Rayleigh wave closely if scattering occurs close to the station*."

I have clarified this in the main text on lines 66-71, including the suggested references from the reviewer:

"An anisotropic medium may also cause a small rotation of surface wave polarization [14–16]. These polarization-distortions are sometimes referred to in the literature as 'quasi-Love waves' also [17], however their characteristics are distinguishable from QL wave scattering as described here (see Methods for further details)."

This is further expanded on lines 450-464 in the Methods:

"In this study the term 'Quasi-Love waves' refers to surface wave polarization anomalies that are characteristic of Love-to-Rayleigh scattering. This is distinct from distortions or rotations of the polarization of surface waves by azimuthal anisotropy that are sometimes also called 'quasi-Love' waves or 'quasi-Rayleigh' waves elsewhere in the literature (Crampin, 1975; Maupin, 1989; Tanimoto, 2004). Such polarization distortions are analogous to the terminology of 'quasi-P' and 'quasi-S' when the polarization of body-waves are altered by Earth 3D heterogeneity (Maupin and Park, 2015). In such polarization-distortion cases, the 'quasi-Love' wave will exhibit particle motion that is still mostly transverse but with a small added vertical component (see Figure 2 of (Tanimoto, 2004)). In contrast, Love-to-Rayleigh scattering generates Quasi-Love waves that are predominantly polarized in the vertical-radial plane, displaying ellipticity characteristic of Rayleigh waves with a 90° phase lag between the vertical and radial components (Maupin and Park, 2015). By comparing the waveform shape of the QL wave on both the vertical component and the first-derivative of the radial component during the measurement process (e.g. Fig. S1d) ensures the presence of characteristic Rayleigh wave motion as expected for QL wave scattering. Incorrect interpretations due to slight polarization-distortions are thus considered unlikely in the present dataset."

Additionally, it seems unlikely to me that the polarisation-distortion anomalies generated by propagation through an anisotropic medium would be able to generate the range of QL delay times observed here (Fig. S8). The waveforms shown in Figure 1 have been replaced with an alternative example displaying a larger delay time to emphasise this point. The QL waves measured here can be substantially offset from G1 (i.e. cannot be explained by a slight rotation of the Love energy onto the vertical component).

When toroidal and spheroidal modes are strongly coupled, in particular through strong anisotropy gradient, energy is transferred from toroidal modes to spheroidal modes and QL propagates at the Rayleigh wave velocity. In the benchmark experiment of Chen and Park (Tectonophysics, 2013), the azimuthal anisotropy is only located in an equatorial band of ~900km width, but the rest of the medium all around is isotropic. In this particular case, the scatterer is correctly located.

This benchmark experiment is mentioned in the text as an idealised example as follows:

"numerical experiments based on simple anisotropic models with an equatorial band of 4% azimuthal anisotropy, in which the source of the QL scatterer could be correctly located to within 100 km following a similar methodology to that applied here (Chen and Park, 2013)"

I also note that similar synthetic experiments have reproduced similar results in other studies e.g. Oda & Onishi, (2001); Yu & Park (1992).

In the approach investigating Love wave propagation in a plane multi-layered medium (see old papers by Crampin, 1975, Maupin, 1989 and more recently of Tanimoto, GJI, 2004), when a Love wave enters an anisotropic medium, it was shown that the polarizations of both Love (T) and Rayleigh waves (R, Z) rotate, giving rise to quasi-Love waves on T, Z and R components and quasi-Rayleigh waves (on R, Z, T components) and the velocity of quasi-surface waves QL and QR is quite complicated (see for example Tanimoto, 2004). But, in a homogeneous anisotropic medium, the velocity of quasi-Love waves on T and R, Z is the same on the three components. The calculation of Tanimoto (2004) is only valid for the fundamental modes, but since the author claims that she gets rid of overtones, it should be a good approximation. However, when the quasi-Love comes out the anisotropic region (in particular the strong anisotropy gradient) and entering another region (isotropic or anisotropic), with lateral variations of properties, quasi-Love waves propagate at the Rayleigh wave phase velocity. So the delay time between G1 and QL might be due to lateral variations of azimuthal anisotropy, not only to the anisotropy gradient.

I believe this comment is mixing up the terminology surrounding 'quasi-Love' waves. See response to previous comment that addresses this. The process being described by the reviewer above is when a Love wave travels through an anisotropic medium resulting in a slight rotation to its polarisation (e.g. figure 2 of Tanimoto, 2004). Anisotropy also causes azimuthal dependence of the Love wave phase velocity (e.g. figure 3 of Tanimoto, 2004).

As the reviewer described, when the Love wave (with possible polarisation distortions) leaves the anisotropic medium, i.e. entering an anisotropic gradient, some of the Love wave energy is scattered and converted to Rayleigh wave. This is what I have been referring to as 'Quasi-Love' wave. By measuring the time delay between the QL wave with Rayleigh wave motion, and the Love-wave (G1) that may or may not have slight polarisation distortions (see Figure S8), this gives an indication of the distance between the receiver and the scattering location.

If the Love wave phase velocity is substantially different for the region defined by δx versus the average for Δ (refer to Figure 1), due to differences in velocity from either isotropic or anisotropic causes then this could result in an error in the scatterer location. This is addressed on lines 521-532:

"A location error may also result regarding the assumption that the average Rayleigh and Love phase velocities between the QL scatterer and the seismic station are the same as the average phase velocities along the entire great-circle path. Considering that many of the propagation paths cross an ocean basin before generating a QL wave and then continue through mainly continental regions after scattering at the ocean-continent boundary, this may cause the phase velocities along the respective path segments to substantially differ, either due to changes in isotropic or anisotropic properties or both. If the average phase velocities were 5% higher between the QL scatter and the receiver (i.e. δx), than between the earthquake source and the receiver (i.e. Δ), then this would directly correspond to a 5% error in the scatterer location as a function of distance along the great circle path. For example, if a typical QL scatterer is estimated to be 20° away from the receiver, then a 5% velocity error would equate to a distance error of 1° (~110 km)."

