Reply to: Anonymous Referee #2
On the manuscript: Seismogenic frictional melting in the magmatic column
by J. E. Kendrick, Y. Lavallée, K.-U. Hess, S. De Angelis, A. Ferk, H. E. Gaunt, D. B. Dingwell, and R. Leonhardt

Original reviewer comments are in dark green and replies to comments are in black.

The authors are greatly appreciative to Reviewer #2 for pointing out some aspects of the manuscript which showed organisational shortfalls and for aiding the rejuvenation of the text. A number of comments were echoed by the fellow reviewers and have been taken on-board by the authors, resulting in an improved manuscript which we believe is worthy of publication in Solid Earth.

The contribution by Kendrick et al. "Seismogenic frictional melting in the magmatic column" addresses an increasingly examined phenomenon in physical volcanology, namely the intimate association of shearing and faulting with extrusion of the magma conduit. Synformational deformation of volcanogenic and magmatic materials has been examined by different authors, with much emphasis on the effect of multiple excursions through the glass transition, and thermal mechanical feedback during shear of viscous magma. This paper examines the formation of a distinctive vein comprising zoned cataclastic and very fine-grained crystallized material that is argued to be frictionally induced melt (pseudotachylyte). Characterization of the vein material is undertaken using differential scanning calorimetry, and magnetic techniques. Both of these approaches indicate distinct differences between the vein and host rock that are ascribed to shear melting of the host. Analysis of the repetitive LP seismicity at Soufrière hills suggests that individual pulses are sufficient to cause melting, and a final statement is that such "drumbeat" seismicity is "inextricably" linked to formation of pseudotachylyte. Notwithstanding the supporting evidence there remain some inconsistent data. I wish to emphasize that I do think friction melts can develop, but because of their significance to our understanding of extrusion mechanics, it is essential that their occurrence be closely characterized
The reviewer has again accurately identified the key aspects that we were hoping to highlight. The authors would like to say that while magma deformation is "an increasingly examined phenomenon" it is still very much a fledgling science, and there is much which is still to be discovered regarding fracture, shearing and healing cycles in the conduit, which will inevitably contribute to the future of our understanding of volcanology.

1-Nature of the Vein/Shear Band - For frictional melts, there are typically generation surfaces and injection veins. Fig. 1 very much resembles an injection vein as opposed to a frictional generation surface. a feature in which flow structure is often most clearly
No distinct evidence of shear is presented, and brings into questions whether it is a shear band. As the samples are from a loose block, it is critical to ascertain from other fabric information what the orientation of the conduit was relative to the vein; this should clarify the concern as to the origin of the feature. The text refers to the occurrence of slip parallel to the conduit wall, as observed elsewhere, so slip zones can be expected in this orientation.
This is an astute point from Reviewer #2, frequently frictional melts are accompanied by injection veins into the surrounding rock, and additionally the reviewer finds that the shear band's appearance may better represent an injection vein itself. The authors' response is 2-fold, and relates to the material properties of the andesite host. The shear band, at ~2m length, consists of interlayered pseudotachylyte and cataclasite, and while it is possible for these to intermingle in an injection vein, to remain coherent and parallel for such a distance (>2m), and with usually 7 layers (figure 1, figure 2) would be quite a feat. Additionally,

injection veins tend to be on the order of cm's length, and tend to have the morphology of a half-bell, tapering rapidly from the vein base and less rapidly toward the tip (see Griffith et al., 2012, EPSL), unlike what we see here, which is an approximately constant thickness vein. This provides some evidence that what we are dealing with is the slip surface (rather than injection vein), but the undulating morphology may be what led reviewer #2 to surmise that this was an injection vein. This, however, is a result of the shear band forming in an >800°C+ andesite magma. The magma, which contains ~20% glass would have been behaving as a viscous fluid, allowing for bulk deformation of the magma and hosted shear band after it had formed in the conduit. While the magma is able to behave as a brittle solid and fracture at strain rates exceeding the timescale of relaxation, as soon as the slip event is over and the strain rate is such that the magma is able to flow. This material property, unique to glass, may also explain the lack of injection veins emanating from the shear band, as the immediate return of the andesite into its fluid state would not allow the brittle propagation of fractures for injection veins. The reviewer also suggests that no direct evidence of shear is present, but the authors contend this, indeed in Figure 2 the lineation of the cataclasite bands, and the flow indicators of the pseudotachylyte in panels b and c are the result of shearing. The authors would like to reiterate that the slip distances inferred here are only on the order of ~15cm, and so shear indicators are not of the scale or design of those on tectonic faults.

Finally, the authors do not feel that it is possible to infer, from textural information, the original location of the block within the conduit when the shear band formed. To speculate can only lead to misinformation, and we do not believe that this would be of benefit to the manuscript. What we can infer is a temperature and pressure condition at which it may have viably formed, and a slip distance and velocity that could be responsible. As to speculation of the orientation with respect to the conduit margin, we know from many previous studies that shear zones can form along conduit margins, especially during the extrusion of highly viscous magma during dome eruptions. But we also know that strain localisation in one area can result in stress build-up in the adjacent rocks and magma, and so related fractures forming simultaneous to the principal slip surface are real possibility, and to achieve a slip distance of just 15cm to form melt is also not unfeasible. In conclusion, we have modified the text of the manuscript and hope that it now reflects these inferences and their justifications.

