Solid Earth Discuss., 4, C652–C665, 2012
www.solid-earth-discuss.net/4/C652/2012/

Solid Earth
Discussions

Interactive comment on "The link between great earthquakes and the subduction of oceanic fracture zones" *by* R. D. Müller and T. C. W. Landgrebe

R. D. Müller and T. C. W. Landgrebe

dietmar.muller@sydney.edu.au

Received and published: 15 November 2012

1 General

We thank the reviewers for their valuable comments and suggestions that we believe will improve the quality of the final paper.

2 Review: C531

Reviewer comment: *This paper provides evidence for an association of great earthquakes and the locations where major fracture zones impinge on subduction zones. The greatest earthquakes are composite events covering at least 500 km of the coupling zone The initial phase of such events, which is most likely to be influenced by local structure, may well be no larger than Mw 8.0. What is not established in this analysis is a reason why the influence of a fracture zone should extend across a substantial swath of a subduction zone and thereby encourage the production of the largest events. What physical process is likely to set the 150 km threshold for the zone around the presence of a fracture zone? The circumstantial correlation is intriguing, but not fully compelling.*

2.0.1

Response: Thank you for these comments. We have assembled a number of arguments and geophysical evidence to provide a reasonable foundation for the establishment of the physical processes involved here. We refer in particular to the analyses associated with Figure 3b and Figure 4. The three case studies shown in Figure 4 indicate the time-space relationship between the location of the near trench fracture zones, and time-varying rupture models of three large events. These case studies are useful in formulating a conceptual model for a link between giant earthquakes and subduction zone-fracture zone intersections. Figure 4c is particularly interesting, where the epicentre is somewhat spatially distant from the main rupture zone. In fact, what this model suggests is that the initial event may have been a catalyst for releasing stress "locked" at the location of the fracture-zone/subduction-zone interface. So the reasoning is that an earthquake event, not necessarily at the location of the fracture-zone intersection, could be playing a role in causing a secondary event in its vicinity. Of course these examples are limited in the insight that can be drawn, but it is also impor-

SED

4, C652–C665, 2012

Interactive Comment

tant in this context to consider the data shown in Figure 3b. In this plot it can be seen that fracture zones that were found to be associated with the largest events tend to have very large bathymetric anomalies, providing a physical link with the association. The reasoning here is that the very large, consistent bathymetric anomalies are playing a substantial role in increasing subduction coupling and/or creating the necessary conditions for temporary “locking” within the coupling zone.

2.0.2

Reviewer comment: *The "top-N" analysis has its merits, but the fact that the second largest event does not show an association with the presence of a fracture zone means that despite the strong correlation of 13 /15 largest events, we cannot rely on this association. Clearly the presence of fracture zones should be taken into consideration for possible other sites of great earthquakes but it cannot be the sole criterion. In consequence the "seismic hazard" map in Figure 5 needs to be described in terms of this particular contribution. Seismic hazard is commonly described by probabilistic representation of ground acceleration and this is not what is presented in Figure 5!*

2.0.3

Response: Our paper provides strong evidence that major fracture zones in a state of subduction play a role in many of the largest earthquake events, with the hypothesis that the large, consistent bathymetric anomalies influence coupling substantially. The paper does not claim that they are the sole cause of all such events, since there are other phenomena that could influence coupling in a similar way, for example a large, isolated seamount. However the significance of this work has to do with the large, predictable nature of the seismic coupling which could conceivably be directly applicable to hazard analyses for a substantial fraction of global subduction zones. On the other

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

hand, predicting similar behaviour due to isolated seamounts cannot be easily undertaken due to the lack of geophysical data mapping or inferring their location within the subduction coupling zone. We will revise the references and descriptions pertaining to Figure 5 as suggested, reflecting what is simply the regions in which the associations are strongest.