In the real Earth, Love waves propagate from the source to the receiver station in several anisotropic regions with different orientations and amplitude, adding complexity to the incoming Love wave train. As mentioned by Kobayashi (GJI, 1998), lateral variations in azimuthal anisotropy are necessary to generate QL-waves and the location of the scatterer is quite difficult to determine.

I completely agree that lateral variations in azimuthal anisotropy, i.e. gradients, are necessary generate QL wave scattering. This is stated several times throughout the manuscript, e.g. on lines 9, 59, 200, 468... Kobayashi (GJI, 1998) show from their synthetic experiments that realistic velocity contrasts are not enough to generate the observed QL waves and thus regard a lateral variation in azimuthal anisotropy as the most probable cause.

I do not find any statement within Kobayashi (GJI, 1998) that the location of the scatterer is difficult to determine. The only mention of 'location' that I could find is the following statement: "*Kobayashi et al. (1997) and Kobayashi & Nakanishi (1998)* ***located*** *the Love-to-Rayleigh conversion areas by using the group velocities of the observed Love, Rayleigh and quasi-Love waves at frequencies of 8–18mHz. The* ***locations concentrate in and around the Kuril trench*** *rather than the Aleutian trench, indicating that the observed quasi-Love waves should be generated around the Kuril trench*."

Plate 2 and Figure 1 below from Kobayashi & Nakanishi (1998) demonstrate that relative to the entire great-circle path (figure on right) that the QL wave scatterers mostly concentrate around the Kuril Trench. I would argue that this lends added support for the basic principle of converting delay time to distance and back-projecting.

Even Kobayashi & Nakanishi (GRL, 1998) found that the conversion point is frequency dependent and sometimes QL waves arrive faster than Love waves.

I agree with the statement that the conversion point is likely frequency dependent, considering the depth sensitivity of surface waves as a function of frequency, and that azimuthal anisotropy likely varies as a function of depth in the upper mantle. Here I am using the same frequency filter for all events so the conversions should relate to structure within the same associated depth range with the same parameters applied to all seismograms. It will be interesting in the future to potentially look at the frequency sensitivity of the QL wave observations in order to place potential further constraints on the depth. However, this may increase the potential for complications from overtones, which is also a concern of the reviewer.

Kobayashi & Nakanishi (GRL, 1998) suggest that the handful of QL waves arriving before the Love wave in their study is an inconsistency that could be explained by path bending on conversion from Love to Quasi-Love. I do not allow QL waves that arrive before G1 in my dataset, as the interpretation of the distance to the scatterer would clearly be wrong in such a case. A waveform displaying the defining characteristic motion of a QL wave, but arriving before G1, would be discarded from my dataset. From memory such an instance is extremely rare, I perhaps only saw this once or twice upon visual inspection out of more than 2300 seismograms, and when the delay time was very small. Again, these are not included in the final dataset.

So, the hypothesis that the conversion for Love waves is a point is very questionable. It means that the uncertainties associated with the scatterer location can be very large. There is no attempt in the present paper to estimate such uncertainties.

I thank the reviewer for sharing their concerns, which have helped improve the manuscript. Based on comments from other reviewers and the editor, a comprehensive discussion of the uncertainties associated with the scatterer location is now addressed in the two new sections under the title "*Errors and uncertainties on the interpretation of Quasi-Love waves*". See lines 195-238 and 449 onwards in the revised manuscript, and other responses to relevant comments throughout this document.

Overall the "potential location errors are estimated to be on the order of 100 km". (line 233)

All paths given on figure 2 cross oceanic areas (Pacific or Indian oceans) which are well known to be strongly anisotropic. It means along their paths, Love waves cross regions with different anisotropic parameters, and have time to generate quasi-Love waves and to accumulate delay time between G1 and QL. It makes the interpretation of the delay time dt between G1 and QL problematic. What happens to QL generated before it crosses anisotropy gradients?

As the reviewer describes, certainly it is likely that multiple gradients and anisotropic regions exist along the great circle path, with the potential to generate multiple QL waves on any given waveform. In the presence of multiple prominent QL waves, the methodology applied here is limited to only recording that which is closest to the seismic station. This does not preclude the existence other anisotropic gradients along the path. This is discussed in the text in the following locations:

Lines 404-406: "It is possible however that multiple QL waveforms may appear in one seismogram if multiple scatterers are located along the great circle path. In such cases, for simplicity, the first QL wave, closest to G1, and therefore closest to Australia is recorded."

Line 539 onwards: "the methodology applied in this study is based upon detecting a single scatterer located closer to the receiver than to the source. This ensures enough separation from the Rayleigh wave on the radial and vertical components in order to be able to identify the QL wave. If a QL scatterer is located near the source then the QL arrival will overlap with the Rayleigh wave making it hard to distinguish. Likewise, in the cases where more than one potential QL wave is identifiable on the seismogram, potentially due to multiple lateral gradients in seismic anisotropy along the propagation path, only that which is closest to the receiver is included in the dataset as it is the easiest to distinguish. If the seismogram contains multiple closely arriving QL waves generating a complicated overlapping signal, then this will be discarded during the quality control process as the QL wave is required to have a similar waveform shape as G1 (Figure S1). "

When a quasi-Love wave is generated, there is as well a quasi-Rayleigh wave, which should be visible on figure S1. Why is QR waves not visible? Since the traces are normalized, may be, the selected Rayleigh waves have a smaller amplitude than the amplitude of Love waves. For Rayleigh waves in the radiation node, the observation of quasi-Rayleigh waves is very difficult since they have a very small amplitude. This point should be clarified. Does the author only look for Rayleigh wave data in their radiation node?

