Dear Editor,

We thank warmly Dr. Velio Coviello and an anonymous referee for their in depth lecture and their many thoughtful and constructive comments. We propose below detailed answers, thoughts and clarification concerning the main points of interrogations of both referees. For clarity, redundant comments of both reviewers and technical/typos comments have been removed or just indicated as OK in the letter.

Sincerely,
Floriane Provost on behalf of all co-authors,

NOTE: In the following document, the referee comments are in normal fonts and the answers are in blue font.

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Reviewer 1: Dr. Velio Coviello

Major comments:

I think that the abstract needs a significant rewording. The first lines sound like an introduction on environmental seismology. Please focus more on objectives, methods and results of your work.
Thanks. We have rewritten part of the abstract in order to state more the focus of the work.

In addition, I disagree with the statement "The seismic networks installed on these sites are roughly similar (i.e. sensor, network geometry)". What does "roughly similar" mean? There is a significant difference between a BB seismic network installed on a large, slow moving earth-flow and a linear array of geophones deployed along a debris flow channel.
We do not completely agree with this affirmation. We rephrase the abstract in order to precise that we analyze the signal recorded by geophones and BB seismic sensors in the same frequency band (between ca. 1 Hz and 100 Hz). We do not investigate the information recorded at lower (BB) or higher (Geophones) frequencies. In order to ease the understanding, we also propose a new table (Table 2) presenting the list and the specifications of the seismic instruments and of the seismic network geometry of the 13 sites where data is presented and analyzed.

Moreover, if the authors are focusing on "seismic events detected at close distances (< 1 km)" the sensor network characteristics and geometry, as well as the geological and geomorphological contexts, have a strong impact on the recorded signals.

Indeed, but this statement is true for every seismological studies. More than the distance alone it is the wavelength of the seismic waves and the source dimension compared to the recording distance that is important. We analyzed seismic networks where at least one sensor is installed on or at a very close vicinity (< 50 m) to the active zone. Regarding the geological and geomorphological contexts, our assumption is that if we can observe similar signal features in different sites they can only be explained by the similarity of seismic sources.

To achieve a standard source characterization, in my opinion there are three major topics that would need to be addressed: i) distance sensor-source, ii) typology of sensor, iii) sensor installation methods. Given the pretty ambitious title, I would expect some discussion of their effects on landslide sources.
As mentioned in the previous comments, we analyzed seismic networks where at least one sensor is installed on or at a very close vicinity (< 50 m) to the active zone and we also filter the signals in the same (low) frequency band to limit the influence of the wave propagation of the signal.
Concerning point ii), to compare signals from different networks the most important sensor-related properties to take into account is the instrumental response of the sensors. For each case presented in our study, we have removed the instrumental response of the recorded signals (and filtered the signal in the same frequency band (f_c to 50 Hz) recorded by every sensors in our dataset to compute quantitatively their properties).
Concerning point iii), if the reviewer means network geometry by "sensor installation" we do not agree that the sensor installation will play an important role in the signal features. The latter is mostly controlled by the source to sensor distance (and we answer to this comment in point i)). The sensor installation will play an important role in the magnitude of completeness and in the location accuracy.
We have added in the Table 2 some information on the distance sensor-sources for each case studies in order to provide more information about the analyzed datasets. We state clearly that we do not investigate low and high frequencies (P10, lines 12 to 15). As we choose highly energetic examples for each class we do not expect a dominant impact of site effect on the features we selected and we discussed if needed be, the effect on the interpretation.

However, I have the impression that the paper leaves more open questions than clear responses. In the following more details on how these three aspects have not been adequately addressed are given. i) The authors briefly touch this point in the discussion: "The differences in the frequency content of simple slopequakes may be explained either by the attenuation of the high frequency at large distances during the propagation or by different rupture velocity and/or the presence of fluid in the fault plane". I encourage them to stress more on the possible limitations of a spectral analysis to be employed in a general classification. For instance, consider what was already published about the effect of the sensor-source distance on the seismic signal produced by flow processes (Gimbert et al., 2014; Schmandt et al., 2013).

We agree that spectral analysis of the seismic signals present some limitations for signal comparison but it is also the most common approach to investigate seismic datasets. Spectral analysis is used in most classification processes (automated and manual) whether it is for volcano or reservoir monitoring, local, regional or even global seismology.
It must be noted that 1) we do not only analyze the spectrum (4 over 9 of the signals properties are not directly correlated to the spectral content), 2) in order to reduce the influence of the seismic to sensor distance, the signals are filtered in the same frequency band (< 50 Hz) before the computation of the features (this is not the case on the signal figures) and 3) we analyze the most energetic recorded signals in order to reduce the influence of the seismic geometry.
Concerning the two mentioned studies, they show that the source mechanism is a predominant factor controlling signal spectral content although the sensor to source distance plays a role in the contribution of certain frequencies to the signals amplitude. As the simplest deconvolutive model, propagation acts as a filter, but the remaining spectral content is controlled by source properties. Hence, even if we loose spectral information due to attenuation, the peculiarity of the spectrum controlled by the source mechanism is most of the time conserved. Therefore we think that including spectral features is relevant in our classification.

ii) At P7 L5-6 the authors state "The relatively low energy released by the landslide related sources makes the choice of the seismological instruments to deploy very important". I agree, and I think that this point should be developed more.
We added a section about the seismic network deployment where we address this comment. We also modify the last paragraph of section 3.1 (P6. l32, P7. l13).

Section 3.1 describes the main classes of sensors employed for the detection of mass movements but I do not see a proper discussion of this point when the authors present their dataset.
Thanks. We refer to the new section "Data" introducing Table 2, and we also indicate more explicitly which sensor types are used and how they are analyzed. As mentioned previously, we corrected every sensor response and we decided to work in the f_c-50 to 100 Hz frequency band were all analyzed sensors are sensitive.

iii) Considering flow detection at channel scale, the sensor installation method has a strong impact on the features of the recorded signal, both in amplitude (e.g., Coviello et al., 2015) and frequency domain (e.g., supplementary material of Kean et al., 2015). Again, this issue is shortly introduced at P3 L11 "The location of the sensors and the type of waveguide are also critical to capture the slope behavior" but a discussion based on the analyzed dataset is missing.
We added a section about the seismic network deployment (Section 3.2) where we address this comment. More than the sensor installation geometry is the

distance to the source that plays an important role in the recorded amplitude and the frequency content. We already answer about this influence in previous comments.

Standardized datasets and field experiments are probably needed to systematically address those topics. I am skeptical about the possibility to develop a standardized source-mechanisms characterization of landslide-induced seismic signals from a collection of heterogeneous case studies.
We are a bit confused by this comment. On one hand the reviewer stresses that "standardized dataset are probably needed" but on the other hand that it is impossible to do so from a collection of case studies. Then how can one compile standardized datasets?
We believe that the compilation of case studies and the standardized processing and representation of the seismic events recorded on landslides we propose is relevant for the following reasons : 1) standardized classifications exist in other fields of micro-seismology such as in reservoir monitoring, slow earthquakes (LFE, VLFE, etc) and volcano monitoring; 2) Those standardized classifications have proven to be useful starting points for further discussions : the classification is never frozen and should evolve following new observations and models; 3) Compiling datasets from very diverse case studies allow to bring out the control of the source on the signals from each class (different media and different propagation paths but same signal characteristics at different sites = source-controlled features).

Additional comments:

P2 L5: references needed
OK. We have introduced different references for glaciers, snow avalanches and landslides.

P2 from L26: concerning repeaters, I would suggest to the authors to read the reviews of the paper by Schopa et al. (2017), an interesting discussion is made there on this point
We added a sentence concerning this discussion (P3. l15-20).

P3 L16: "low frequency ranges (1-500 Hz)", why do you define this pretty broad frequency range as low? Compared to what?
We recognize that this sentence is awkward. We meant compare to Acoustic Emission signals. The term "low frequency" has been removed for clarity.

P4 L30: "13 monitored sites", 13 or 14?
OK. The correct number of sites is 13.

P4 L33-35: concerning "we first discuss all the physical processes that occur on landslides: We further present the seismologically-instrumented landslides in the world: Then we establish a classification scheme", I suggest the authors to

rephrase in order to be more realistic. I think that the main physical processes were discussed, that only a few (14) of the seismologically-instrumented landslides in the world were presented and that a possible classification scheme was proposed.
We have rephrased the sentence: *"Then we establish a classification scheme of the landslide seismic signals from relevant signal features based on the analysis of the datasets of 13 sites."*

P8 L13-24: these lines sound more as part of introduction than data. The paragraph data should start from current L25 but a description of the analyzed dataset is actually missing: which is the length of the analyzed time series? How many events did you analyze? How did you select the events analyzed in the following paragraphs? I guess those were well-known events, or did you applied an automatic detection methods?
We added these information in the new version of the paper and in Table 2, section 4 and section 5 of the new version.

P8 L26: "For all sites, the instruments are deployed close to the landslide", what does "close" mean? Please be more specific. I guess that authors agree that, for example, two seismic sensors, one installed at 10 m and another one at 900 m from the very same landslide, would record signals pretty different, especially in terms of spectral content.
We added these informations in the description of the sites and in Table 2 and section 4. We mentioned that for each seismic network analyzed, at least one sensor is installed on the active zone or at its vicinity (< 50 m). Moreover, we choose to work with the most energetic trace for each recorded events that we assume to be the closest station to the source and hence, the most representative of the seismic sources properties.
Of course, the distance and the medium contributes in the features of the seismic signals and we do not decorrelate its contribution. But as mentioned in earlier answer, the source mechanism also contribute to the signals feature. We already justified our approach to limit the wave propagation influence (see earlier answers to the same comment). Basically, our assumption is (as mentioned in previous comment): different media and different propagation paths but same characteristics at different sites = source-controlled features.

P15 L14: "The signals present significant differences with the chosen features", please reword, the reader does not understand the meaning of this sentence.
We have rephrased the sentence.

P15 L15: "in the field, the differentiation", I am not sure to have correctly understood, maybe you meant "only from the seismic signal analysis, the difference between"?
OK. We have rephrased the sentence.

P17 L23: please avoid references that are not published work, i.e. Helmstetter

et al., (2017a), especially if the reference is used to support a very strong statement such as “the high correlation between the repetitive events could only be explained by stick-slip movement of the locked section(s)”. A sentence like this must be accompanied by supporting data or published results.
We removed the mentioned reference in this sentence.

P17 L29: concerning “most collapses occurred without precursory sequences (Allstadt et al., 2017)”, I would suggest tuning down this statement, which is also in contradiction with P2 L24. There are a number of cases where precursory seismic signals related to small rockfalls were documented, especially when a station is installed nearby the slope or there is a local monitoring network. On the contrary, when the closest station is distant or we do not dispose of other monitoring data, recognizing those precursory events is difficult but potentially there are. I also believe that the reference Allstadt et al. (2017) is not consistent here.
OK. We agree and removed this sentence.

P18 L16-20: I do agree with “several descriptions of the seismic sources are proposed for each study case” and a standard classification would help to discuss and compare landslide-induced seismic signals. I understand that the authors are proposing their classification as general reference, but I would suggest to the authors to delete the sentence “we encourage future studies to use and possibly enrich the proposed typology”. In my opinion the scientific community does not need to be encouraged to adopt one classification or another.
We disagree with this statement – standard typology does exist for instance for volcano-related seismic sources or for glacier-related sources and have been very useful to progress in the comparison of the seismic signals on all volcanoes and in the creation of comparable catalogs. Though any standardization/harmonization methods can be questionable, we believe that proposing a nomenclature of sources is important for further discussions including rejecting the proposed classification or interpretation.

By the way, why you do not adopt the classification proposed by Allstadt et al. (2017)?
The classification proposed by Allstadt is not comparable to our classification as it is related to detection and cataloging landslide failures at regional scales (> 1 km); the purpose of our classification is the slope scale.

P18 L25-27: reference needed
Done. We added the reference.

Reference list: the style is not consistent with the journal guidelines, in many cases the doi is missing, there are repeated references (Hibert et al., 2014a), others are missing (Provost et al., 2018) and there is some text here and there probably out of place (e.g., P29 L10-11). An accurate revision of the reference list is needed.

We corrected the style of the references taking into account the journal guidelines, and also updated the reference list.

Moreover, I do acknowledge the significant contribution of some of the authors to the field but I have the impression that self-citations are really abundant (five papers by Hibert et al., six by Helmstetter et al.). Please try to select your most significant works and refer to them.
We believe the citations related to the papers of Helmstetter and Hibert are relevant. We also added several new references to the manuscript from other research groups as proposed by reviewer # 1. We tried to be exhaustive in the references and we cite more than 130 papers (a significant number due to Table 1), in total around 18% of the citations are self-citations of the co-authors which we think is not over-abundant.

Figure 1: I would prefer the author to focus more on the sites from which they present some data instead of showing a collection of points in a global map. In addition, Figure 1 is redundant if one considers the list presented in Table 1.
We added a table gathering the informations about the analyzed sites and their seismic networks (Table 2). We removed Figure 1.