2.0.4

Reviewer comment: *The critical Figure 1 is presented at far too small scale, even with a factor of 4 enlargement is is difficult to pick out the red stars for the largest events. Ironically the grey symbols for the next group of events are easier to see. For these biggest events a ovate shape representative of the extent of the event along the coupling zone would seem more appropriate, with perhaps a star at the epicenter. If the authors wish to press for an association with just the epicenter, then they need to provide some reasoning for why the presence of a structural feature would encourage triggered larger failure. The apparent separation of sites of high and low frequency radiation in the 2011 Tohoku event by a structural feature that might be the extension of the Kashima FZ, does not by itself explain why the great event occurred in that region.*

2.0.5

Response: Figure 1 will be revised to ensure the largest events (red stars) are sufficiently prominent, and relatively more prominent from the grey symbols. Regarding the comment about the extent of the event, the global plot attempts to illustrate the various geological datasets used in this study. Furthermore, the extent of each event could be difficult to obtain, especially considering the older events that have limited information. We refer here to the comments made in the first response, which apply to this query

SED

4, C652–C665, 2012

Interactive Comment

too. Tohoku event: We do not maintain or pretend that we have an explanation for why that well-studied event occurred. We merely observe, in the context of our global analysis, that the epicentre falls within a region that corresponds to the extension of the Kashima fracture zone into the subduction coupling zone. Because the seafloor subducted there is very old, and the oceanic basement topography is covered by thick sediments, the extension of that fracture zone as inferred by our analysis is not obvious from bathymetry or gravity data. The purpose of our paper is not to present detailed cases for all fracture zone intersections involved, as this would far exceed the scope of this paper, given the large amount of data and literature associated with many of the regions involved. Instead we take a step back and observe that there is an association, globally, between megathrust events at and adjacent to subduction zone-fracture zone intersections, and we demonstrate that our observations cannot be accounted for by a random data distribution - only about 25% of giant subduction earthquakes should be associated with these intersection regions if it is just by chance that they sometimes fall in the vicinity of these areas. Having observed this global correlation, we merely suggest that perhaps the hypothesis that a buried, subducting fracture zone may have played any role in the Tohoku event would be worthwhile to investigate further.

2.0.6

Reviewer comments *With respect to the way that a fracture-zone should interact with the coupling zone for megathrust events a number of questions come to mind as to the expected effects: How much of the fracture-zone ridge topography can be expected to survive into the subduction zone? What is the influence of the strike of a transform relative to the trench and convergence direction?*

SED
4, C652–C665, 2012

2.0.7

Response: We agree that these are important questions. The first question around how long fracture-zone ridge topography can be expected to survive into the subduction zone is addressed first. It has already been demonstrated that large, isolated seamounts can survive a passage into the subduction coupling zone (Kodaira et al., 2000; subducted seamount imaged in the rupture zone of the 1946 Nankaido earthquake, Science, 289, 104-106). Seamounts are known to have a complex internal structure (Watts et al., 2010, Seamount subduction and earthquakes, Oceanography, 23, 166-173) with an internal velocity structure significantly slower than that of normal ocean crust, suggesting a relatively high porosity and the presence of volcanic intrusives (Hildebrand et al., 1989, Seismic tomography of Jasper seamount, Geophys. Res. Lett, 16, 1355-1358). If a large seamount such as that imaged by Kodaira et al. can survive the passage into the subduction coupling zone, then one would expect this survival for linear fracture zone ridges to be much easier, considering that they typically represent uplifted normal ocean crust, which does not suffer from the structural weaknesses that characterise seamounts. One of the best examples where the survival of a subducting fracture zone ridge has been seismically imaged is that of the Investigator fracture zone in western Sumatra (Lange et al., 2010, The Fine Structure of the Subducted Investigator Fracture Zone in Western Sumatra as Seen by Local Seismicity, Earth Planet. Sci. Lett., 298, 47-56).