A relevant discussion on Quasi-Rayleigh waves has been added to lines 472-479:

"It is worth noting that lateral anisotropic gradients will also cause Rayleigh-to-Love scattering, generating Quasi-Rayleigh waves, in addition to Quasi-Love waves (Maupin and Park, 2015; Pettersen and Maupin, 2002). Such Quasi-Rayleigh waves appear on the transverse component trailing G1 and thus are more challenging and less commonly studied compared to QL waves that arrive ahead of R1 on the vertical and radial components (Pettersen and Maupin, 2002). As relatively large amplitude of G1 is a pre-requirement of this study (SNR>5), the amplitude of R1 is often comparatively less, and thus Quasi-Rayleigh waves are not expected to be visible on the same seismograms as prominent QL waves (Figure S1)."

I have not made any restriction to be in the radiation node of Rayleigh waves, or the radiation maximum of Love waves, but I do require G1 to have a relatively large amplitude (SNR>5) as mentioned above, which ultimately likely has the same desired effect.

Higher modes/overtones issue: It is mentioned that data are low-passed filtered at 100s to suppress overtones. I am not convinced that data are really devoided of overtones. The overtones, even for shallow earthquakes, can have a significant amplitude. In the plane layered medium approach, the coupling between the fundamental modes of Love and Rayleigh (G1 and R1) is usually small and it is necessary to consider the coupling between Love waves G1 and Rayleigh higher modes to generate QL.

While there are some potential similarities between higher mode Rayleigh waves and QL waves it is considered unlikely that this would widely contribute to false or inaccurate QL wave detections, given the specific processing steps that have been followed to suppress this. The following text has been added to line 549 onwards to directly address this concern:

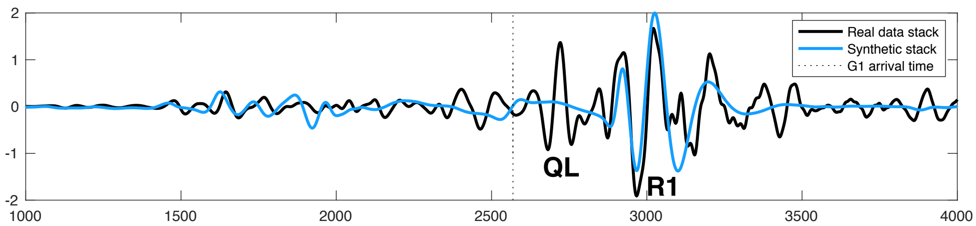
"it is possible for QL waves to resemble higher-mode Rayleigh waves [47,48]. In this study only shallow events less than 50 km depth are considered are these should primarily excite the fundamental modes rather than overtones, and all seismograms are low pass filtered at 100s which should aid separation of the modes [49]. During the quality control process, the requirement that the QL wave should have a similar waveform shape to G1 (see Fig. S1), should also help distinguish potential interference from higher mode Rayleigh waves, as these would not be expected to possess the same waveform shape as G1. Following these conditions, synthetic seismograms demonstrate that the observed QL waves are unlikely to be the result of higher mode Rayleigh waves (Fig. S6)[18,26,47]. "

I also note the following from Park & Yu (Science, 1993) which states that Quasi-Love waves (due to scattering) are primarily generated due to coupling between the fundamental modes: "Numerical experiments indicate that long- period quasi-Love waves are generated chiefly by interaction between the fundamental dispersion branches. "

By the way, the depth of events is never mentioned in figures S1, S3, S4, not mentioned in the table provided in the supplementary information. It should be very easy to check whether Rayleigh overtones have a small amplitude by computing synthetic seismograms with widely available normal mode codes. If overtones are not negligible, there is a strong coupling between fundamental Love mode and Rayleigh higher modes, since they have similar group velocities. And this might significantly bias the measurement of dt.

As originally stated at the start of Methods, only events with source depths <100km were initially included in the study. The vast majority however were less than 50km depth, so this new shallower depth restriction has now been applied (see line 82), as these events are expected to most strongly excite the fundamental Rayleigh mode, and less so for higher modes. A full list of event depths has now been included in the supplementary information (Table S1) as requested.

Synthetic seismograms have now been calculated and plotted in Figure S6 for comparison with the analysis of real data shown in Figure S4. An example from station CNB is copied below for illustration purposes. As expected, the fundamental R1 arrival is similar between the synthetics and the real data. However, in all cases the Quasi-Love wave is not present on the synthetic seismograms, as the reference model does not contain lateral gradients in seismic anisotropy.



There is no discussion of the error bars of the location of scatterers (strong anisotropic gradients). I do not want to say that the whole interpretation is wrong, but that the location of scatterers is not necessarily accurate. And the estimate of the uncertainties on the location of scatterers should be welcome.

This has been substantially addressed in the revision. Please see response to previous comments, including Reviewer 1 and the summary at the start of this document. A comprehensive overview of the uncertainties and size of the errors associated with the scatterer location is now presented in the two newly added sections (see Discussion & Methods) under the title "*Errors and uncertainties on the interpretation of Quasi-Love waves*". Please also see Figures 4 and S9.

When looking at the distribution of scattering points (figure 3), it looks like a random distribution, and I confess that a lot of imagination is necessary to see the correlation with the complex geology of Australia. When looking at the maps displayed in Figures 3c,d the probability for finding a scatterer close to a geological structure (within 1°) is probably not negligible. Some scatterers do not seem to be correlated with geological features.

Please see response to Reviewer 1 who provided helpful suggestions for statistical analyses of spatial correlation, which have now been applied. Results show that the distributions of QL scatterers are preferentially located closer to the continental margins and major geological provinces than would be expected (new Figure 4). The null hypothesis, that the distribution cannot be distinguished from random, can be rejected at 4% and 0.06% significance level for the margins and geological boundaries respectively.