Table 1: some details/revisions are needed. 7 Alestch-Moosfluh: this landslide is also monitored with a geophone network (Manconi and Coviello, 2018); 8 Torgiovannetto, Assise: please modify in Assisi; 15 Aiguilles: Aiguilles Pas de l'Ours?; 22 US highway 50, CA: there is no reference/website about that?; 24 Millcoma Meander, Oregon: same as above; 33 Matterhorn peak/Mont Cervin: please use the international name (Matterhorn) or the Italian one (Cervino) and add the reference describing the more recent monitoring network (Occhiena et al., 2012); 48 Piton de la Fournaise caldeira: Piton de la Fournaise is not enough?; 53 Marderello torrent: the reference for this net- work is Coviello et al. (2015); 69 La Colima volcano: please use the international name (Colima Volcano) or the Mexican one (Volcán de Colima); 70 Merapi volcano flanks: please use Merapi volcano, be consistent with the list format; in addition, a number of sites are missing, especially overseas in USA (e.g., Kean et al., 2015), New Zeland (e.g., Lube et al., 2012), and South America (e.g., Kumagai et al., 2009; Worni et al., 2012).
OK. Thanks for providing this detailed information. We have corrected the Figure and Table 1 accordingly.

Figure 2: what about adding a sketch of the signal associated to each process?
We do not think this would had information at this stage of the paper. It seems to us that simple sketching cannot capture the complexity of seismic signals and that the representation we propose on figure 13 is more suited to expose this complexity.

Figure 13: I guess this is the most important figure of the paper, why does it only appear in the discussion?

This figure summarizes the presented signals properties. We do not think that an earlier presentation of this figure is necessary.

Given the large seismic dataset I suppose you have at your disposal, why did you plot only between 2 (most of the cases) and 6 (few cases) examples? I wonder if the variability of the attribute shapes is representative given limited number of examples here presented.

We present more examples in the discussion in the new version of the paper (Figure 12) and comment the variability of the attributes in the discussion (P17. l2-15).

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Reviewer 2: anonymous referee

After reviewing the manuscript I read the review of Dr. Coviello. I fully agree with his comments. I will not repeat his comments in my review. I found in the manuscript some mistakes and problems. Accordingly, I propose a major revision of the paper (if not rejected in its present form), which is in line with my comments and those of V. Coviello. The document is verbose, with a lot of information (perhaps with little consistency in terms of content) and poor in conclusions. Please, be more concise and remove the unnecessary information. Justify the purpose of the paper better. References must be selected to shorten their number.
We thank the reviewer for these statements. The introduction of the paper has been thoroughly revised to better highlight the focus of the work. We also rephrased or deleted some sentences considered as verbose by the reviewer. All these changes are indicated in track mode changes in the revised version of the manuscript.

In general, I am very skeptical about the purpose of the paper: to establish a standard typology of endogenous seismic sources.
This comment has also been addressed by Reviewer #1. We believe that the compilation of case studies and the standardized processing and representation of the seismic events recorded on landslides we propose is relevant for the following reasons : 1) standardized classifications exist in other fields of micro-seismology such as in reservoir monitoring, slow earthquakes (LFE, VLFE, etc) and volcano monitoring; 2) Those standardized classifications have proven to be useful starting points for further discussions : the classification is never frozen and should evolve following new observations and models; 3) Compiling datasets from very diverse case studies allow to bring out the control of the source on the signals from each class (different media and different propagation paths but same signal characteristics at different sites = source-controlled features).

It is true that there has been a dramatic increase of monitoring/detecting seismic signals generated by different ground phenomena in the last five years. However, we have to bear in mind that seismic measurements are not a direct measure as they could be extensometers, for example. The terrain is so complex that I am skeptical about whether seismic monitoring could give detailed information about the phenomena.
We disagree with this statement. The arguments for using seismology, waveform analysis and analysis of the temporal and spatial distribution of seismic sources on landslides as complementary sources of information on the mechanics of the

processes are:
1) The temporal resolution of seismic instruments provides very accurate timing of the deformation processes and is non-invasive as it can detect events at distance from the sensor installation. These advantages are hardly met simultaneously with other types of sensor. Several studies have demonstrated the major contribution of seismology to built near-exhaustive catalogs of events at slope scale (Helmstetter et al, 2011; Dietze et al, 2017b), at regional scale (Hammer et al, 2016) and its potential for early-warning of debris-flows (Walter et al, 2017; Arratano et al., 1999; Burtin et al., 2009).
2) It records also the spatial distribution of the sources occurring in depth (Spillmann et al, 2007, Lacroix et al, 2011, Tang et al, 2015) which is not the case of extensometers for example. The location of the seismic activity represent valuable information to update geo-mechanical models determining the factor of safety of the slope (Tang et al., 2015).
3) The seismic signal features are controlled by the source mechanism providing insights in the mechanical behavior of the deformation.
4) Recent papers have also documented seismic signatures preceding the collapse of large landslides (Amittrano et al., 2005; Yamada et al., 2016; Poli 2017; Schöpa et al., 2018) proving the presence of seismic signals associated to slope instabilities deformation.

So, seismic data alone are very difficult to manage for mass movement studies, mainly if the signals are very short and are related to small energy release. We must be aware of the type of phenomena. In my opinion, it is the combination of different measurements that can contribute to information about the phenomena.
We agree and we never mentioned to consider seismology as a standalone technique for landslide monitoring.

For this paper, I suggest you only include the very significant seismic signals and avoid small events.
The purpose of the paper is clearly mentioned: we analyze the signals recorded at close distance to the slope ($<$ 1km) with seismic sensor sensitive to the $\tilde{1}$-100 Hz frequency band. This means that we are exploring larger events and more distant events than Acoustic Emission studies (Dixon et al, 2015; Michlmayr, 2012) but smaller events than large slope failure (volume $> 1O^6$ m^3, Ekstrom and Stark, 2013). Obviously, the examples are "significant" signals at this scale as they are clearly above the noise level.

Mainly, because of the difficulty of a subsequent interpretation. This is in some ways one of the conclusions of the authors, given that they unify the "new named" slopequakes by including them all in one group. The slopequakes can be so complicated that the present catalogue is probably not complete.
We agree with the statement that slopequake signals can be "complicated" and "that the present catalogue is probably not complete". However, we also propose sub-classes taking into account the complexity of this class while keeping

a uniform denomination because they are usually analyzed as one class in the previous and current studies. The name “slopequake” was chosen in order to remove the source mechanisms interpretation induced by the name “slidequake” or “micro-earthquake”. As mentioned earlier, the present classification is not frozen and can be enriched and/or discussed. In particular, for certain subclasses we explicitly mentioned that surface processes may also generate these type of signals (SQ-tremor like signals and SQ-with precursory).

All efforts in this line should be devoted to monitoring one site with different instruments and to interpreting the events in coordination with different specialists.
This is done on most of the recent sites being instrumented by different research groups. However, the source mechanisms and the variability of the slopequake features remain poorly documented. Understanding this variability and the underlying physical processes remains a strong challenge, and we hope that the classification we propose will bring some insights leading toward a better grasp of those processes.

Having said this, see below for further comments.

1) Table 1. This is a very risky approach. Given the present increase in mass monitored studies you probably miss one unless it is the intention of the authors only to mention those in which they are involved. In this case, you must mention this specifically, and give your reasons.
We agree that we probably missed some sites especially the new sites recently instrumented. We added the missed sites suggested by V. Coviello (4 over 70). If we are missing further references, please, let us know and we will add them to the table.

2) As regards field instrumentation, it would be useful to better explain the characteristics of the instruments and their different site conditions. Site effects are completely ignored in the interpretation/description of the signals. In fact, most of the presented data were already the subject of different interpretations and I assume that these have been described in the corresponding papers. However, when seeking to establish a standard typology, consideration of the peculiarities (or not) of the site effects is very important.
This comment was already addressed by Reviewer #1.
Concerning the field instrumentation, we propose a new section “Data” (section 4) to describe precisely the seismic network configuration (also summarized in table 2). The geomorphological and geological context are indicated in Table 1 with the references for further information.
Concerning the instruments, we corrected the instrument response and analyzed their common frequency band.
Concerning the site effects, it is true that we do not correct. However, we believe that the comparison of signals from different sites of various geomorphological and geological contexts is precisely a good strategy to discriminate the contri-

bution of the source mechanism from the site effects/attenuation. We hence describe the features shared by all the selected examples without focusing on particular features of certain signals that are likely linked to site effects.

3) In the definition of the parameters of processing methodology, if I am not mistaken, no amplitudes are considered (only once on pag. 15 line 21). Why are the amplitudes (nm/s) not indicated in the events? It is true that attenuation can also affect amplitudes, not only the frequency content, but it could be useful for differentiating events. The relative "energy" released together with the duration of the signals can give significance to some events.
Amplitudes are indicated on the figures for each trace of each example in nm/s. We did not choose to analyze the amplitudes or Energy/duration relationships (even so, they can be significantly different from one class to the other) because we are focusing in the features that can be related to the source mechanisms and not to its magnitude.

4) Additionally, the authors devote a large description to the frequency content of the events. However, in figure 13, the maximum attention is devoted to other parameters that are basically in the time domain.
Over 9 parameters presented on figure 13, 5 are related to the frequency content and 4 to the time domain. The waveforms presented on figure 13 gather information on both time and frequency content. Moreover, we think that the format of the figure used to present examples for each classes (Figures 3 to 12) summarizes all the informations needed to discuss the signals. On Figure 13, we adopted "star" diagrams in order to ease the visualization of all the selected features and not to focus only on frequency nor time domain properties.

Moreover, the parameters introduced in the processing methodology section are not sufficiently considered in the description of the events. Note that in the description, few of these parameters are mentioned.
OK. We reviewed these sections to add these informations.

Furthermore, the last sentence of section 4 merits a detailed explanation and challenges the classification. In this sentence, the authors mention the real problem of the dependence of the defined parameters on the source to sensor distances and on the propagation media properties.
OK. We have rewritten this part of section 4 (Section 5. in the revised manuscript) to describe our approach to analyze the datasets and compare them (P10. l21-30).

5) Pag. 11. Explanations and description of the signals are very poor. Some explanations correspond to other cases. I include my comments about the case of RF (pag. 11) only as an example.
We reviewed these sections to add further informations.

Pag. 11 Line 2. Please, indicate if the rockfall was monitored. Information specific on this event is necessary.

OK. We added information about this event on the description of the datasets.

Line 5. What does it means:. energy below 10 Hz is present for volume larger than 1 m^3 (Fig 3a). Is this your case, because you mention this figure here?

It is not only the case of this specific event. We added references to support this statement in the next paragraph: *"The frequency content is also controlled by the block mass i.e. the frequency of spectral maximum energy decreases when the block mass increases (Farin et al, 2015; Burtin et al, 2016; Huang et al, 2007"*.

Line 7. The study of Farin et al., (2014) is an experiment in lab. and cannot be extrapolated to nature as it is observed (the high freq. disappear). This contribution is no relevant here.

OK. We removed this statement.

Line 9. P- and S- waves are hardly distinguishable. Is this in this specific case? You cannot generalize.

The statement is supported by different references.

Line 11. First arrivals are mainly impulsive. At the scale of representation I have to believe it.

We removed statements concerning the impulsive nature of the signals as it may vary from site to site.

Line 12. Figure 4 is incomplete. Information is required. If the signal belongs to a publication, the references must be included. Otherwise a comment is necessary.

The reference of the dataset from which the presented events are taken from are added in the caption when the presented (or similar events) have been published.

Line 13. Why do you suspect that the signals could be different if what you are recording is the movement of the mass falling down the slope? Normally, there is a time lag between ground and blast signals and the signals of the rock fall as observed in earlier publications.

We meant that natural rockfall are often composed of several falling blocks subject to break-up. In the case of the Riou-Bourdoux experiment only single block falls were monitored. It is true that in other studies when the rockfall is triggered from the rock cliff, very similar mechanisms and signals can be observed. We hence rephrased the sentence accordingly.

Lines. 18 and 20. Le Roy et al. 2017and 2018. Complete appropriately these references

OK. We have corrected the references.

Line 22. Burtin et al, 2016. This paper is devoted to torrential process. By the

way, the reasoning in the outlook section is of interest.
Fig1. of Burtin et al, 2016 shows the influence of the block mass on the frequency content even so, it is not discussed in the text. We added Huang et al, 2007 that discusses the same experiment.

Line 24. You mention "[...] may be emergent due to simultaneous arrivals of the waves". Explain this better. Do you mean that it could be interference between the impulses? What happens with the wave field? It also depends of the frequency content.
OK. We rephrased the sentence as: " [...] may be emergent due to simultaneous arrivals of waves generated by impactors of different sizes impacting the ground at closely spaced time intervals".

6) Figure 13 is perhaps one of most interesting figures but it must be better explained. As I mentioned before, small events must be avoided.
We enriched the discussion of this figure (P.16 l34 to P.17 l.7). We already respond to the "small events" issue in a previous comment. Basically, we selected events clearly above the noise level.

7) Pag. 16 Line 3-4. The authors justify the differences in the frequency content mentioning attenuation because of large distances, but this is not the case here because it is indicated in the paper and in the abstract that the signals are from events at r< 1 km. Is this consistent?
Attenuation is function of the distance and the wavelength of the seismic waves observed. c.f. previous response to comments of Reviewer #1. At our scale, "large distances" ranges from 100 m and more, depending on the magnitude of the source and the network geometry. One can clearly observed the influence of the distance in most the presented examples (Figures 3 to 11), even if the location of the source is not computed. Moreover, this comment is in contradiction with all the previous comments concerning the influence of the wave propagation on the recorded signals as a strong limitation of our study.

8) The term seismologically is not used correctly in the text. Replace it by seismic instruments. What does seismologically instrumented mean? In the world of seismologists the instruments are seismic instruments or not. They could have different resolution, characteristics, etc: : : "Seismologically" refers to a discipline, but not to the installation. Basically, the parameters you are considering are devoted to data processing signals and signal characteristics and not to wave transmission which is the subject of seismology. And as regards the installation, what does a non-seismologically installed seismic instrument mean?
OK. We corrected accordingly.