2.0.8

The second question around the influence of the strike relative to the trench and convergence direction is somewhat difficult to answer due to the sample sizes involved, but it seems intuitive that these these could be controlling factors, especially knowing that very low convergence rates do not typically result in megathrust earthquakes. Taking a look at an estimation of the angles between the most pertinent fracture zones as shown in Fig. 3b and the trench normal, we obtain the following:

Fracture zone	*Angle normal to trench (degrees)*
Valdivia	30
Salang	40-45
Kashima	55-60
Mocha	50
Nazca	0
Rat	0
Trujillo	0
Santiago	45
Adak	15

It can be seen that these angles vary substantially. How the strikes of these features relative to the trench influence the nature of megathrust events is currently not known, and we have no obvious way of establishing such a relationship. The same holds for plate convergence directions (large variability, and there is no obvious dependence on convergence directions). This could be a subject for future study.

2.0.9

Reviewer comments: *Tomographic studies seem to suggest that the arrival of major volcanic ridges/plateaus can have a significant effect on the overall morphology of subduction zones, in contrast to seamounts. It may well be that these two types of interaction should be treated separately, but in that case the issue of statistics for very small numbers becomes even more important.*

SED

4, C652–C665, 2012

2.0.10

Response: Yes agreed, in this study we used a publicly available dataset consisting of a combination of well defined seamount chains and volcanic ridges. Even grouped together, we only obtained a total of 14 intersection locations. In the paper we stated that even this combined dataset leads to conclusions limited in confidence due to the sample size, so splitting the dataset up even further would not yield significant results. This is nevertheless a topic that could possibly be taken further in future studies, where other seamount datasets are studied in a similar fashion.

2.0.11

Review comments: *Minor points: Mb - body wave magnitude saturates at around Mw 5.5 so is only suitable for small events - not as stated.*

2.0.12

Response: Thanks for that - this will be corrected.

2.0.13

Review comments: *Section 2.5: A clearer explanation is needed of the "arbitrary case" - it appears that this means the situation in which an event occurs by chance - but perhaps "stochastic" would be a better term.*

SED

4, C652–C665, 2012

Interactive Comment

2.0.14

Response: This will be clarified - yes the definition of the “arbitrary case” is the null hypothesis, or the case one would expect given there is no association. This is considered to be one of the most critical aspects for this paper, since it is the essential evidence that shows how the association would look given our hypothesis does not hold. Perhaps the term “stochastic” would also be confusing/problematic for readers (though the manner in which the null hypothesis is tested is of course stochastic in nature), so we suggest just clearly clarifying the definition of the arbitrary case near the beginning of the paper.

2.0.15

Review comments: *Section 2.6: The term "baseline hazard zone" appears suddenly - is this meant to be the same as the "baseline coupling zone". This entire section could benefit from expansion so that the arguments are easier to follow.*

2.0.16

Response: Yes, this will be clarified.

2.0.17

Review comments: *In Figure 3 it is not clear whether the convergence rates are trench perpendicular or absolute.*

SED

4, C652–C665, 2012

2.0.18

Response: This will be clarified. The values are trench perpendicular.

2.0.19

Review comments: *The slip mechanisms from Robinson (2007) shown in Figure 4 seem rather different from other published models for the 2004 Sumatran event that would not appear to show such a direct link to an impinging structure. Further is "slip" rather than "energy release" the right quantity to consider? Slip is highly dependent on the local seismic wavespeed structure.*

2.0.20

Response: The Robinson slip model was chosen because it provides some indication of the spatio-temporal relationship between the initial event, and the role that subduction zone intersections may be playing. We did not find published models for this event that show either slip or energy release as a function of time after the event as Robinson does. His model was not chosen to suit our analysis aims. We will add an explanation in the paper that there are several other, alternative slip mechanism models for this event.