Figure 4c displays the long wavelength distribution of azimuthal anisotropy but is it useful? I did not read any attempt to try to find correlations or relationships between the distribution and amplitude of scatterers and azimuthal anisotropy.

Figure 4c has been moved to Figure 3d and updated to show the azimuthal anisotropy as a function of colour, as requested by Reviewer 3. This figure serves two key purposes that warrant its inclusion:

(1) It illustrates that tomographic models produce smoothly varying structure that do resolve sharp gradients or changes in anisotropy, like those sensed by QL wave scattering. Hence why the observations shown here are new and have not been seen before. A statement to this effect has been added to the first line of the Conclusion as follows:

“Observations of QL waves have revealed extensive lateral anisotropic gradients beneath the Australian continent and its margins that have otherwise, until now, been impossible to resolve with smooth seismic tomographic methods (e.g. Fig. 3d)”

(2) It illustrates that to first order azimuthal anisotropy in the asthenosphere beneath the Australian plate is strong and largely aligned with absolute plate motion, whereas the lithospheric azimuthal anisotropy within the continent is aligned differently. Both are relevant to the interpretation and conclusions of this study (e.g. new Figure 5, and lines 256-258).

“QL scatterers along this boundary may therefore simply reflect the transition from active flow in the asthenosphere to anisotropy fossilized within the lithosphere (Fig. 5), which is supported by the first-order patterns seen in tomographic models of azimuthal anisotropy (Figs. 3d and S11).”

In conclusion, even though it is an interesting paper, with original data, the methodology based on the interpretation of QL waves is not really innovative and even not robust, so the location of scatterers is unsettled. The originality stems from the investigation of the Australian continent. The same approach of using QL was also followed in other groups in other parts of the Earth, since the use of QL waves is a new way to make “geology”. So, the work is not really original except that the approach is applied to the first extensive study of the Australian continent. But I am not convinced by the reliability of the results. Some modeling of results should be important to support the observations. I do not recommend the publication of this paper as it is.

I appreciate the reviewer sharing their insights throughout this review, which has offered the opportunity to strengthen the arguments within the manuscript. I fully agree that the primary significance of this study is the new and extensive observations, and that the methodology and strategy for interpretation that I have followed is consistent with current standard practise that has been published on countless occasions over the last two decades by several other groups. I would strongly argue that this is a reason to support the publication of this work rather than to not recommend it.

The reviewer's primary criticism appears to be with the basic principle of converting time delay to distance and back-projecting, suggesting that the location of scatterers is not '*robust*' or '*reliable*' when this procedure applies to all previously published QL scattering studies. If my '*methodology based on the interpretation of QL waves is not really innovative*' then they would have to agree that it is at least of a standard consistent with an extensive body of previously published work.

I would argue that this revised manuscript has now gone above and beyond the expectations of most other QL wave studies. Not only is it the most geographically diverse QL wave dataset to date, it is the only such study that I am aware of that has performed and demonstrated a test of statistical significance of the spatial distribution of QL scatterers with associated features. In addition, the lengthy description of the errors and uncertainties associated with QL wave interpretation is not readily available in most other QL studies, including the consideration of polarisation-distortions due to azimuthal anisotropy as the reviewer has requested.

I recognise that the results of this work will be controversial to some, as I have taken a slightly different approach in terms of casting the net far and wide to see where QL waves can be detected. This is in contrast to most previous QL studies which carefully select a small number of events in order to target a particular location or feature of the Earth where lateral anisotropic gradients are anticipated, such as subduction zones. This more widespread approach has however revealed new, unexpected, and important observations about the Earth that would be difficult to otherwise detect with traditional imaging methods such as seismic tomography, or receiver functions.

The significance of the observations is far greater than just for the Australian region, it is the first time that Quasi-Love wave scattering has been inferred within a stable continental interior with implications for the strength of the continental lithosphere both with depth and time, consistent with recently published high-profile work of the Australian lithosphere (e.g. Hoggard et al., Nature Geoscience, 2020; https://doi.org/10.1038/s41561-020-0593-2). It is also the first time that lateral gradients in anisotropy have been detected along passive margins on a continental-wide scale, rather than the more regional focus of Servalli et al., (Tectonophysics, 2020). This has fundamental implications for the underlying dynamics of these regions globally, regions which are often difficult to seismically image considering the offshore nature of the continental shelf and limitations in the distribution of seismic receivers (e.g. Lynner & Bodmer, Geology, 2017; https://doi.org/10.1130/G38980.1).

Lastly, the most recent QL wave scattering study to date, published just months ago in a short-format high-impact Geophysics journal (Cheng et al., GRL, 2021; https://doi.org/10.1029/2020GL091232) follows a similar methodology for back-projecting the scatterer (see equation 1 within) and presents just 22 QL wave observations (figure 3). They interpret their results as a vertically coherent tectonic boundary between west and east Antarctica. I conclude that the work presented here in this manuscript has an order of magnitude more observations (276 in the study area), as well as, more significant implications for the dynamics of the Earth, in-particular the mantle dynamics beneath and surrounding long-lived stable continents.

Technical points:

Figure 4b,c: why does the author plot the model of Schaeffer & Lebedev for velocities and the model of Debayle et al. for azimuthal anisotropy? and why not the regional models of Debayle et al. (2005) or Simmons et al. (2002) who obtained consistent models of S-wave velocities and azimuthal anisotropy.

This figure has now been removed and replaced by Figure 3d. In this new figure I've plotted the LAB from AusREM, the Australian Seismological Reference Model (Kennett & Salmon, 2013) instead of showing the background shear velocity. This is the most complete model of the LAB for the Australian region that is based on a compilation of a variety of datasets (see here: http://rses.anu.edu.au/seismology/AuSREM/Data-Sources/), and is thus more reliable than a single study.