9) Pag. 16 line 19 and below. All this information devoted to harmonic signals in the discussion section is out of place. Moreover, it does not correspond to the data presented by you.

We present data from our gathered dataset. Except the one recorded at the Slumgullion landslide (Gomberg et al.), none of these signals have been published before. We discuss why we do not refer to these signals in the proposed classification.

10) Discussion. From line 19 to the end. The information provided does not correspond to a discussion of what is presented in the paper. It mainly concerns previous results without comparing them with the data presented in the manuscript.
We have thoroughly rewritten the discussion section.

Most of the sentences in the discussion could be included in the introduction, because the information is previous to the results presented in the paper and with little relation to them, at least in the present form.
We have rewritten the introduction and the discussion to take into account this comment and the previous ones.

Moreover, I do not understand why the harmonic signals are included in the discussion.
We discussed the harmonic signals in the Discussion section as we are not including them in the proposed classification whereas they have been presented in other studies. We find surprising that, on the one hand, reviewers reproach us not to compare our data to other and then, on the other hand, find the paragraph where we do this comparison not relevant.

11) As the authors mention on pag. 4 citing (Walter et al., 2017) in MS processing chains (by the way, I do not understand why you include this information in this section): "Many studies approximate the media attenuation field and/or the ground velocity, or do not take into account the topography, leading to mislocation of the events that prevents for accurate interpretation of certain sources and leads to false alarms". Is this the case of the data presented here?
We talked about location of the source which is an important information to associate the recorded signals to slope deformation. However, we mentioned here that location using attenuation law and assuming a homogeneous attenuation factor may lead to mislocation of the seismic events. Consequently, if the location error is of the same order of the distribution of geomorphological structures, it can be difficult to interpret the source of the recorded signals.
In the present study we did not locate the events and focus on the signals features that can be related to the seismic source mechanism. The later is discussed in each sub-classes presentation with reference to studies that modeled the seismic sources from the seismic signals or to studies that observe similar signals in different context (e.g. glacier motion).

12) Papers under revision although they are public must not be cited, nor must papers in volumes without a standard scientific recognition.
We cite posters and abstracts only to present the monitoring sites and/or the

datasets (Table 1 and Figure 2 to 10). We removed reference to posters/abstract when supporting statements in the text. For the papers under revision, we let the editor decides whether they should be included in the reference list (most of them being today accepted).

Some comments on the analyses of data. 13) As regards the tremor-like slope-quake (you do not mention this in this way in the title of figure caption of Fig. 12), the PSD is in the range of 8-13Hz, (not 10 Hz as mentioned) and the mean frequency of 20Hz is not clearly deduced from the plots.
OK. We corrected the description of this class and the caption.

14) Slope-quake with harmonic coda (H-SQ). I do not only observe the coda in the Chamousset signal (fig.10a) (note there is an error in this figure) of 08 August, but also in that of 6 October (fig. 11c). Super-Sauze site slope-quake signal of 24 Oct. (Fig. 10b) and the rock fall signal of 5 Nov (Fig. 4d) also present this behavior. This harmonic coda is present in different events. I think this is significant, and perhaps this is not related to the source but to the site effect for specific frequencies.
We agree that for this particular case, wave propagation could be a better explanation for the signal feature. Consequently, we removed this class from the classification and we discuss this signal feature in the new version of the discussion.

15) As regards all figures, but specifically Fig. 3 since it is the reference. Please, indicate the information contained in the plots in the figure caption. What is Amax? Is the parameter defined in section 4? It could be informative to show the maximum amplitude in ground speed units. What are the different traces in different colors shown in plot a? Indicate correctly the power of 10 (10 ˆx and not eˆx).
OK. We indicated that A_{max} refers to the maximum amplitude (nm/s). The different traces in different colors correspond to the other sensors present on the site, we added this comment in the caption. We modify the power accordingly.

Towards a standard typology of endogenous landslide seismic sources

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Abstract. ~~In the last decade, numerous studies focused on the analysis of seismic waves generated by Earth surface processes such as landslides. The installation of seismometers on unstable slopes revealed a variety~~

The objective of this work is to propose a standard classification of seismic signals ~~suspected to be generated by slope deformation, weathering of the slope material or fluid circulation. A standard classification for seismic sources generated by unstable slopes needs to be proposed in order to compare the seismic activity of several unstable slopes and identify possible correlation of the seismic activity rate with triggering factors. The objective of this work is to discuss the typology and source mechanisms of seismic events~~ generated by unstable slopes and detected at close distances (< 1 km)~~and generated by the deformation, failure or propagation of landslides. Seismic~~. We first review the different studies where seismic instruments have been installed at the slope scale. The choice of the seismic instruments and the network geometries are presented and discussed. To construct the proposed typology, seismic observations acquired at 14 sites are analyzed. The sites are representative of various landslide types (i.e. slide, fall, topple, and flow) and material (i.e. from unconsolidated soils to consolidated rocks). ~~The seismic networks installed on these sites are roughly similar (i.e. sensor , network geometry)~~ We investigate the 1-100Hz frequency band where most of the seismic energy is recorded at these sensor to source distances allowing comparison of the recorded seismic signals. Several signal properties (i.e. duration, spectral content and spectrogram shape) are taken into account to describe the sources. The signals properties are corrected from the sensor signal response and are computed in the same frequency band to enable comparison. We observe that similar ~~signals recorded~~ processes generate similar signals at different sites~~present the same properties. A typology is proposed and~~. Three main classes are proposed:“Slopequake”

gathering sources potentially occurring within the landslide body and “Rockfall” and “Granular Flow” gathering the seismic signals generated by deformation occurring at the surface of the landslide. Several sub-classes are proposed to differentiate specific signals properties (e.g. resonance, harmonic content,etc.). We describe the signal properties of each class and present several examples of signals ~~recorded at the different sites are presented. The similarity of the sources and their occurrence for several site configurations make it reasonable to infer the dominant source mechanisms~~of the same class recorded at different sites and discuss their potential sources. The proposed typology aims to serve as a ~~reference and a~~ framework for further comparisons of the endogenous micro-seismicity recorded on landslides. The signals discussed in the manuscript are distributed as supplementary material.

1 Introduction

Seismology can be used to record (remotely and in a non-invasive way) ground deformation processes and to measure stress/strain conditions through the hydro-mechanical interactions occurring in the media. Seismology is widely used to understand the physical processes taking place on tectonic faults or volcanoes, to investigate fluid reservoir ~~production~~circulation, and more recently to analyze the dynamics of Earth surface processes such as glaciers (?), snow avalanches ~~and landslides~~(?????) and landslides (????). In this manuscript, the term landslide describes a wide variety of processes resulting from the downslope movement of slope-forming materials by falling, toppling, sliding or flowing mechanisms (?). Thus, landslides cover a large range of deformation processes, that can be differentiated in terms of sizes and volumes (smaller than 1 ~~to~~ m^3 up to more than 10^7 m^3), in terms of displacement rates ($mm.yr^{-}1$ to $m.s^{-}1$), and in terms of mobilized material (hard/soft rocks, debris, poorly consolidated soils, and artificial fills).

~~The analysis of the seismic waves generated by landslides allow monitoring spatio-temporal changes of the stress-strain field in the material from the scale of microscopic internal damage (???) to the initiation (e.g. pre-failure) of large ruptures (????). Both the failure and the propagation of the mass generate seismic waves. Physical properties (mass, bulk momentum, velocity, trajectory) of the landslide can be inferred from the analysis of the seismic signals (??????). Thanks to the~~ With the increasing number of seismic sensors deployed worldwide and to the development of automatic seismological processing chains, the construction of landslide ~~regional~~ catalogs using seismology is now possible, especially at the regional scale (e.g. Switzerland, ~~??~~??; France, ~~?). Despite the aforementioned progress~~?). However, the forecast of a particular landslide rupture or acceleration is still challenging at the slope scale~~.~~

~~On clayey landslides, drop of shear wave velocity has been observed before acceleration episodes. This shear wave variation through time has been documented using noise correlation techniques for laboratory experiments (?), and for a few cases in the field at Pont-Bourquin landslide (Switzerland, ?), and at Harmaliére landslide (France; ?). Precursory seismic signals are also expected and documented before large failures. Repetition of seismic signals has been observed first before the fall of a coastal cliff (Mesnil-Val, France, ?) and more recently before the Rausu landslide (Japan, ?), the Nuugaatsiaq landslide (Greenland, ?) and the Askja caldera July 2014 landslide (Iceland, ?). For the rockslide collapse, the precursory events are assumed to be stick-slip events preceding the rupture but their locations and sizes remain unknown. Therefore, the monitoring~~

~~of endogenous micro-seismicity may represent a promising approach especially, with the advent of robust, cheaper and portable seismic sensors and digitizers. It is now possible to install dense sensor networks close to the unstable slopes and record low amplitude signals in broad frequency bands. A wide variety of unstable slopes are currently monitored (i. e. through permanent or campaign installation) with seismic networks of different sizes and instruments (Table 1). The further sections discuss the seismic instrumentation installed on landslides since the 1960s.~~

1.1 ~~Historical implementation of Acoustic Emission (AE) and Micro-Seismicity (MS) instrumentation~~

, which is the focus of this work. In the 1960s, ~~(?)~~ **?** observed an increase of Acoustic Emissions (AE) generated by slopes tilted towards failure at both laboratory and field scales. AEs are high frequency (10-1000 kHz) body waves generated by the release of strain energy through grain rearrangement (**?**). Further studies confirmed these results for several slopes ~~(????)~~ (**????**) where correlations between AE~~increase~~, surface displacement ~~increase~~ and heavy rainfall were ~~observed . AE can~~ documented. AEs record deep deformation processes before signs of displacement are identifiable at the surface. However, AEs are rapidly attenuated with the distance to the sources. The location of the sensors and the type of waveguide are also critical to capture the slope behavior. Recent developments of Fiber Optic Distributed ~~Acousting~~ Acoustic Systems (FO-DAS) offer the opportunity to overcome attenuation limitations and deploy measures over long distances (**?**).

More recently, several studies ~~investigated the~~ focused on the analysis of the micro-seismicity (MS) observed on unstable slopes. MS studies analyze the seismic waves generated ~~in low frequency ranges (1-500 Hz)~~ by the release of strain energy in the ground at larger scale than the grain to grain interactions in the frequency range of 1 to 500 Hz. The method offers the opportunity to remotely record the spatial distribution of the deformation through time (**??**) and is less sensitive to attenuation than AE methods. ~~(?) install~~ **?** installed seismometers on the Slumgullion slow-moving landslide (Colorado, USA) ~~slow-moving landslide, to describe the various recorded signals and to characterize the sources~~ in order to ~~retrieve~~ understand the mechanical processes taking place during landslide deformation. Further studies used the same method for several slope configurations (hard/soft rocks, soils, very slow to rapid movements) but also investigated the possible links between the displacement rate and the seismic energy release (**?????**). **?** correlated the seismic response of the Séchilienne rockslide with the surface displacement rate and the rainfall amount.

1.1 ~~MS processing chains~~

~~One of the current challenges for landslide MS analysis is the development of dedicated processing chains able to analyze the unconventional seismic signals observed on landslides . The three steps of MS processing are successively: the detection, the classification and the location of~~ The analysis of the ~~endogenous seismic events.The development of robust and versatile processing chains for analyzing landslide micro-seismicity is challenging because of 1) the small magnitude of~~ seismic waves generated by landslides allows monitoring spatio-temporal changes of the ~~events and the attenuation of the media that results in low Signal-to-Noise Ratio (SNR) records, 2) the seismic source radiation patterns that may be single centroid source, double couple source or volumetric source, and, 3)~~ stress-strain field in the material from the scale of microscopic internal damage (**???**) to the initiation (e.g. pre-failure) of large ruptures (**????**). Both the failure and surface processes (e.g. rockfall, debris flow) generate seismic waves. Physical properties (mass, bulk momentum, velocity, trajectory) of the landslide can be inferred from the analysis of the seismic signals (???????). On clayey landslides, drops of shear wave velocity have been observed before acceleration episodes. This shear wave variation through time has been documented using noise correlation techniques for laboratory experiments (?), and for a few cases in the field at Pont-Bourquin landslide (Switzerland, ?), at Harmaliére landslide (France, ?) and at Just-Tegoborze landslide (Poland, ?). Precursory seismic signals are also expected and documented before large failures. Precursory increase in micro-seismic activity (in terms of event rates and/or average amplitudes) has been observed first before the fall of a coastal cliff (Mesnil-Val, France, ?) and was interpreted as the propagation of a fracture. More recently, repeating events have been detected before the Rausu landslide (Japan, ?) and the Nuugaatsiaq landslide (Greenland, ?). These events are likely associated with the repeated failure of asperities surrounded by aseismic slip, driven by the acceleration of the ~~heterogeneity and variation in time (i.e. topography, water table levels, fissures) of the underground structure preventing the construction of precise velocity models and hence, accurate source locations. Regarding the first challenge of detecting the events, the use of spectrograms to detect manually or automatically seismic events is common. Spectrograms (or sonograms) represents the evolution of the frequency content in time by computing the Fourier Transform on small moving time windows (e.g. <~~ slope displacement during the nucleation phase of the landslide rupture. ? recorded harmonic tremors that started 30 min before the failure of the Askja caldera landslide (Iceland) with temporal fluctuations of resonance frequency around 2.5 Hz. This complex tremor signal was interpreted as repeating stick-slip events with very short recurrence times (less than 1 s) ~~. Automatic detection is usually achieved with the STA/LTA (Short-Term Average/Long-Term Average) detector (?) applied on the summed energy of the spectrogram (???). Second, classifying the detected signals can then be carried out automatically by discarding exogenous events with simple criteria (i.e. threshold on the signal duration, inter-trace correlation, apparent velocity) . Machine learning algorithms offer nowadays the possibility to automatize and improve this step. (?) developed a Hidden Markov Model (HMM)that can detect automatically in the time series the occurrence of one particular type of events. The success rate of HMM is reasonable and this technique has the advantage of requiring only one single example to scan the time series . The Random Forest algorithm has proven its efficiency for volcanic and landslide signals classification with higher success rate and versatility (??). New signals are successfully classified in multiple pre-defined classes and changes in the source properties may be detected by change on the uncertainties (?). It must be noticed that this approach requires a training set with sufficient elements to build the model. Good success rates (i.e. > 85 %) are rapidly reached with 100 elements or more per class.~~