2-Relationship to Seismicity – The combination of expected slip along the conduit boundary and the frequency of events would suggest that melt events, if tied to the "drumbeats", would be much more common than a single vein/block. Without precluding melting, this would argue for the described structure being an injection vein, as opposed to shear surface. By comparison, the Mt. St. Helens (MSH) conduit boundaries are densely sheared. Also, repetitive seismicity at MSH appears linked to post-crystallization (de-gassing) within the conduit, at conditions under which brittle deformation initiates.

The reviewer makes an interesting point again, and the authors agree that with such a link between seismicity and fracturing then the process is relatively common. I think that a key point here is that these features undoubtedly are more common than we have observed, but their chance of survival and subsequent deposition on the surface of a block in an accessible part of the block and ash flow at the base of the volcano is slim (assuming that they may form within ~2m of the conduit margin in a ~30m conduit, and that the conduit margin is then overprinted by gouge formation at shallow depths and that, during dome collapse particles from μm's to 10's meter scale are formed, leaving only a small percentage accessible for study). With the ongoing eruption at Montserrat the study of the in-situ dome is not yet possible, although this would aid the investigation into shear bands significantly.

The authors would like to highlight a number of differences between the shear feature observed here and the sheared conduit margin of Mount St. Helens. The reviewer is correct, in the highly studied early spines at Mount St. Helens the shear zone measures >2m thickness, but at this point extrusion rate surpassed that of Soufriere Hills by up to *10, and the seismic events were concordantly larger. Later in the eruption, when extrusion rates decreased significantly, the shear zone thickness dropped to ~2cm (Kendrick et. al., 2012, JSG), the drumbeat frequency and amplitude dropped and pseudotachylyte appeared in the rock record for the first time. It may be considered that it began forming for the first time, or another deduction might lead to the conclusion that only when extrusion rate dropped was the pseudotachylyte able to survive the subsequent shearing in the upper conduit to breach the surface. While there are parallels between the eruptions of Mount St. Helens and Soufriere Hills, there are also many differences- for example the reviewer notes that the drumbeats at MSH have been linked to degassed, fully crystalline magma ("at conditions under which brittle deformation initiates") and herein lies the clue to the biggest difference- glass. While Mount St. Helens, at its extrusion temperature of ~900^{o}C was a solid, and behaved in a brittle manner from approx. 1km depth, Soufriere Hills andesite contains a significant portion of glass, which, at any temperature above the glass transition (Tg, approx. 700^{o}C) allows the andesite to behave both as a liquid, and also as a solid at strain rates fast enough, thus allowing it to fracture, but also permitting it to flow. When we note also the mineralogical contrasts, bulk chemistry (andesite v dacite which is more viscous) and porosity (which for MSH is as low as 4% but which is 23% in the host here) as well as volatile content and extrusion rates which all contrast greatly between the 2 volcanoes, what's remarkable is that the 2 volcanoes can produce such similar seismic events.

3- Nature of the Vein Material – Almost from the beginning of the presentation, there seems to be acceptance that the fine-grained material is friction melt. This should be established more systematically e.g. what says definitely melt, what distinguishes healed cataclasite from melt, etc., especially in the microstructural descriptions. The mixing of cataclasites and other material can occur in injection veins as well as generation bands, so indirectly indicates multiple slip episodes. Characterization of finegrained microstructures by higher resolution techniques (TEM?) could clarify some of the ambiguities.
The reviewer seems adamant that the shear band is actually an injection vein, but the authors do not believe that is the case as explained in the responses above. As this is so, we do not believe that TEM is required to determine this, and would also like to state that other scientists have reached the same conclusion as us, that the vein is a shear band (see Plail et al., 2014, EPSL). During the modification of the manuscript we hope that we have clarified any misunderstandings that may have arisen from imprecise language etc. and that we have addressed this point and others from the reviewers by restructuring, including more clearly dividing results from interpretations.

Document editorial comments

p.1661, l.3 – SHV - expand to Soufrière Hills volcanics as this is first occurrence in text
Done

p.1661, l.15 -25 References – several of these are listed in mixed or reverse chronological order – re-order? Also occurs throughout the MS.
According to the website "In terms of in-text citations, the order can be based on relevance, as well as chronological or alphabetical listing, depending on the author's preference." The listing is alphabetical, but can be changed if the editor wishes.

p.1662, l. 6 – see comments about whether this is unambiguously a shear feature
See response above

p.1663, l.29 – mixed pseudotachylyte and cataclasis – this needs extended description and explanation
Done

p.1664, l.1 – . . .. surface; hence, . . .
Done

p.1665, l.24 – include more primary reference e.g. Sibson 1977 or another of his early papers
We have added more primary references in the text, including Sibson 1975, 1977, and Swanson 1992 and others throughout the text.

p.1667, l.23 – as noted, I think "inextricably" linking drumbeats and melting is not proven
Changed in light of this comment and that of reviewer #1.