For the azimuthal anisotropy in Figure 3d, I still show the model of Debayle et al., (2016) as it is automatically updated, and therefore the most current and up-to-date model of azimuthal anisotropy available for the region. The two models suggested by the reviewer, Debayle et al., (2005) and Simmons et al., (2002), are both 15-20 years old now, so I prefer to use something which is more recent.

Figures S4 and S5: these figures display scatterers for a specific event. I do not understand why very close stations provide completely different locations of scatterers, for example, the two stations in south-west Australia or other close stations in south-east Australia. Some stations are almost aligned along the ray path and should provide the same location for scatterers.

I would argue that most do show the same scatterer location, demonstrating their overall consistency. In Figure S5, 10 out of 13 stations in SE Australia map back to the same scatterer location along the northwest continental margin. For the handful that don't, I have added the outline of the geological provinces within Australia to figure S5 along with the explanation below in the caption:

"A couple of stations in southeast Australia detect QL scatterers associated with the edges of the Pilbara (P) and Kimberley (K) cratonic blocks in northwest Australia. Note that not all great-circle paths traverse the same geological structure within Australia (geological provinces outlined in grey). Where the geometry is favourable for Love-to-Rayleigh scattering in multiple locations along the path, the methodology employed here will only record the location of QL scattering that is closest to the seismic station. This may cause some variability in the detected scatterer locations."

For the two stations in south-west Australia, the map clearly shows that the great-circle paths interact with the continental margin in different locations and with different geometries. The generation of Quasi-Love waves is therefore not expected to be identical for these two stations.

Not quoted references:

Crampin, GJRAS, 40, 177-186, 1975.
Kobayashi & Nakanishi, Geophys. Res. Lett., 25, 1067-1070, 1998.
Maupin, G.J.I., 98, 553-563, 1989.
Simons et al., G.J.I., 151, 738-754, 2002.
Tanimoto, G.J.I., 156, 73-78, 2004.

Thank-you for helpfully providing references. Most of these have been included in the revision.

Reviewer #3

Comments to Editor

The manuscript investigates the geographical correlation between the scattering of surface waves and geological margins in the lithosphere around Australia. The location of scatterers displays similarities with these margins. Based on this evidence, the author concludes and hypothesizes new insights. To find the scatterer locations Quasi-Love waves have been used that representing the location of lateral gradients or sudden changes in seismic anisotropy.

I recommend the manuscript to be published in Communications Earth & Environment after **a minor revision**. The manuscript is scientifically well written. Arguments and conclusions are clear and convincing and based on conclusive evidence. Methodology is clearly explained.

Thank-you to the reviewer for their positive comments.

Comments to Authors

Main Comments

- Line 148, you use a back-projected distance to find the location of scatterers assuming the great- circle path. How much lateral velocity variations can change the path from the great circle? This can affect the location of scatterers and therefore probably your conclusions. How to answer this concern. Explain it.

A discussion on the effect of velocity variations along the great-circle path on the location of scatterers has been added on lines 521-532 as follows:

"A location error may also result regarding the assumption that the average Rayleigh and Love phase velocities between the QL scatterer and the seismic station are the same as the average phase velocities along the entire great-circle path. Considering that many of the propagation paths cross an ocean basin before generating a QL wave and then continue through mainly continental regions after scattering at the ocean-continent boundary, this may cause the phase velocities along the respective path segments to substantially differ, either due to changes in isotropic or anisotropic properties or both. If the average phase velocities are 5% higher between the QL scatter and the receiver, than between the earthquake source and the receiver, then this would directly correspond to a 5% error in the scatterer location as a function of distance along the great circle path. For example, if a typical QL scatterer is estimated to be 20° away from the receiver, then a 5% velocity error would equate to a distance error of 1° (~110 km)."

- Fig 4b, we know that in the mentioned period, surface waves are mostly sensitive to the depth range of 100-200 km. However, they are affected by other depths. Although Fig 4b is informative, but depicting scatterers only between 100-200 km could be misleading. I mean scatterers could originate from other depths, and showing them only between 100-200 km may not be appropriate.

Figure 4 has since been replaced but in the new figure 5 I have refrained from directly plotting the scatterers at 100-200 km depth. I have however kept the dashed lines to illustrate the zone of peak sensitivity.

The range of depth sensitivity is clarified in the revision on lines 227-231.

"Depth sensitivity kernels calculated for a QL wave with a dominant frequency of 0.01 Hz (100 s) suggest a broad range of sensitivity throughout the upper mantle, with a peak around 100-200 km depth (refer to Fig. S1 of Levin et al. (2007), Fig. 9 of Chen and Park (2013)). While potential contributions from shallower or deeper depths cannot be entirely ruled out, the source of the QL waves most likely resides within the upper mantle, and not within the crust."

- Fig 4c, it is an interesting figure showing the azimuthal anisotropy and velocity. Is it possible to make a figure with scatterer location and background color of directional variations of the azimuthal anisotropy? This means that sudden changes of the azimuthal anisotropy could correlate with the location of scatterers. Refer to my previous comment, it is possible to check this correlation at other depths and may find some clues about the depth of scatterers.

Nice suggestion. Figure 4c has now moved to Figure 3d. In this figure I have coloured the arrows according to their fast-direction as requested. This does improve the clarity of the pattern of azimuthal anisotropy, however, tomographic models tend to smooth over sharp gradients and thus sudden changes in azimuthal anisotropy are not readily visible in such models (see related response to Reviewer 2). It is therefore difficult to do a direct comparison with the QL wave dataset. At the request of the reviewer I have however included similar slices of azimuthal anisotropy at various depths in the upper mantle for visual comparison in newly added Figure S11. Within the caption I have added a description of the patterns at the various depths relevant to the conclusions drawn.

Minor Comments

- Line 59, replace blue circles with cyan circles

This has been replaced.

- Line 68, to be consistent with Line 60, say how much percentile is 80 scatterers.

This section of text has since been rewritten following the new statistical analysis.