3 Review: C569

Review comments: *This paper examines the spatial correlation between fracture zone ’96 trench intersections and giant subduction earthquakes. The purpose is to identify whether giant earthquakes are preferentially associated with such intersections. A pos-*

SED

4, C652–C665, 2012

Interactive Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

itive correlation would allow the construction of better seismic hazard maps for such regions. I find the evidence of positive correlation presented in this paper convincing enough. Given the small amount of data available, the authors have developed an interesting way of testing for correlations. I think however that McCaffrey92s (2007, 2008) idea that, given a long enough trench and enough time, giant earthquakes may well happen at any subduction zone, should be at least mentioned and discussed in this paper. It does not invalidate the conclusions that the majority of observed giant earthquakes seem to have occurred at trench 96 fracture zone intersections. However, it does have a bearing on the issue of hazard maps. If McCaffrey92s statement is true, then finding these intersections would not be too relevant for the identification of potential hazard zones, because hazard would simply be determined by trench length (for max expected magnitude) and convergence rates (for frequency). After all, it does not matter for hazard purposes if an earthquake has nucleated 700 km away from a certain location: as long as the rupture spreads that far, this location has still high seismic hazard. Also, trench 96 fracture intersection in itself does not guarantee rupture propagation, if the subduction zone terminates laterally nearby. In such a setting, only uni-directional large ruptures are possible. Thus trench length and continuity may be more straightforward parameters to use for hazard assessment.

3.0.21

Response: Thank you for your comments. We will do as you suggest and add this discussion in. Our main defence here is carried by the data. Even though the main results relate to the associations with the Top 25 subduction-based earthquakes, the effect we see remains significant beyond the largest few HUNDRED events. Here we refer to Figure 2a and b where a very careful approach has been used to look at the distribution of the Top-N earthquakes within 150 km of the intersection regions, and comparing them to distributions one would expect given there is no association. Even though we see the effect weakening as the magnitudes drop off, the fact that the events

SED
4, C652–C665, 2012

Interactive Comment

are significantly different to the “arbitrary” case is the key observation here, since the association with the epicentres within the 150 km based on these large numbers of events is strongly in favour of the parameters we propose being significant. If the associations were found to be strong only at longer distances, that would be in favour of the scenario you raised above, and thus to summarise it is both the localisation of the effect, and the effect holding for a few hundred (magnitude sorted) events on record, that are in our favour here.

3.0.22

Review comments: *On the topic of hazard maps, the authors should not confuse hazard with risk. I also agree with the other referee92s comment that hazard maps are normally presented in probabilistic terms. If not, then the authors should explicitly state what they mean with "hazard map".*

3.0.23

Response: This will be revised and clarified.

3.0.24

Review comments in text: *General Comment: I suggest to simplify the language, shortening long sentences as much as possible and using more straightforward terminology. I have placed a few examples in the introduction to show what I mean.*

SED

4, C652–C665, 2012

Interactive Comment

3.0.25

Response: Thank you. We will make a pass through the text and improve as suggested.

3.0.26

Review comments in text: *"hazard risk map" is an object that does not exist. Hazard and risk have specific definitions. A map based on the premises above can only be a hazard map.*

3.0.27

Response: This will be amended.

3.0.28

Review comments in text: *Figure enlargements*

3.0.29

Response: The figures discussed will be enlarged as proposed in the text. Regarding Figure 1, we prepared figures B1, B2 and B3 to show these pertinent geological regions at a higher scale. Figure 1 is intended to illustrate the primary datasets used in this study on a global scale.

SED

4, C652–C665, 2012

Interactive Comment

3.0.30

Review comments in text: *Again, hazard and risk should not be confused. See for example definitions here:* $http://www.ccohs.ca/oshanswers/hsprograms/hazard_risk.html$. *A hazard map is not the same as a risk map. The usage of these terms should be checked throughout the paper.*

3.0.31

Response: This will be amended.

Interactive comment on Solid Earth Discuss., 4, 1229, 2012.

SED

4, C652–C665, 2012

Interactive Comment