~~Finally, the location of the sources is the final and probably most challenging step. Common location methods (such as NonLinLoc) were used in combination to 3D-velocity models for locating impulsive micro-earthquakes occurring at the Randa rockslide (?). However, a certain number of recorded signals do not exhibit impulsive first arrivals and clear P and S-waves onsets. For this kind of signal, location methods based on the inter-trace correlation of~~ producing a continuous signal. However, the characterization of the size of the asperity and the ~~surface waves (?) or on the amplitude (??) are more suitable and easier to automatize. However, they approximate the media attenuation field and/or the ground velocity, and often do not take into account the topography leading to mis-location of the events that prevents for accurate interpretation of certain sources and leads to false alarms (?). Other methods such as HypoLine (?) aim at integrating different strategies~~ velocity of the ruptures associated to these precursory signals are difficult to invert mostly because of the lack of dense seismic network at close proximity of the slope instability (?). Therefore, the monitoring of endogenous MS may represent a promising approach especially, with the advent of robust, cheaper and portable seismic sensors and digitizers. It is now possible to install dense sensor networks close to the unstable slopes and record low amplitude signals in broad frequency bands. A wide variety of unstable slopes are currently monitored (i.e. ~~first arrival picking, inter-trace correlation and beam-forming) to locate accurately the epicenter under the control of an operator. Provost et al., 2018 (in press)aimed at combining Amplitude Source Location (ASL) and inter-trace correlation of the first arrivals in an automatic scheme. This strategy showed accurate location of impulsive events while the error on the epicenter of emergent events is reduced by the use of ASL to constrain the location.~~ through permanent or campaign installation) with seismic networks of different sizes and instruments (Table 1).

~~Notwithstanding the number of studies on landslide MS, understanding the~~ Understanding the possible mechanisms generating these seismic signals needs to be achieved. The discrimination of the endogenous landslide seismic signals is difficult and need to be established. The objective of this paper is thus to propose a typology of the landslide micro-seismic signals ~~from seismic records~~ recorded in the field. The proposed typology is based on the analysis of ~~records from 13~~ observations from 14 monitored sites. The typology includes all the seismic sources recorded at near distances (< 1 km) and in the frequency range of MS studies (1-500 Hz), and generated by landslides 1) developed in hard/soft rocks and soils, 2) characterized by fragile (i.e. rupture) and ductile (i.e. viscous) deformation mechanisms.

In ~~this study~~our work, we first discuss all the physical processes that occur on landslides and may generate seismic signals. We further present the ~~seismologically-instrumented landslides in the world and describe the instrumentation~~available seismic sensors, the most commonly used network geometry and the instrumented sites. Then we establish a classification scheme of the landslide seismic signals from relevant signal features based on the analysis of the datasets of 14 sites. We further discuss the perspectives and remaining challenges of monitoring landslide deformation with MS approaches. The seismic signals associated with very large rock/debris avalanches and slides observed at regional distances are out of the scope of this work.

2 Description of landslide endogenous seismic sources

This section describes the possible ~~mechanical~~ hydro-mechanical processes observed on landslides and susceptible to generate seismic sources. We present the conditions ~~surrounding~~ controlling their occurrences (type of material, topography), their sizes, and their mechanical properties.

2.1 Fracture related sources

The term fracture denominates any discontinuous surface observed in consolidated media and originating from the formation of the rocks (i.e. joint) or the action of tectonic (i.e. schistosity), gravitational or hydraulic loads. In the case of slow-moving landslides, the propagation of the material also creates fractures ~~at~~ on the edge and at the base of the moving material.

Fractures occur in all type of materials at different scales from grain rupture to metric faults. The term fissure is sometimes used to describe fractures affecting the surface of the ground and for fractures affecting poorly consolidated material. We here include all these surface discontinuities under the general term ~~of~~ "fracture".

Fractures are generated in three basic modes (I: opening, II: sliding and III: tearing) depending on the movement of the medium on the sides of the fracture plane. They result from either brittle failure of the media or from dessication effects forming polygonal failures during soil drying. On landslides, most of the fractures occur in a tensile mode because of the low tensile toughness of the landslide material and the shallow depth (**?**). The formation of fractures can also be generated in depth by progressive degradation of the rock through ground shaking and/or through weathering and long-term damage due to gravitational load. At the base and on the edges of the landslide, the movement is assumed to develop fractures in shear mode, creating sliding surfaces.

Shearing on the fracture plane and tensile fracture opening/closing generate seismic signals. Shearing takes place at different scales from earthquakes on tectonic plates to grain friction and generates a variety of seismic signals (**?**). ~~Brief and impulsive~~ Unstable regime leads to stick-slip behavior where the stress is regularly suddenly released generating impulsive seismic events. Tremor like signals or isolated impulsive or emergent events are also generated during plate motions. This variety of signals ~~with clear phase onsets characterize most of the stick-slip events . They generate some of the deep icequakes recorded on glaciers (??????). Tensile fracture opening/closing generate similar signals on glacier at the surface and at depth (???). Focal mechanism and location of the source allow to differentiate between tensile and shear mechanism. Sliding can also produced tremor signals . They can be reproduced in laboratory experiments of plate sliding (?) but~~ are observed during glacier motion. Deep icequakes are usually associated to basal motion (**??????**). Tremor like signals are also recorded ~~on tectonic faults(?), during iceberg collision (?) and during~~ during glacier motion (**?**). They are characterized by long duration signals of low amplitudes with no clear phase onsets. They are associated with repetitive stick-slip events on the fracture plane. Tensile fracture opening/closing generate similar signals on glacier at the surface and at depth (**???**). Focal mechanism and location of the source allow to differentiate between tensile and shear mechanism.

2.2 Topple and fall related sources

On vertical to sub-vertical slopes, mass movement occurs as the topple of rock columns or as the free-fall (and possibly bouncing and rolling) of rocky blocks (**?**). In the case of toppling, the movement starts with a slow rotation of the rock blocks under the effects of water infiltration or ground shaking and ends with the free fall of larger blocks. Rockfalls, during the propagation phase, impact the ground at some location along their trajectory. These impacts generate seismic waves that can be recorded remotely by seismometers. The range of rockfall volumes can be very large, varying from less than one cubic meter to thousand cubic of meters.

2.3 Mass flow related sources

Mass flows gather different run-out processes of debris or of a mixture of water and debris. They cover a large range of volumes from large rock avalanches of several millions cubic meters to small (hundreds cubic of meters) debris falls and flows (**?**). They can occur in wet or dry conditions~~on low to steep slopes~~. The contacts of the rock/debris fragments with the bedrock and in the mass flow generate seismic radiations ~~(?????????)~~(??????????). The seismic signal is hence a combination of grain contacts within the granular flow and of grain to ground surface contacts and hence generate a complex seismic signal.

2.4 Fluid related sources

Hydrological forcing (e.g. precipitation, ~~snowmelt~~snow-melt) is one of the most common landslide trigger. The presence of fracture networks, water pipes and the heterogeneity of the rock/soil media result in the development of preferential water flow paths (**??**). These preferential flows induced local saturated area where the increase of pore water pressure may destabilize shallow or deep shear surfaces. In soils, the dissolution of material into finer granular debris creates weak zones prone to collapse either by suffusion (i.e. non cohesive material wash out under mechanical action) or by dispersion (i.e. chemical dissolution of fractured clay soils; Richards, Jones, 1981). In rocks, pipes may develop by erosion. In these saturated fracture networks, hydraulic fracturing can occur creating ~~low-frequency~~ earthquakes and harmonic tremors related to flow migration in the fractures ~~(??????)~~(??????).

3 Landslide ~~seismological instrumentation~~seismic investigation

3.1 Sensors used in landslide monitoring

Body and surface mechanical waves may be generated by the sources described in Section 2. Body waves (Primary -P-, Secondary -S-) radiate inside the media. P-waves shake the ground in the same direction they propagate while ~~S- waves~~ S-waves shake the ground perpendicularly to their propagation direction. Surface waves only travel along the surface of the ground and their velocity, frequency content and intensity change with the depth of propagation. Acoustic waves can be generated by the conversion of body waves at the surface. These waves travel in the air at a velocity of about 340 m.s^{-1}, slightly varying with temperature and air pressure. Acoustic waves are often generated by anthropic or atmospheric sources (e.g., gun shots, explosions, storms...), but can also be generated by rockfalls, debris flows or shallow fracture events. All these mechanical waves are subject to attenuation with the travel distance; ~~high frequency being~~ the high frequency waves are attenuated faster than the low frequency waves. The relatively low energy released by the landslide related sources makes the choice of the ~~seismological~~ seismic instruments to deploy very important. Four types of instruments are used to record ground motion for different frequency ranges and sensitivities. For landslide monitoring, Short-Period (SP) seismometers and geophones, Broad-Band (BB) seismometers, accelerometers, and AE sensors are commonly installed in the field.

- Broad-Band seismometers are force-balanced sensors with very low corner frequency ($<$ 0.01 Hz) that can record the ground motion with a flat response in a large frequency range [0.01-25] Hz. They require a careful mass calibration during their installation and are sensitive to temperature and pressure variations. They are mostly used to record very weak ground motion and ambient noise;

- SP-seismometers are passive or force-balanced instruments with high corner frequency (> 1Hz). They measure the velocity of the ground with high sensitivity and a flat response in the [1-100] Hz frequency band. They are recommended for volcanic and glacier monitoring among other applications. They are less sensitive to air temperature and pressure variations and do not require mass calibration. They are hence particularly suitable for landslide monitoring. Geophones are similar to ~~SP seismometers~~ SP-seismometers but usually cover higher frequencies [1-600]Hz with lower sensitivity. They are mainly used for active seismic ~~campaign~~ campaigns but may also be installed for the same purposes as ~~SP seismometers~~SP-seismometers;

- Accelerometers are strong motion sensors able to record high amplitudes and high frequencies seismic waves. They can resolve accelerations in the frequency bands from 0.1 to 10 kHz. The response of the sensor is proportional to ground acceleration for all frequencies (there is no corner frequency). But the noise level is important for low frequencies and the sensitivity is not as good as for velocimeters. They are used to record strong ground motion in ~~particularly~~ particular when installed close to epicenters (< 100 km) of large earthquakes where seismometers usually saturate. For landslide, they are usually used as inclinometers;

- AE sensors can record ground ~~vibration~~ vibrations at very high frequencies (10 kHz-10 MHz) and low ~~amplitude~~amplitudes. There are two types of AE sensors: the first type is very sensitive to a narrow frequency band only while the second type is sensitive to a broader frequency band (**?**). In the field, a waveguide is often installed together with AE ~~sensor~~ sensors in order to counteract the attenuation of the signal. They are ~~very often~~ used in combination with accelerometers for structural monitoring and for laboratory experiments (e.g. loading, shear, flume tests) and can be used on landslide to monitor very low magnitude sources at the grain-to-grain interactions (**???**)~~.~~ ;

- in addition, microphones or infrasound sensors can be useful to detect, locate and classify landslides seismic signals (**???**). The detection of acoustic waves and body waves at one point, because they propagate at different velocities, can be used to estimate the distance from the source. The relative amplitude of seismic and acoustic waves can also provide information on the depth of the source, because shallow sources generate more acoustic waves than deeper ones.

~~The choice of the instrumentation is very important when monitoring a slope.~~

It must be noted that AE sensors only record acoustic emissions generated at ~~less than few meters from the source due to the high attenuation of the high-frequencies.~~ very high frequencies (> 10kHz) and consequently are very sensitive to attenuation. Indeed, attenuation factor Q is estimated to range between 10^{-2} and 10^{1} dB.cm^{-1} (**?**). Even with a waveguide, they must be collocated with the cracks or the sliding surfaces observed on the slope ~~. In the contrary,~~ (**?**). BB, SP seismometers and geophones record seismic signals in the common band of 10^{0}-10^{2} Hz and hence offer a solution to monitor more distant sources. ~~BB seismometers can~~ The detection of a seismic sources by MS sensors depends on the seismic energy released by the source, the sensor to the source distance and the attenuation of the media. Installation of MS sensors at the proximity of the geomorphological features of interest (e.g. scarp, faults, sliding surfaces, superficial crack networks, etc.) optimize the detection of the seismic signals generated by those processes but distant sources (> 1 m) can also be recorded by MS sensors.

The latter do not need to be ~~used to explore the low-frequency. They also record higher frequencies although Geophones and SP seismometers~~ co-located with the geomorphological features of interest. After correcting the sensor response, the signals generated by these sensors can be analyzed and compared in their common frequency range. Installation of BB seismometers can complete SP network and enable to investigate the low-frequency signals generated by the slope while geophones are more adapted ~~and cheaper~~to explore very high frequency content ($>$ 100 Hz). Dense networks of the latter instruments are recommended to investigate the seismicity induced by landslide deformation while the installation of one unique BB seismometer is enough to investigate the low-frequency radiations of the landslide.