- Line 74-76, use the same abbreviations as Fig 3 caption in the text.

The abbreviations for the geological provinces used in Fig. 3 have now been added to the locations named in the text.

- Fig 3b, what is the meaning of dark and light gray colors in Australia and Zealandia? This was to signify oceanic versus continental crust. This sub-figure has since been removed in the changes to the revised manuscript.

30th Jul 21

Dear Dr Eakin,

Your manuscript titled "The Deep Roots of Geology: Tectonic History of Australia and its Margins expressed as Mantle Anisotropy" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. In particular, please ensure that you acknowledge in the manuscript that, despite your quantification of the uncertainties, they remain relatively high and that therefore geological implications are still somewhat speculative. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table". Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joao Duarte, PhD
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Joe Aslin
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Review of "The Deep Roots of Geology: Tectonic History of Australia and its Margins expressed by Mantle Anisotropy" submitted to Communications Earth & Environment by C. Eakin

I enjoyed reading the revised version of this manuscript. In particular, I welcome the addition of statistical analyses to evaluate the robustness of the vicinity of scatterers to tectonic boundaries. With respect to the Kolmogorov–Smirnov test, it would be helpful to explain what the null hypothesis is before it is first mentioned (l. 83; more context is provided l. 98-99 when the null hypothesis is mentioned for the second time). Rather than the p-value, I think it would be helpful to report the K-S probability that the null hypothesis can be rejected at a significance level of 0.05 (the level should be the same across the reported tests, which is currently not the case). See for example Davies et al. (2015, EPSL). From the empirical distribution functions (rather than cumulative distribution functions) in Figure 4 and Figure S10, the spatial relationship is strongest within the continent (Fig. 4b) and for the scatterers that fall within the ocean (Fig. S10a). While the relationship to plate boundaries can be shown to be statistically significant, this significance is not very strong (see for example Hoggard et al., 2020; Davies et al., 2015 for examples of clearly distinct CDFs), which might be worth mentioning. Nevertheless, I think that including this statistical analysis strengthened the argument developed in the manuscript.

Typographic errors and minor suggestions:

l. 17: "driven"

l. 128: "potentially"

l. 217: "more difficult" rather than "harder"?

l. 326 "occurs" rather than "will occur"

Reference for an example on reporting results of a Kolmogorov–Smirnov test (K-S probability at a significance level of 0.05): Davies, D.R., Goes, S. and Sambridge, M., 2015. On the relationship between volcanic hotspot locations, the reconstructed eruption sites of large igneous provinces and deep mantle seismic structure. Earth and Planetary Science Letters, 411, pp.121-130.

Nicolas Flament, Wollongong, 9 July 2021

Reviewer #2 (Remarks to the Author):

Review of the paper "The Deep Roots of Geology: Tectonic History of Australia and its margin expressed by Mantle Anisotropy" by C. Eakin (revised version).

As I said in my previous review, the basic idea to use quasi-Love (QL) anisotropic data to make structural geology is excellent and the dataset of QL data in Australia is impressive. But I am not yet convinced by their interpretation due to the uncertainties on the location of scatterers. The author did much efforts to reply to the three reviewers and the paper has been really improved.
Other reviewers (in particular #1) also addressed the issue of uncertainties and of the randomness of the scatterer distribution.
The section on the uncertainties is fine, eventhough it does not account for the potential bias explained below.
As for the section on the randomness of scatterers, I acknowledge the effort to have a statistical approach of this issue, but I would like to know why so small statistical significances of 4% for the continental margins and 0.06 % for the geological provinces demonstrate that the distribution of scatterers is significant and not random. May be, I do not know some theorem demonstrating that a significance of 4% is great!

Let me try to explain again why the interpretation of qL is approximate and might not be correct in certain circumstances. The argument saying that the same interpretation was previously done in many previous investigations is not good since people can reproduce the same mistakes or approximations and it does not mean that they are right. I will try to consider a physical point of view for the propagation of Love waves in anisotropic medium.
Let us consider a Love wave propagating in a medium with 2 regions, one anisotropic and the 2nd one isotropic separated by a discontinuity. A discontinuity is the extreme case of a strong gradient and also gives rise to scattering. For the case of a strong gradient, it depends on its spatial scale. If it

is wide enough, it can be considered as a succession of discontinuities. In the first anisotropic region, Love wave propagates as a quasi Love wave with the largest signal L1 on the transverse component T and a small signal qL1 on the radial R and vertical Z components with a given phase (or group) velocity VL1 (according to the solution of Tanimoto, 2004). When arriving into the 2nd region, the qL1 (on Z and R forgetting its past) will propagate with the Rayleigh velocity VR, giving rise to a δt between T component and Z, dR/dt . In that case, it is possible to apply the formula (3) and the scatterer will be correctly located. If we consider now 2 anisotropic regions with different orientations. qL1 entering in the second region (with R, Z components) will propagate to first order as a Rayleigh wave (velocity VR) accumulating delay time with L2, but L1 arriving in anisotropic region 2 will propagate as a quasi-Love with a large train L2 on T and a smaller component qL2 on R and Z propagating at a velocity close to VL2. Since the dominant period of the signal is 100s, both trains qL2 (VL velocity) and qL1 (VR velocity) will interact making the measurement of δt quite uncertain and the location of the scatterer very approximate and biased (probably δx will be underestimated). In addition, figure 3 (and figure S11) shows that the Australian continent presents a significant anisotropy in many regions and that this case of 2 anisotropic regions occurs. This approach can be generalized to more complicated anisotropic regions. In case of a strong anisotropy gradient considered as a succession of discontinuities, the previous qL wave on R and Z will travel as Rayleigh waves, but a component of qL (with VL velocity) on R and Z will still exist. This simple physical approach is also in agreement with Park & Yu (1992) and following papers saying that quasi Love wave is sensitive to the amount of change of anisotropy (discontinuity or gradient). This effect is not considered in this paper as a potential important source of error, but I agree that it is not so easy to model.

In conclusion, even though it is an interesting paper with original data, which has been greatly improved in the revised version, the methodology based on the interpretation of QL waves is not robust, and the location of scatterers is very approximate. The originality stems from a complete investigation of scatterers in the Australian continent. But, I am not yet completely convinced by the reliability of the results and their relationship with geological provinces.

Response to Reviewers

Reviewer #1 (Remarks to the Author):

Review of "The Deep Roots of Geology: Tectonic History of Australia and its Margins expressed by Mantle Anisotropy" submitted to Communications Earth & Environment by C. Eakin

I enjoyed reading the revised version of this manuscript. In particular, I welcome the addition of statistical analyses to evaluate the robustness of the vicinity of scatterers to tectonic boundaries.
I thank the reviewer for their suggestion that helped improve the manuscript.

With respect to the Kolmogorov–Smirnov test, it would be helpful to explain what the null hypothesis is before it is first mentioned (l. 83; more context is provided l. 98-99 when the null hypothesis is mentioned for the second time).

Several new sentences have been added (starting at line 89) to better explain the concept of the Kolmogorov–Smirnov test and the null hypothesis before the test results are discussed:

"A two-sample Kolmogorov–Smirnov (K-S) test provides a measure of the difference between two cumulative distribution functions (CDF) [30–32], against which the null hypothesis, that two datasets are drawn from the same continuous distribution, can be tested. The null hypothesis is rejected when the K-S probability is smaller than a critical value based on the significance level, indicating that the two datasets are likely drawn from different distributions. As is standard, a significance level of 0.05 (5%) is applied here [32]."

Rather than the p-value, I think it would be helpful to report the K-S probability that the null hypothesis can be rejected at a significance level of 0.05 (the level should be the same across the reported tests, which is currently not the case). See for example Davies et al. (2015, EPSL).

The "p-value" has now been replaced with the K-S probability in all instances, and the same significance level of 0.05 applied across all the reported tests as suggested. A reference to Davies et al. (2015, EPSL) is included, i.e. citation number 32.

From the empirical distribution functions (rather than cumulative distribution functions) in Figure 4 and Figure S10, the spatial relationship is strongest within the continent (Fig. 4b) and for the scatterers that fall within the ocean (Fig. S10a). While the relationship to plate boundaries can be shown to be statistically significant, this significance is not very strong (see for example Hoggard et al., 2020; Davies et al., 2015 for examples of clearly distinct CDFs), which might be worth mentioning.

The null hypothesis can be rejected at the chosen 5% significance level for both the ocean-continent boundary and the geological provinces. As the reviewer points out it is clear from Figure 4, that the spatial relationship is stronger for the geological provinces than for the continental margins, and from Figure 10 that the spatial relationship for the continental margins is improved by only considering oceanic scatters. This is described on lines 102-109 copied below:

“A two-sample K-S test [30–32] for the two CDFs returns a K-S probability of 0.04 (4%), indicating that the null hypothesis can be rejected, and thus suggesting that the QL scatterers can be distinguished from a random distribution, ***although the significance is not especially strong***. However, sub-dividing the dataset into oceanic versus continental scatterers (Fig. S10) indicates that the spatial correlation is stronger within the oceans (K-S probability = 0.01), with 38% of the oceanic scatterers located within 100 km of the ocean-continent boundary, which is more than 2.5 standard deviations higher than the mean of the random distributions.”

The statistical significance of plate boundaries was not been tested in this study. I assume the reviewer meant to write the “ocean-continent boundaries” (e.g. Fig 4a) instead of “plate boundaries” given their precluding statement. I have acknowledged, as requested, in the above text (refer to phrasing in ***bold italics***), that although the relationship is statistically significant, it is not very strong.

Nevertheless, I think that including this statistical analysis strengthened the argument developed in the manuscript.
I fully agree.

Typographic errors and minor suggestions:

l. 17: "driven"

l. 128: "potentially"

l. 217: "more difficult" rather than "harder"?

l. 326 "occurs" rather than "will occur"

I thank the reviewer for their careful reading of the revised manuscript and for pointing out these small typos. They have all been fixed.

Reference for an example on reporting results of a Kolmogorov–Smirnov test (K-S probability at a significance level of 0.05): Davies, D.R., Goes, S. and Sambridge, M., 2015. On the relationship between volcanic hotspot locations, the reconstructed eruption sites of large igneous provinces and deep mantle seismic structure. Earth and Planetary Science Letters, 411, pp.121-130.

This work is included in the reference list and cited on several occasions as an example of the implementation of the two-sample Kolmogorov–Smirnov test.

Nicolas Flament, Wollongong, 9 July 2021

Reviewer #2 (Remarks to the Author):

Review of the paper "The Deep Roots of Geology: Tectonic History of Australia and its margin expressed by Mantle Anisotropy" by C. Eakin (revised version).

As I said in my previous review, the basic idea to use quasi-Love (QL) anisotropic data to make structural geology is excellent and the dataset of QL data in Australia is impressive. But I am not yet convinced by their interpretation due to the uncertainties on the location of scatterers. The author did much efforts to reply to the three reviewers and the paper has been really improved.
Other reviewers (in particular #1) also addressed the issue of uncertainties and of the randomness of the scatterer distribution. The section on the uncertainties is fine, even though it does not account for the potential bias explained below.
I thank the reviewer for their detailed review and comments that have helped improve the manuscript.