3.2 ~~Landslide instrumented sites~~Network geometry

~~Seismic networks have been installed on several unstable slopes worldwide since the initial study of **?**. Seismic observations can be analyzed using two approaches,~~

Several network configurations have been tested in different studies. It must be noted that the network geometry in the case of landslides is constrained by the site configuration. Indeed, the maintenance of seismic sensors is very challenging when installed on the moving parts of the landslide; therefore, an installation on the most stable parts of the landslide or at its vicinity is often preferred for permanent monitoring (**???**). During field campaigns, maintenance of sensors installed on the unstable slopes is possible and often realized (**???**). Therefore, the main challenges for seismic sensor installation at this scale is 1) to locate the sensor at close distance to the sources, 2) to maximize the number of stations and to locate the sensor close to each other to record the same event at different seismic station and 3) minimize the azimuthal gap between the sensors. The number of deployed sensors plays an important in the magnitude of completeness (M_c) of the seismic network. While the geometry of the network (i.e. inter-sensor distances, azimuthal gap) mostly control the accuracy of source locations.

Seismic sensors can be deployed in network of single sensors or network of sensor arrays. The difference between seismic network and seismic arrays is related to the distance at which the signals recorded by two sensors can be correlated. In the case of seismic arrays, the distance between the sensors is reduced to maximize the correlation of the signals recorded by each sensor. Otherwise the installation is called a seismic network **?**. Although the inter-sensor distance is often small ($<$ 1 km) in the case of landslide monitoring, decorrelation of the signals is often observed even at small distances due to the complexity of the underground structure especially at high frequencies. The use of the "seismic array" approach in landslide monitoring often refers to specific geometries of collocated sensors (inter-sensors distances $<$ 50 m) organized with a central sensor (often a three-component seismometer) and several satellite sensors (often vertical sensors). This kind of installation presents many advantages such as enhancing the Signal-to-Noise (SNR) ratio and allowing the computation of the back-azimuth of the source with beam-forming methods.

For the majority of the instrumented landslides, seismic networks are organized with single sensors located on or at close distance of the unstable slopes. The inter-sensors distance and the azimuthal gap are often controlled by the location of easily accessible or stable portions of the slopes. However, specific geometry can be adopted such as (almost) linear geometry. This is particularly the case for the monitoring the propagation of debris flows in stream channels. Dense networks (number of sensors $>$ 50) can also be deployed. In this case the sensors are installed using a grid geometry with regular inter-sensor distances.

This kind of installation is probably the most optimal but is currently mostly realized during short acquisition campaigns due to the difficulty to maintain a large number of sensors over long periods (battery, data storage, possible movement of the sensor), especially when installed directly on the unstable zones of landslides. Finally, the installation of sensors at depth ($>$ 1 m) is challenging for landslide and it has currently only been realized on hard-rock slopes (e.g. ~~micro-seismicity analysis and seismic noise analysis. The first approach consists of cataloging the seismic signals triggered by the slope deformation, locating these sources and correlating the spatio-temporal occurrence to different deformation patterns. The second approach consists of analyzing the seismic noise. The resonance frequency of the noise can be related to the rigidity of the unstable mass and thermal forcing and the correlation between different sensors can be used to estimate the surface wave velocity and its evolution in time (?, and references therein).~~ Randa, **?** or Séchilienne, **?**). This kind of installation are however very valuable to constrain the depth of the sources.

3.3 MS processing chains

One of the current challenge for landslide MS analysis is the development of dedicated processing chains able to analyze the unconventional seismic signals observed on landslides. The three steps of MS processing are successively: the detection, the classification and the location of the endogenous seismic events. The development of robust and versatile processing chains for analyzing landslide micro-seismicity is challenging because of 1) the low magnitude of the events and the attenuation of the media that results in emergent and low Signal-to-Noise Ratio (SNR) records, 2) the seismic source radiation patterns that may be single centroid source, double couple source or volumetric source, and, 3) the heterogeneity and variation in time (i.e. topography, water table levels, fissures) of the underground structure preventing the construction of precise velocity models and hence, accurate source locations.

First, for detecting automatically or manually the seismic events, the use of spectrograms is common. Spectrograms represent the evolution of the frequency content in time by computing the Fourier Transform on small moving time windows (e.g. $<$ 1 s). Automatic detection is usually carried out with the STA/LTA (Short-Term Average/Long-Term Average) detector (**?**) applied on the summed energy of the spectrogram (**???**).

Second, classifying the detected signals can be carried out automatically by discarding exogenous events with simple criteria (i.e. threshold on the signal duration, inter-trace correlation, apparent velocity) but the determination of the threshold to differentiate the class of signals may be difficult. Machine learning algorithms offer nowadays the possibility to automatize and improve this step. **?** developed a Hidden Markov Model (HMM) that can detect automatically in the time series the occurrence of one particular type of events. The success rate of HMM is reasonable and this technique has the advantage of requiring only one single example to scan the time series. The Random Forest algorithm has proven its efficiency for volcanic and landslide signals classification with higher success rate and versatility (**??**). New signals are successfully classified in multiple pre-defined classes and changes in the source properties may be detected by change on the uncertainties (**?**). It must be noticed that this approach requires a training set with sufficient elements to build the model. Good success rates (i.e. $>$ 85 %) are rapidly reached with 100 elements or more per class. Template-matching filters have also been used in many studies of landslide collapse and glaciers (**???????**) in order to detect and classify seismic signals. This method consist in scanning continuous data to search for signals with waveforms similar to template signals. It can detect seismic signals of very small amplitude, smaller than the noise level. Seismic signals are grouped in clusters of similar waveforms, implying similar source locations and focal mechanism.

Finally, the location of the sources is the most challenging step. Common location methods (such as NonLinLoc; (**??**)) were used in combination to 3D-velocity models for locating impulsive micro-earthquakes occurring at the Randa rockslide (**?**). However, a certain number of recorded signals do not exhibit impulsive first arrivals and clear P- and S-waves onsets. For this kind of signal, location methods based on the inter-trace correlation of the surface waves (**?**) or on the amplitude (**??**) are more suitable and easier to automatize. Other methods such as HypoLine (**?**) aim at integrating different strategies (i.e. first arrival picking, inter-trace correlation and beam-forming) to locate accurately the epicenter under the control of an operator. Provost et al., 2018 (in press) developed a method combining Amplitude Source Location (ASL) and inter-trace correlation of the first arrivals in an automatic scheme. This strategy showed accurate location of impulsive events while the error on the epicenter of emergent events is reduced by the use of ASL to constrain the location. Many studies approximate the media attenuation field and/or the ground velocity, or do not take into account the topography, leading to mis-location of the events that prevents for accurate interpretation of certain sources and leads to false alarms (**?**).

3.4 Instrumented sites

In the last two decades, seismic networks have been installed on several unstable slopes worldwide. Table 1 synthesizes the unstable slopes or debris flow prone catchments instrumented with ~~seismological~~ seismic sensors worldwide. The sites are classified in terms of landslide types (i.e. slide, fall and flow) according to the geomorphological typology of Cruden (1996) (**?**). Studies on snow avalanches (**?????**) are not integrated. Most of the instrumented sites are located in the European Alps (France, Italy and Switzerland). Short-Period (SP) seismometers and Geophones (G) are the most common type of instruments. Their installation and maintenance is easy as they do not require mass calibration in comparison to Broad-band (BB) or long-period (LP) seismometers. ~~Seismological networks installed on unstable slopes are often designed as terms of clustered arrays of a minimum four seismometers. The common geometry of these types of arrays consists in one central three component SP seismometer at the center of three (or more) vertical component SP seismometers. This geometry enables a better identification of the source azimuth with a Beam-Forming location method and increases the number of sensors recording the events (?????).~~

4 ~~Landslide seismological observations and processing methodology~~

~~The methodology used to propose a reference typology of landslide endogenous seismic sources is based on the comparison of seismic signals recorded at different sites. Nine signal parameters are quantified; then the signals with similar properties are clustered in classes~~

4 Data

Seismic observations from 14 sites are used to propose the typology. The sites are representative of various types of slope movements and lithology (Table 1) with four slides occurring in hard rocks, four slides occurring in soft rocks, three rockfall-prone cliffs occurring in hard and soft rocks and one catchment prone to debris flows. The seismic instruments installed on these sites are recording the seismicity generated by the slope deformation and are installed either permanently or were acquired during short campaigns (Table 1). The Riou-Bourdoux catchment is the only site where the seismic signals were manually triggered as rock blocks were thrown down the cliff and monitored with cameras, LiDAR and seismic sensors (**?**).

4.1 ~~Data~~

~~Seismological observations from 14 sites have been used to propose the typology (Table 1~~The dimension of the unstable slopes range from 60 m $\times$ 30 m for the Chamousset cliff to 7 km $\times$ 300 m for the St.-Eynard cliff (Table 2). The ~~sites are representative of various types of slope instabilities and rocks. For all sites, the instruments are deployed close to the landslide. The instruments are mainly~~ seismic networks are deployed with various geometry depending on the configuration of the slope, its activity and the duration of the installation. For most of the sites, at least one seismic sensor is deployed on the active zone or very close to (Table 2). The maximal distance to the slope instabilities is 500 m for the St.-Eynard cliff being the largest investigated site of our study.

The seismic network geometry of the majority of sites are distributed seismic network where sensors location are regularly installed over the active zone or at its vicinity. In the case of the Rebaixader catchment, the seismic network is installed at the border of the stream channel almost linearly. At the Slumgullion landslide, a dense network has been installed with regular spacing of the seismic sensors. Seismic arrays are installed at the other sites. The geometry of the seismic arrays are triangular shape with the exception of the Séchilienne landslide where an hexagonal shape is used.

The instruments are mostly SP seismometers with ~~short sensor-to-sensor distances and~~ cut-off frequencies of 1 Hz to 5 Hz ~~. Certain networks are deployed permanently and are used as reference to document the evolution of the seismogenic landslide activity over time (e. g. France, **?** ; Switzerland, **??**). Other networks are deployed for campaign measurements in order to document specific activity periods (e.g. acceleration). Controlled rockfall experiments have also been monitored with seismic networks (**?????**) but are not presented in table 1.~~ and 50 to 100 Hz. Fewer geophones and BB seismometers are installed at the sites. The instrument response is corrected for all the dataset. To be consistent with the sensitivity of all the sensors, we do not investigate the data below 1 Hz for BB seismometers and above 100 Hz for SP seismometers and geophones.

4.1 ~~Methodology: seismic features~~

The dataset being analyzed is composed of either published seismic events or published catalogs. The comparison of these events and catalogs enable to compare the signals and to compose the classes of the typology. In the case that no published events or catalogs are available, we analyzed manually the dataset to complete the number of examples for each proposed class (see Section 5 for detailed information).

~~The classification of the landslide seismic sources is~~

5 Methodology

The seismic signals recorded at different sites are compared in order to identify common features. Seismic signals result from the convolution of both the wave propagation and of the seismic source mechanism. Consequently, the observation of common signal features in signals recorded at different sites can only be explained by similar source mechanisms. The proposed typology is hence based on the ~~description of the signals with nine parameters~~ analysis of these common features. We then selected nine signal features in order to quantify the differences and similarities between the different classes. The nine parameters are chosen because they correspond to the criteria used by experts to analyze and classify a seismic signal and also because they can be used in automatic classification algorithms (**??????????**). They can be computed for any signal types and present a robust framework for future comparison. The selected signal features are:

- the duration of the signal T (expressed in second), computed on the stacked spectrogram of the traces (**?**).
- the dissymetry coefficient of the signal (expressed in percent), computed as:

  $$s = \frac{t_m - t_1}{t_2 - t_1} \times 100 \tag{1}$$

  with t_1, t_2 and t_m the time of the signal onset, ending and maximum respectively.
- the number of peaks of the signal envelop N_{peaks}, computed as the number of local maximum above 50% of maximal value of the signal envelop. The envelop of the signal is computed as the absolute value of the Hilbert transform of the signal. The envelop is smoothed by a computing the average of on a moving window of length: $\delta t = \frac{100}{f_s T}$.
- the duration of the signal auto-correlation, defined as:

  $$A_{max} = \frac{t_c}{T} \tag{2}$$

  with,

  $$t_c = \max_t (C(t) < 0.2 * max(C)) \tag{3}$$

  with ~~C~~ C equal to the signal auto-correlation. A_{max} is expressed in percent (%) and represents the duration of the signal correlating with itself. As an example, a signal with a rapid and abrupt change in frequency content will rapidly be uncorrelated (low A_{max}) while a signal with a constant frequency content will have a long auto-correlation (high A_{max}).
- the mean frequency (expressed in Hertz), computed as:

  $$F_{mean} = \frac{\sum_{i=1}^{N} PSD(f_i) f_i}{\sum_{i=1}^{N} PSD(f_i)} \tag{4}$$

with the Power Spectral Density (PSD) defined as:

$$PSD(f) = \frac{2|FFT(y)|^2}{Nf_s} \frac{2|FFT(y)|^2}{Nf_s} \tag{5}$$

with f_s and N being the sampling frequency of the signal and the number of samples respectively. The mean frequency is chosen here as it more representative of the signal spectrum energy and less sensitive to noise than the ~~maximum frequency~~ frequency of maximum energy. (**?**).

- the frequency corresponding to the maximal energy of the spectrum F_{max} (expressed in Hertz).

- the frequency bandwidth F_w defined as:

$$F_w = 2\sqrt{\frac{\sum_{i=1}^{N} PSD(f_i) f_i^2}{\sum_{i=1}^{N} PSD(f_i)} - F_{mean}^2} \tag{6}$$

- the minimal frequency of the signal spectrum, computed as:

$$f_{min} = \min_f (PSD(f) < 0.2 \times \max(PSD)) \tag{7}$$

- the maximal frequency of the signal spectrum, computed as:

$$f_{max} = \max_f (PSD(f) < 0.2 \times \max(PSD)) \tag{8}$$

the maximal frequency of the signal spectrum f_{max} (not to be confused with parameter F_{max} defined above).

~~These nine parameters are chosen because they correspond to the criteria used by experts to analyze and classify a seismic signal and also because they can be used in automatic classification algorithms (**??????????**). They can be computed for any signal types and present a robust framework for future comparison. Moreover, recently use of Random Forest algorithm makes it possible to confirm the utility of this choice (**??**). Most of these parameters are dependent on the source sizes, the source to sensor distances and the media properties (attenuation, dispersion). The attributes are~~ The signal features are always computed on the trace with the maximal amplitude ~~bandpassed~~ band-passed in the range [~~1-50~~f_c-50] Hz ~~enabling both~~ (f_c: cut-off frequency). This enables to limit the influence of the wave propagation and to compare signals with different sampling frequencies (i.e 120 Hz to 1000 Hz).

Based on already published events and further interpretations, we propose a standard classification of landslide endogenous seismic sources. The non-published datasets are used to investigate the presence of these signals at other sites and to increase the number of examples for different contexts. Numerous signals were analyzed to draw the proposed classification and selected examples are further presented to describe the different classes.

6 Seismic description of the signals - typology

The typology of the signals is ~~mainly~~ based on the duration and the frequency content of the seismic signals. The signals are classified in three main classes: “Slopequake” (SQ), “Rockfall” (RF) and “Granular flow” (GF)~~signals~~. For “Slopequake”, sub-classes are proposed and discussed based on the frequency content of the signals. Several examples of signals recorded at different sites are presented and the sources are discussed in the corresponding section.

6.1 Rockfall (RF)

~~Figure~~ Fig 2 displays the seismic waves recorded for a single ~~rock~~ block fall at the ~~Rioux-Bourdoux~~ Riou-Bourdoux catchment (French Alps~~; ?~~). The block was manually launch in the catchment and recorded with seismic sensors and cameras (**?**). The signal is characterized by successive impacts visible both on the waveform and on the spectrograms ~~. Depending on the height of the cliff, the signal lasts between 5s and tens of seconds~~and lasts around 20 s. The spectral content contains mostly frequencies above 10 Hz ~~. However,~~ but energy below 10 Hz is present for certain impacts ~~for rocks with volumes larger than 1 m^3 (Figure~~ (Fig 2a). At closer distance, very high frequencies can be recorded up to 100 Hz (~~Figure~~ Fig 2a). ~~Theoretically, the corner frequency of such events is expected between 100 Hz and 500 Hz depending on the attenuation of the media (**?**) but in most of the cases the attenuation of the medium eliminates frequencies greater than 100 Hz. Little energy is recorded for frequency below 10 Hz.~~ The auto-correlation remains large over time due to the similitude of the individual impacts signals ($T_{corr} > 10\%$). P- and S- waves are hardly distinguishable on the record and the signals recorded at the seismic sensors are dominated by surface waves ~~(**????**). The first arrivals are mainly impulsive.~~ (**????**).

Seismic signals of natural masses detaching from cliffs are presented in ~~Figure~~ Fig 3. They present similar characteristics ~~than~~ to the artificially triggered rockfall. ~~The highest measureably~~ Depending on the height of the cliff, the signal lasts between 5 and tens of seconds. The symmetry of the signal ranges from 0 to 80 % depending on the cliff configuration. In general, the most energetic impacts are recorded at the middle or after the middle of the signal (skewness > 50%). The highest measurable frequency depends on the source-to-sensor distance ~~.~~ and can be very high (> 100 Hz). The spectral energy is concentrated in frequencies above 5 Hz, with the largest PSD values (F_max) ranging from 20 to 40 Hz. Generally, the Power Spectral Density energy is low below 10-15 Hz with the exception of some case (Fig 5.c) where spectral energy can be observed. The initial falling masses can themselves broke into smaller units during propagation. In this case, the signal does not return to the noise level between the impacts due to developing granular flow (~~Figure~~ Fig 3b,e,f) leading to the decrease of the duration of the auto-correlation of the signal. When several blocks are falling at the same time, impacts may overlap, so do the peaks of the signals. In certain cases, the first rock free-fall is preceded by a signal that can be associated ~~to~~ with the rock detachment. An example of this precursory signal can be observed in ~~Figure~~ Fig 3a,f and in (**??**). The seismic signals of rockfalls contain information ~~of~~ on the physics of ~~these phenomenon~~the process. The seismic energy of rockfall signals ~~has been shown to be~~ is proportional to the volume (**??**). Scaling laws are also ~~shown in the case of block falls~~ established between seismic energy, momentum, block mass and velocity before impacts (**?**). The frequency content is ~~also~~ mainly controlled by the block mass~~(**??**). If the block falls~~ . The frequency of the spectral maximum energy decreases when the block mass increases (**???**).

If the rockfalls are well isolated, each impact generates impulsive waves. In the case of multiple ~~block falls~~ rockfalls or short distances between the seismic ~~source and the sensor~~sources and the sensors, the first arrivals may be emergent due to ~~the~~ simultaneous arrivals of ~~the waves~~ waves generated by impactors of different sizes impacting the ground at closely spaced time intervals (**??**).

6.2 Granular Flow (GF)

Granular flows are characterized by cigare-shape signals lasting between tens to thousands of seconds. They are subdivided in two classes:

- **Dry ~~Granular~~ granular flow** (~~Figure~~ Fig 4): ~~They~~ These signals are characterized by cigare-shape waveforms of ~~relatively~~ long duration (< 500 s)~~due~~. Due to the absence of water~~the source propagate on~~, the source generally propagates over small distances. ~~when the signal is not filtered, no~~ The duration of auto-correlation is very weak (T_{corr} ≈0%) and no seismic phase can be distinguished. No distinguishable impacts can be observed in the waveform nor in the spectrogram ~~, in contrast to rockfall signalsalthough amplitude spikes may be visible. The~~ at the opposite of rockfall signals. The signal onsets is emergent and P- and S- waves are hardly distinguishable and the signal is dominated by surface waves (Deparis et al., 2008; Dammeier et al., 2011; Helmstetter and Garambois, 2010; Hibert et al., 2014; Levy et al., 2015).The dissymetry coefficient of the signal varies between 30% and 75% and depends on the acceleration and the volume of mass involved in the flow through time (**?????**). The ~~autocorrelation decreases rapidly in the first third of the signal duration. The~~ frequency ranges from 1 to 35 Hz. The ~~mean~~ maximal frequency of the PSD varies between ~~5Hz~~ 5 and 10 Hz and can be larger (up to 20 Hz) when the seismic sensors are located close to the propagation path. The ~~auto-correlation is very weak with T_{corr} =0%) and no seismic phase can be distinguish~~PSD values are significantly low below 3 Hz and incrase rapidely between 3 and 20 Hz.

- **Wet ~~Granular~~ granular flow** (~~Figure~~ Fig 5): These signals last several thousands of seconds to several hours and correspond to debris flows. They occur during rainfall episodes when fine material and boulders ~~run down the stream~~ propagates downstream over long distances (> 500 m). Like dry granular flow, the duration auto-correlation is very weak (T_{corr} =0%) and no seismic phase can be distinguished. The seismic sensors are often installed at very close distance to the flow path so high frequencies up to 100 Hz may be recorded (**???**). Little energy is present in the low-frequencies (< 10 Hz) depending on the amount of water and the size of the ~~size of the rock blocks involved~~ rocky blocks integrated in the flow (**?**). The signal is emergent and the amplitude variation ~~correspond to~~ depends on the mass involved in the flow passing in the vicinity of the sensor. Debris ~~flow~~ flows are very often divided in a front with the largest boulders and the highest velocity followed by a body and a tail where the sediment concentration and the velocity ~~progressively decrease~~ decreases (**?**). The seismic signal amplitude hence increases progressively as the front is passing ~~in~~ at the vicinity of the sensor (**????**) and ~~decrease~~ decreases progressively, as the front is moving away from the sensor (skewness $>$ 50%). Large spikes and low-frequencies may be observed in the seismic signal corresponding to the front of the debris flow generated by large boulders impacts. The frequency content also changes and, progressively, energy in the lower frequencies decreases (~~Figure~~ Fig 5.a). ~~The auto-correlation is very weak with T_{corr} =0%) and no seismic phase can be distinguish.~~

6.3 Slopequake (SQ)

The "Slopequake" class gathers all the seismic signals generated by sources located within the slope at ~~its~~ the sub-surface or ~~in~~ at depth such as fracture related sources or fluid migration (cf. section 2). ~~They are mainly~~ Different names have already been proposed for this kind of signals: "slidequakes" (?), "micro-earthquake" (??), "quakes" (??) or "Landslide Micro-Quake (LMQ)" (?). We here proposed the term "Slopequake" as a general name for these events. They are characterized by short duration ($<$ 10 s) ~~. They~~ and are sub-divided in two classes "Simple" and "Complex".

6.3.1 Simple Slopequake

~~The first class~~ "Simple Slopequake" ~~of short duration signals is characterized by short~~ signals are of short ($<$ 2 s) to very short duration ($<$ 1 s) signals. Their main ~~characteristic~~ feature is the triangular-shape of the spectrogram with largest amplitudes being recorded in the first part of the signal (skewness $<$ 50%). The first arrivals contain the highest frequencies of the signal and are followed by a decrease of the frequencies. Depending on the frequency content, these signals can be sub-divided into three classes:

- **Low-Frequency Slopequake (LF-SQ)** (~~Figure~~ Fig 6): The signal ~~last~~ lasts between 1 and ~~5s~~5 s. The maximal amplitude of the signal waveform occurs at the beginning or at the center of the signal (15% $<$ ~~s~~ skewness $<$ 50%). The waveform presents only one peak and most of the first arrivals are emergent. Phase onsets are difficult to identify. The signals ~~seem to be~~ are mostly dominated by surface waves. Consequently, the duration auto-correlation of the signals is large ($>$ 10%). The largest PSD values are observed between 5 and 25 Hz with a mean frequency ranging between 10 and 15 Hz.

- **High-Frequency Slopequake (HF-SQ)** (~~Figure~~ Fig 7)): The signal ~~is very brief (<~~ lasts between 1 ~~s) and energetic~~and 5 s. The maximal amplitude of the signal waveform occurs close to the beginning of the signal (~~s~~ skewness $<$ 30%). The waveform presents only one peak and ~~most of~~ the first arrivals are ~~impulsive. Although, the beginning of some of the signal becomes emergent with the distance and the maximal amplitude is shifted to the center of the signal (Figure 7).~~ mainly impulsive. Different phases may be observed (??): P-arrivals are detected at the beginning of the signal and correspond to the high frequency waves, surface waves are then observed at the time the frequency decreases. However, in general the short sensor to source distance makes difficult the differentiation between the different seismic phases. The auto-correlation these signals is hence lower than for LF-SQ ($<$ 10 %). In most of the cases, the picking of the different waves onset is made difficult because of the ~~sensor to source distances . The travel-time difference between the different wave onsets is very short (<~~ sensor-to-source distances and the low frequency sampling. The largest PSD values are observed between 3 and 45 Hz with a mean frequency ranging between 20 ~~ms) in most of the cases and body and surface waves may be difficult to identify. It results from the fact that most of the studied landslides (especially for~~

~~soft-rock landslides) present shallow basal surfaces and most of the sources are very weak (M_L <0) so they can only be recorded at really close distance.~~ and 30 Hz.

- **Hybrid Slopequake (Hybrid-SQ)** (~~Figure~~ Fig 8)): The signal ~~last~~ lasts between 1 and ~~2s~~2 s. It presents the characteristics of the two precedent signals. The brief first arrivals are very impulsive and last less than one second. They are followed by a low-frequency coda similar to the ~~Low-frequency slopequake~~LF-SQ. The maximal amplitude of the signal waveform occurs close to the beginning of the signal (~~s~~ skewness $<$ 40%). The waveform presents only one peak and the first arrivals are impulsive. ~~P-waves and surface waves can be easily identified.~~

~~Simple slopequakes were already presented under different names "slidequakes" (**?**), "Micro-earthquake" (**??**), "quakes" (**??**) or "landslide Micro-Quake (LMQ)" (**?**). We here proposed the term "Slopequake" as the general name for these events. They~~ These signals are suspected to be associated to ~~bounder~~ boundary or basal sliding (**????**) or fracturing of the slope ~~(**?**).~~

~~Hybrid slopequakes are very similar to the events recorded on volcanoes and glaciers with the presence of fluids in conduits or crevasses (**?**). The source of this event is assumed to be related to hydro-fracturing. The first high-frequency events corresponding to a brittle failure followed the flow of the water into the newly opened cracks (**??**).~~

~~Presently,~~ (**??**). Currently, only few studies have proposed inversion of the source tensor (**?**). ~~Therefore, the focal mechanism of the sources remain uncertainly known. Consequently, it remains undertermined if the Low-Frequency slopequakes are distant slopequakes (HF or Hybrid) or not. The lack of high frequencies may be explain either by attenuation during propagation of the seismic waves or by the source itself~~To the best of our knowledge, for soft-rock landslides, no source mechanism was modeled. Therefore, it remain difficult to set if the observation of LF- and HF-slopequakes is due to attenuation of the high frequencies with the distance or to the source mechanism. Indeed, the rupture velocity may explain the difference of frequency content ~~. Low-frequency earthquakes are generated~~ and low-frequency earthquakes are observed on tectonic faults (**???**). They are characterized by low magnitude ($M_w < 2$) and short duration ($<$ 1 s) and constitute at least part of the seismic tremor signal. Therefore, the main assumption for the source of these events are slow rupture (**?**). ~~LF-Slopequake may also be distant Mix-slopequake due to high attenuation due to highly fractured areas (**???**). Finally, in glacier, low frequency icequakes~~ Another interpretation for the low frequency quakes dominated by surface waves ~~are interpreted as surface sources generated by crevasse opening (**??**)~~is crevasse opening (at the surface) as observed in glacier (**??**). (**?**) analyzed AE at laboratory scales generated during thermal fracturing. During this experiment, high-frequency AEs are recorded during the heating stage up to the failure of the rock sample and are interpreted as thermal cracking events (**?**). Low-frequency AEs are recorded during cooling stage (after failure) and are associated to stick-slip events (**?**).