As for the section on the randomness of scatterers, I acknowledge the effort to have a statistical approach of this issue, but I would like to know why so small statistical significances of 4% for the continental margins and 0.06 % for the geological provinces demonstrate that the distribution of scatterers is significant and not random. May be, I do not know some theorem demonstrating that a significance of 4% is great!
As suggested by reviewer 1, and as implemented in the revised manuscript, the appropriate statistical test to determine non-randomness of the scatterers is the Kolmogorov–Smirnov test. Further details describing this test are now provided (starting on line 89) and copied below:

"A two-sample Kolmogorov–Smirnov (K-S) test provides a measure of the difference between two cumulative distribution functions (CDF) [30–32], against which the null hypothesis, that two datasets are drawn from the same continuous distribution, can be tested. The null hypothesis is rejected when the K-S probability is smaller than a critical value based on the significance level, indicating that the two datasets are likely drawn from different distributions. As is standard, a significance level of 0.05 (5%) is applied here [32]."

Previous similar studies (e.g. Davies et al., EPSL 2015) and standardised implementations of the K-S test (e.g. Matlab, https://au.mathworks.com/help/stats/kstest2.html) typically apply 5% as the significance level at which the null hypothesis is rejected. Both datasets, continental margins and geological provinces, return K-S probabilities smaller than 5%, indicating that the null hypothesis be rejected, i.e. that the distribution of scatterers is not likely to be random.

Let me try to explain again why the interpretation of qL is approximate and might not be correct in certain circumstances. The argument saying that the same interpretation was previously done in many previous investigations is not good since people can reproduce the same mistakes or approximations and it does not mean that they are right.
I agree with the sentiment expressed here, but in this case I have included all references suggested by the reviewer in the previously revised manuscript, described the associated underlying processes, and explained either how they differ to what is being done here or why the present dataset is not likely to be affected (e.g. lines 349-388). I would therefore counter-argue that it is unfair to single-out this

particular manuscript on the basis of an alternative opinion which has not been explicitly demonstrated in the existing literature.

I will try to consider a physical point of view for the propagation of Love waves in anisotropic medium.
Let us consider a Love wave propagating in a medium with 2 regions, one anisotropic and the 2nd one isotropic separated by a discontinuity. A discontinuity is the extreme case of a strong gradient and also gives rise to scattering. For the case of a strong gradient, it depends on its spatial scale. If it is wide enough, it can be considered as a succession of discontinuities. In the first anisotropic region, Love wave propagates as a quasi Love wave with the largest signal L1 on the transverse component T and a small signal qL1 on the radial R and vertical Z components with a given phase (or group) velocity VL1 (according to the solution of Tanimoto, 2004). When arriving into the 2nd region, the qL1 (on Z and R forgetting its past) will propagate with the Rayleigh velocity VR, giving rise to a δt between T component and Z, dR/dt . In that case, it is possible to apply the formula (3) and the scatterer will be correctly located.
If we consider now 2 anisotropic regions with different orientations. qL1 entering in the second region (with R, Z components) will propagate to first order as a Rayleigh wave (velocity VR) accumulating delay time with L2, but L1 arriving in anisotropic region 2 will propagate as a quasi-Love with a large train L2 on T and a smaller component qL2 on R and Z propagating at a velocity close to VL2. Since the dominant period of the signal is 100s, both trains qL2 (VL velocity) and qL1 (VR velocity) will interact making the measurement of δt quite uncertain and the location of the scatterer very approximate and biased (probably δx will be underestimated).
In addition, figure 3 (and figure S11) shows that the Australian continent presents a significant anisotropy in many regions and that this case of 2 anisotropic regions occurs. This approach can be generalized to more complicated anisotropic regions.
In case of a strong anisotropy gradient considered as a succession of discontinuities, the previous qL wave on R and Z
will travel as Rayleigh waves, but a component of qL (with VL velocity) on R and Z will still exist. This simple physical approach is also in agreement with Park & Yu (1992) and following papers saying that quasi Love wave is sensitive to the amount of change of anisotropy (discontinuity or gradient). This effect is not considered in this paper as a potential important source of error, but I agree that it is not so easy to model.

I thank the reviewer for this additional information which has clarified their point of what to expect when the station is located within an anisotropic region. As requested, I have added a new paragraph to the manuscript (starting on line 376 and copied below) acknowledging this process and its potential as a source of error:

"There may however be certain scenarios where the region surrounding the seismic station is anisotropic, that such polarization-distortions of the Love wave on the radial and vertical components may still interfere with QL waves generated from a nearby lateral anisotropic gradient. This could potentially induce error in the measurement of the QL delay time, and thus the location of the QL scatterer, when δt is less than the typical period of G1 (i.e. ~100 s). However, such interference should also modify the waveform shape of the QL wave, and would disrupt the expected pattern of Rayleigh wave ellipticity between the radial and vertical components. Under such circumstances, the waveforms are unlikely to pass visual inspection during the quality control process (e.g. Fig. S1), when a similar shape between G1 and the QL wave is required, as well as a similarity between the QL wave on the vertical component and first-derivative of the radial component. Such quality control steps should ensure that the effect of interference from polarization-distortions due to anisotropy near the station is minimized for the QL dataset presented here. ”

In conclusion, even though it is an interesting paper with original data, which has been greatly improved in the revised version, the methodology based on the interpretation of QL waves is not robust, and the location of scatterers is very approximate. The originality stems from a complete investigation of scatterers in the Australian continent. But, I am not yet completely convinced by the reliability of the results and their relationship with geological provinces.

All sources of error and uncertainty suggested by the reviewer have been fully acknowledged and quantified as much as possible in the text. The estimated magnitude of the location error (~100km, see lines 188 and line 458 onwards) is in keeping with the overall interpretations (e.g. Fig. 3), and is supported by statistical tests that demonstrate that the scatterers are preferentially located near certain geological boundaries to within such error margins (e.g. lines 107-108, 113-116).

Finally, the following statement acknowledging the magnitude of the errors has been added to lines 193-195, before the interpretation of the results:

“Nonetheless, the quantification of associated errors and uncertainties suggests they are moderately high, and should be kept in mind when interpreting the results and considering their geological implications.”