Hybrid slopequakes are very similar to the events recorded on volcanoes and glaciers with the presence of fluids in conduits or crevasses (**??**). The sources of these events are assumed to be related to hydro-fracturing. The first high-frequency events corresponding to a brittle failure is followed by water flow into the newly opened cracks (**??**).

6.3.2 ~~Complex Slopequake (CQ)~~

The frequency content depends on the sensor to source distance and on the source mechanism. Observation of LF- and HF-SQ may be the signature of on-going processes taking place within the slope instabilities justifying the three proposed classes for simple slopequakes.

6.3.2 Complex Slopequake

The second class of short duration signals has the same general properties than the ~~Simple Slopequakes~~ simple slopequakes but exhibits particular frequency content or precursory events. These additional characteristics change the possible interpretation of the sources. Consequently, these signals are gathered in ~~anoter~~ the class "Complex Slopequake". Three different sub-classes ~~can be built~~are proposed:

– ~~**Monochromatic slopequake (Mono-SQ)** (Figure ??): The first type of Complex Slopequake signals present an almost monochromatic frequency content with no harmonic. The signals are almost symmetrical and no fracture event is observed at the beginning which differentiate them from Mix-SQ. Conversely to the LF-SQ, their frequency bandwidth is narrow. In the case of Slumgullion (Figure **??**.b), 90 repeaters of this event were measured during the month of observation (**?**). The fundamental frequency is 11.9 Hz with a standard deviation of 0.7 Hz computed from the stack of the signals with a correlation coefficient higher than 0.7 (**?**). The authors argued that the resonance is a property of the source considering the stability of the fundamental frequency through time and the absence of anthropogenic sources in the vicinity of the landslide. They hypothesize that the waves were trapped along the side-bounding strike-slip fault generated by shear events. The location of the source, the distribution of the amplitude, the stability of the fundamental frequency and the daily temporal occurrence of the source supports this assumption. Similar kind of events occur at the Super-Sauze landslide.~~

– **Slopequake with ~~harmonic coda (H-SQ)~~precursors** (~~Figure~~ Fig 9): ~~These signals present a nearly monochromatic coda at high frequencies (i.e. 20 and 43Hz). The resonance is not present before the beginning of the signal and hence can not be due to anthropogenic noise (i.e. motors). In the case of Chamousset (Figure 9.b), the presence of this monochromatic coda is explained by the resonance of the rock column after the occurrence of the rock bridge breakage **?**. The resonance coda is rapidly attenuated with the distance and is not recorded by all the sensors (**?**). Considering the distance between the main scarp and the seismic arrays (> 300 m) at the Super-Sauze, similar resonant coda are observed at the end of certain rockfalls (Figure 3.d). The occurrence of this kind of resonance is very surprising in this case.~~

– ~~**Slopequake with precursors** (Figure 10): The~~ The third class of short duration signals are similar to the slopequake signals but are preceded by a precursory signal of smaller amplitude (~~Figure 10~~Fig 9). The content of the precursory signal ranges from 5 to 100 Hz depending on the site and is slightly lower than the highest frequency generated by slopequake-like event. The precursory arrival last up to 1.2 s in the presented examples and no clear phases are detected. The frequency content ranges from 5 to 100 Hz but varies significantly at each site. At all sites, the amplitude of the signal is significantly higher for one of the sensor (3 to 50 times higher) when considering vertical traces. The precursory signal is buried in the noise at the sensors with lowest amplitudes and the signal is similar to a LF-slopequake. Such events have never been documented to our knowledge. They are likely to be generated by a strong and local source located at the very close vicinity of one of the sensor (< 10 m) due to the maximal amplitude ($> 10^5$ nm.s^{-1}) and the rapid decrease of the amplitude recorded by the other sensors. Although the signal is similar to certain earthquakes (the precursory signals interpreted as P-waves arrivals and the strong arrivals as surface waves), no earthquake location can explain the signal recorded at the time these events are recorded. Their occurrence in the night time also prevent any human activity to be the source. The most probable source would then be the detachment of a single block and its fall in the vicinity to one of the sensor. This kind of precursory signals are observed for some rockfalls (~~Figure~~ Fig 3.a) and at a the Saint-Martin-le-Vinoux quarry (France; ~~?~~**?**). At the Saint-Martin-le-Vinoux underground quarry, the duration between the detachment and the signal impact is well correlated to the ~~scarp~~ room height. This interpretation is coherent with the drop of amplitude before the ~~main~~ more energetic event at the Chamousset rock column (~~Figure 10~~Fig 9.c) where a progressive decrease of the precursory signal is observed. However, on the other sites (~~Figure 10~~Fig 9.a,.b) such decrease is not present. The one second lasting precursory signal ~~have~~ has a constant amplitude and frequency content~~suggesting another interpretation. Sequence of foreshocks are observed before some large earthquakes (???) as well as before some landslide ruptures (??). Tremors are also recorded before few earthquakes P-waves arrivals (??) and landslide rupture (?). These tremors are similar to the precursory signals presented in this section. Their origin is interpreted as either aseismic slow-slip events occurring during the acceleration of the fault displacement or cascade model of foreshocks whose size is growing with time (??). In our case, though, no continuous increase of the amplitude is observed in contrast of (?). In ?, a decrease of the tremor amplitude and down and up gliding frequencies are observed before the beginning of the landslide collapse but no gliding is observed in the signal presented here.~~ . Another interpretation could be that these precursory signals are a succession of overlaping slip or fracture events. The interpretation of these signals cannot be established with certainty and further analysis (i.e. location, time of occurrence) and other examples are needed to discriminate the mechanism at work.

6.3.3 ~~Tremor-like slopequake~~

– **Tremor-like slopequake** (Fig 10): The last class of short duration signals often last between 1 and 5 seconds (~~Figure 11~~Fig 10). They present a symmetrical waveform (S=50%) with emergent arrivals and slow decrease of the amplitude to the noise level. The frequency ranges from 5 Hz to 25 Hz. High-frequencies may be briefly recorded in certain events (~~Figure 11~~Fig 10.c) . The maximal energy of the PSD corresponds to a frequency of ~~10~~ 8 to 13 Hz while the mean energy corresponds to a frequency of ~~20~~ 13 to 17 Hz. No seismic phases are identified. The signal is not recorded by all the sensors even when the sensors are organized in small arrays with short inter-sensor distances (< 50 m). Their waveforms and frequency content are similar to the one of the granular flows (~~Figure~~ Fig 4). Small debris flows have been observed at La Clapière and Super-Sauze landslides and are likely to generate seismic waves; however, small debris flows are not observed at the Pas de l'Ours landslide when these ~~kind~~ kinds of seismic signals are recorded. Another possible source mechanisms for such events may also be a very rapid succession (< 1 s) of shear events along the basal or the side bounding strike-slip faults ~~?~~(?). Further investigations are needed to analyze their occurrences over time and their location to confirm one or the other assumptions.

7 Discussion

The proposed typology is summarized in ~~Figure 12~~Fig 11. The approach consisted in comparing the datasets of different sites in order to identify the common features of the recorded seismic signals. Figure 11 show that the three main classes may be differentiate from the length of the signals, the number of peaks and the duration of the auto-correlation whose highly discriminate the wet granular flows. Figure 12 shows more example of the signal variability for the sites where long seismic catalogs have been recorded (e.g. Aaknes, Chamousset, Séchilienne, Super-Sauze and La Clapière). Only the signals classified as Rockfall, LF- and HF-slopequake are presented because too few events of the other classes were present in the investigated datasets. The signal features are in good agreement with the defined classes proposed in the present classification (Fig 11). Similar feature and in general, narrow variability is observed on the feature values among the different sites and consequently, the observed features are likely associated to the source mechanism and not to propagation effects. ~~The signals present significant differences with the chosen features .~~

~~It must be noted that, in the field, the~~ Our analysis does not allow at this stage, to conclude whether the frequency content of simple slopequake is associated to source mechanism because complete catalogs differentiating these two classes are not yet available. (**?**) suggested that HF-slopequake are the dominant class of slopequake at the Madonna del Sasso cliff (hard-rock) and were generated by thermal cracking while LF-slopequake associated to frictional sliding are less frequent. Although we did not investigate the whole datasets, no LF-slopequakes were provided at two hard-rock cliffs: Aaknes and Chamousset (Fig 12) while LF-slopequake are recorded at hard-rock slides: La Clapiè re and Séchilienne (Fig 12). This observation seems to confirm the results of (**?**). However, further comparison of the occurrence of the different slopequakes at specific sites must be done to improve the comprehension of these sources and confirm this statement.

Some variability exist for rockfall events due to the large variability of this source but also to the site geometry. Indeed, the volume of the block and possible beak-up control the frequency content and the auto-correlation duration while the height of the scarp will play a significant role in the duration of the event. Depending on the site, rockfall signal can be very similar (e.g. Séchilienne, Fig 12) suggesting a constant source mechanism or very variable (e.g. Super-Sauze, 12). In the case of the Super-Sauze datasets, rockfall are characterize by lower frequency content due in this case to the distance between the seismic network and the scarp. Installation of additional sensors could be the easiest way to get rid of this variability. It must also be noted that, the differentiation between flow and fall signals may be challenging. Indeed, some of the events are very likely a mix of these two sources. Rockfalls of various blocks may generate granular flows with metric block impacts, both overlapping in the recorded seismic signals. Presence of metric rocks is also observed in debris flow prone torrents; for this type of events, the block impacts within the mass flows are recorded in the seismic signals (**?**).

Harmonic signals have been also been documented recorded at the Pechgraben and Super-Sauze landslides ~~and are presented in ?. The~~ **?**. These signals last from 1 to 5 s and repeat during minute-lasting sequences. The proposed interpretation includes hydro-fracturing or repetitive swarms of micro-earthquakes (?). The same signals are recorded at the La ~~Clapiere~~ Clapière and the Aiguilles landslides with a fundamental frequency of 8 ± 1 Hz (~~Figure 13). These signals last from 1 to~~ Fig 13.b,c). At Séchilienne landslide, harmonic signals are also detected (Fig 13.d), mostly during the day, with different resonant frequencies between 2 ~~s and may repeat during minute-lasting sequences. The proposed interpretation includes hydro-fracturing or repetitive swarms of micro-earthquakes (?). The similarity of the fundamental frequency and its stationarity through time for all the sites suggest that all these events are generated by the same kind of source. All these sites are characterized by different medium and different sizes.~~ and 12 Hz, simultaneously or for different time periods. Similar signals are observed at the Slumgullion and Super-Sauze but without clear harmonics in the PSD (Fig 13.e,f). **?** hypothesizes that the waves were trapped along the side-bounding strike-slip fault generated by shear events. The presence of pipes and drains on or in the vicinity of these sites ~~is likely to~~ could also explain the origin of these signals~~and their similarities~~. It justifies why these signals are not included in the Slopequake class because they are likely not generated by a slope deformation process.

~~The differences in the frequency content of simple slopequakes may be explained either by the attenuation of the high frequency at large distances during the propagation or by different rupture velocity and /or the presence of fluid in the fault plane. It is currently impossible to distinguish these two effects as the source time function cannot be inverted. Simple slopequakes are currently assumed to be generated by shear movement along a plane or tensile opening of cracks (???). At the Chamousset rock column, the source mechanism is retrieved by the P -and S-waves amplitude ratio (?). Shear events are found to be located at the bottom of the column while tensile opening is occurring in the upper part (?). To the best of our knowledge, for soft-rock landslides, no source mechanism were modeled.For fine material, the inversion of the source mechanism is currently challenging due to : 1)~~The location of the source, the distribution of the ~~attenuation of~~ amplitude, the stability of the fundamental frequency and the ~~seismic waves and especially of~~ daily temporal occurrence of the ~~first arrivals, 2) the inaccurate location, in particular the depth of the source, 3) the complexity of the landslide geometry making several source mechanisms possible at the same location. Moreover, the small amount of installed sensors and the geometry of the networks (controlled by the location of the stable zones; (?))is not always optimal to compute source focal mechanisms~~source supports this assumption or result from wave propagation. More precise location of these events are needed to determine if they must integrated or not in the general typology in the case they are generated by fluid resonance in fractures.

Harmonic coda are also observe for certain signals (Fig 3d, Fig 9c) at high frequencies (i.e. 20 and 43Hz). The resonance is not present before the beginning of the signal and hence can not be due to anthropogenic noise (i.e. motors). In the case of Chamousset cliff, **?** explained the presence of this monochromatic coda by the resonance of the rock column after the occurrence of the rock bridge breakage. At the Super-Sauze, similar resonant coda are observed at the end of certain rockfalls (Figure 4.d). Considering the distance between the main scarp and the seismic arrays (> 300 m) and the absence of large fracture on the scarp, the occurrence of this kind of resonance is very surprising in this case. This signals feature could also result from the wave propagation (i.e. trapped waves).

No long-lasting tremors are presented in this study. ~~?~~ **?** recorded a tremor with gliding before the occurrence of the Askja ~~Caldera~~ caldera landslide. Similar tremors are found on ~~glacier during their motion (??)~~the Whillans ice stream in Antarctica during slow slip events (**??**), which repeat twice a day with a slip of about 10 cm lasting for about 20 minutes. Therefore, ~~this~~

~~kind of signals are expected to be recorded by landslide seismic networks~~such signals may also occur during the nucleation phase of landslide failure. The question remains unclear if they are not observed because ~~of noise contamination (i.e. human activity, rainfall) or because~~ landslide acceleration is aseismic due to high pore fluid pressure (?) or low normal stress at the sub-surface of the slope.

~~Thanks to the catalogs of seismic endogenous events being progressively built, solid assumptions on the nature of several seismic sources can be proposed. However, difficulties~~ Difficulties still arise in providing an exhaustive description and interpretation of all the sources, particularly those generating short-duration signals. Several limitations currently prevent such analysis. First, the location of the sources remain difficult to establish due to the complexity of some of the signals, the size of the instrumented sites and the geometry (number, location) of the sensors installed close to the unstable slopes. ~~In order to improve the precision of the location, realistic 3-D models in both P- and S-waves are needed (?) as well as appropriate location strategies taking into account the complexity of the signal phases. Several approaches have been proposed based either on the amplitude of the signal (??), on the surface waves correlation (???), on the picking of the first arrivals (i.e. P-waves, (???) or the picking of surface waves, (??).~~ The location of the epicenter of most of the events seems coherent with the instabilities deformation although resolving dispersion and 3-D heterogeneities of the velocity fields currently prevents to infer the depth of the events and their focal mechanisms. ~~Most of the seismic networks are also not dense enough to resolve both location at depth and focal mechanisms.~~

~~A~~ Secondly, a complementary approach to explain the origin of the sources is the analysis of their occurrence with respect to surface or basal displacement and monitoring of the water content and pore fluid pressures. It requires both exhaustive catalogs of landslide seismicity over long time periods and continuous and distributed datasets of displacements and pore fluid pressures ~~. Automatic classification algorithms have shown their efficiency to classify landslide seismic signals(?????).~~ which remains challenging to acquire. Finally, on addition to the characteristics of seismic signals, further information on the sources processes can be obtained from the distribution of the events in time, space and size. Events that occur regularly in time with similar amplitudes are likely associated with the repeated failure of an asperity surrounded by aseismic slip, for instance, at the base of a glacier (?) or of a landslide (??). Signal amplitudes and recurrence times often display progressive variations in time. In contrast, events that are clustered in time and space, with a broad distribution of energies, are more likely associated with the propagation of a fracture (?). The daily distribution of events time can also be helpful to identify anthropic sources, that occur mostly during the day. In contrast, natural events are more frequently detected at night, when the noise level is smaller.

Simulations and models are also required to explain the current observations. Indeed, experimental results suggest an increase of acoustic emissions correlated with the increase of the slope velocity (?) or an increase of acoustic emission due to the creation of the rupture area (?). Acceleration of pre-existing rupture surface(s) ~~seem~~ seems to be the mechanism responsible for the seismicity recorded before large rockslide collapse. ~~??~~ ?? argued that the high correlation between the repetitive events could only be explained by stick-slip movement of the locked section(s), while a cracking process would imply a migration of the location of the events and a change in the events ~~wavefroms. ?~~ waveforms. ? argued that the presence of gliding frequencies could only be produced by similar sources and hence close location. ~~In~~ On the contrary, in the case of the ~~Mesnil-val column, ? interpret the frequency decay of the seismic~~ Mesnil-Val column, ? interpreted the evolution from high frequency to low frequency events as the progressive formation of the rupture surface followed by the final rupture process immediately before the column collapse where both tensile cracks and shearing motion on the created rupture are generated. ~~However, some collapse occurred without precursory sequences (?) and during long-term monitoring most of the deformation seems to occur aseismically (?). Experimental and numerical simulations are needed to better characterize the transition from seismic to aseismic deformation especially for soft-rock landslides where transition from brittle to ductile behavior are observed (??). In most of the studies, the number of events is significantly correlated with rainfall and displacement rates (??????) although some increases of seismicity rates are not correlated to any surface displacement (????).~~

8 Conclusions

Over the last decades, numerous studies have recorded seismic signals generated by various types of landslides (i.e. slide, topple, fall and flow), for different kinematic regimes and rock/soil ~~types~~media. These studies demonstrated the added-value of ~~the analysis of~~ analyzing landslide-induced micro-seismicity to improve our understanding of the mechanisms ~~of landslides~~ and to progress in the forecast of landslide evolution.

In this work we propose a review of the endogenous seismic sources generated by the deformation of unstable slopes. ~~Dataset of 14 different slopes are~~ A dataset of fourteen slopes is gathered and analyzed. Each of the source is described by ~~9~~ nine quantitative features of the recorded seismic signals. Those features provide distinct characteristics for each type of source. A library of relevant signals recorded at relevant site is shared as supplementary material. We propose three main class "slopequake", "rockfall" and "granular flow" to describe the main type of deformation observed on the slopes. Slopequakes are related to shearing or fracturing processes. This family exhibits the most variability due to the complexity of the sources. These variations are likely to be generated by different source mechanisms. "~~rockfall~~Rockfall" and "granular flow" classes are associated to mass propagation on the slope surface. They are distinguishable by the number of peaks clearly identified in the seismic signals.

Presently, several descriptions of the seismic sources are proposed for each study case. We believe that a standard typology will allow to discuss and compare seismic signals recorded at many unstable slopes. We encourage future studies to use and possibly enrich the proposed typology. This also requires publication of the datasets and/or catalogs to progress towards a common interpretation. Recently, organizations such as the United States Geological Survey (USGS) or the French Landslide Observatory (OMIV) have started this work (**??**).

A better understanding of the different sources endogenous to unstable slopes can also be achieved through the development of new adapted processing strategies to classify, locate and invert focal mechanism. Those developments must also be associated with the deployment of denser seismic networks, by taking advantages of the recent arrival on the market of ~~cheap,~~ relatively cheap and autonomous seismometers (~~e. g. NodeZand-Fairfield, RasberryShake~~eg. ZLand node systems, Raspberry-Shake systems). Moreover, the recent operational applications of Ground-Based SAR (Synthetic Aperture Radar) and terrestrial LiDAR technologies for monitoring purposes shows their relevance to monitor distributed surface displacements.

On-going monitoring on several landslides combining those innovative approaches will certainly help to associate SQ events to deformation processes **???**.

~~Finally, the~~ The proposed typology will help to constrain the design of new models to confirm the assumptions on the nature and the ~~characteristics~~ properties of the seismic sources. This will be particularly important for 1) explaining the variability of the SQ sources observed ~~on~~ at the sites, 2) progressing in the physical understanding of the SQ sources, and 3) ascertaining the ~~seismic/aseismic regimes~~ spatio-temporal variations of the seismic activity observed at some unstable slopes ~~,~~ in relation with their deformation as well as~~the transition between the two regimes in relation with external forcing~~ , with external forcings such as intense rainfalls and earthquakes.

Data availability. The library of the endogenous seismic signals recorded at the sites and described in the manuscript is shared as supplementary material. The seismic data are shared in Matlab *.mat* format.

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~~Map of seismologically-instrumented unstable slopes. Refer to table 1 for the name of the sites corresponding to the number.~~

~~Harmonic slopequake recorded at the a) Super-Sauze and b) Slumgullion slopes. See Figure 2 for description of the figure.~~

Table 1: Table of the instrumented sites. The bolded names correspond to the sites investigated in the present paper to establish the typology.

Number	Site	Location	Type	Material	Sensor	Duration	Reference/Research Group
1	Randa	Switzerland	Slide	Hard rock	G	SC	~~(?)~~ ?
2	**Séchilienne**	France	Slide	Hard rock	G, SP	P	~~(???)~~ ???
3	**La ~~Clapière~~Clapière**	France	Slide	Hard rock	SP(?)	P	~~(??)~~ ??
4	**Aaknes**	Norway	Slide	Hard rock	G,BB	P	~~(?)~~ ?
5	Peschiera Spring	Italy	Slide	Hard rock	A	SC	~~(?)~~ ?
6	Gradenbach	Austria	Slide	Hard rock	SP	P(?)	~~(?)~~ ?
7	Alestch-Moosfluh	Switzerland	Slide	Hard rock	BB	P	~~(?)~~ ??
8	Torgiovannetto, ~~Assise~~ Assisi	Italy	Slide	Hard rock	SP	SC	~~(?)~~ ?

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Table 1 – continued from previous page

Number	Site	Location	Type	Material	Sensor	Duration	Reference/Research Group
9	~~Harmalière France Slide Hard rock SP,BB P (?) 10~~ Akatami landslide	Japan	Slide	Hard rock	(?)	(?)	~~(?)~~
~~11~~ 10	Akkeshi landslide	Japan	Slide	Hard rock	SP	P	~~(?)~~ ?
~~12~~ 11	Rausu landslide	Japan	Slide	Hard rock	BB	P	~~(?)~~ ?
~~13~~ 12	Fergurson slide / Mercel River	USA / California	Slide	Hard rock	(?)	(?)	~~(?)~~ ?
~~14~~ 13	Turtle Mountain - Frank slide	Canada	Slide	Hard rock	G	P	~~(?)~~ ?
~~15~~14	**~~Aiguilles~~Aiguilles-Pas de l'Ours**	France	Slide	Soft rock / Earth	BB	SC	~~(?)~~ ?
15	Harmalière	France	Slide	Soft-rock	SP,BB	P	?
16	Utiku	New Zealand	Slide	Soft rock / Earth	(?)	P	~~(?)~~ ?
17	Villerville	France	Slide	Soft rock / Mud	BB	SC,P	~~(?)~~ ?
18	**Super-Sauze**	France	Slide	Soft rock / Mud	SP	P, RC	~~(????)~~ ????
19	**Pont Bourquin**	Switzerland	Slide	Mud	SP(?)	P	~~(??)~~ ??
20	Valoria	Italy	Slide	Mud	SP	SC	~~(?)~~ ?
21	**Pechgraben**	Austria	Slide	Mud	SP,BB	RC	~~(?)~~ ?
22	US highway 50, CA	USA	Slide	Earth	G	P	USGS (https://landslides.usgs.gov/monitoring/)
23	**Slumgullion**	USA	Slide	Earth	G	RC	~~(??)~~ ??
24	Millcoma Meander, Oregon	USA	Slide	Earth	G	P	USGS (https://landslides.usgs.gov/monitoring/)
25	Xishancun	China	Slide	Earth	BB	SC	-
26	Chambon Tunnel	France	Slide	Earth	SP	P	-
27	Maca	Peru	Slide	Soft rock / Earth	SP	P(?)	~~(?)~~ ?
28	Heumoes	Germany	Slide	Soft rock / Earth	SP	RC	~~(?)~~ ?
29	Mission Peak landslide	USA / California	Slide	Soft rock / Earth	BB	P	~~(?)~~ ?
30	Char d'Osset	France	Slide, Fall	Soft rock / Mud			-
31	Mesnil-Val	France	Fall	Hard rock	G	SC	~~(??)~~ ??
32	North Yorkshire coast	United Kingdom	Fall	Hard rock	BB	P	~~(?)~~ ?
33	Matterhorn peak ~~/Mont Cervin~~	Italy	Fall	Hard rock	G	RC	~~(?)~~ ??
34	Madonna del sasso	Italy	Fall	Hard rock	SP	P(?)	~~(?)~~ ?
35	**Chamousset**	France	Fall	Hard rock	SH	RC	~~(??)~~ ??
36	Mont-Granier	France	Fall	Hard rock	BB	P	-
37	Les Arches	France	Fall	Hard rock	SP	P(?)	~~(??)~~ ??
38	La Praz	France	Fall	Hard rock	SP	P(?)	~~(?)~~ ?
39	Rubi	France	Fall	Hard rock	SP	P(?)	~~(?)~~ ?
40	La Suche	Switzerland	Fall	Hard rock	SP	P(?)	~~(?)~~ ?
41	**St. Eynard~~cliff~~**	France	Fall	Hard rock	SP	P(?)	~~-~~ ??
42	Cap d'Ailly	France	Fall	Hard rock			-
43	Lauterbrunnen valley	Switzerland	Fall	Hard rock	BB	SC	~~(??)~~ ??
44	Three Brothers	USA	Fall	Hard rock	SP	SC	~~(?)~~ ?
45	Mount Néron	France	Fall (triggered)	Hard rock	BB	SC	~~(?)~~ ?
46	**Riou Bourdoux**	France	Fall (triggered)	Hard rock	SP,BB	SC	~~(?)~~ ?
47	Montserrat	Spain	Fall (triggered)	Hard rock	SP	SC	~~(?)~~ ?
48	**Piton de la Fournaise~~caldeira~~**	France	Fall, Flow	Volcanic rock	BB	P	OPVF/IPGP, ~~(????)~~ ????
49	Bolungavík - Oshlíðslope	Iceland	Fall, Flow	Hard rock	A	P	~~(?)~~ ?
50	**Rebaixader**	Spain	Flow	Debris	G	P	~~(????)~~ ????
51	Manival torrent	France	Flow	Debris	G	P	~~(?)~~ ?
52	Réal torrent	France	Flow	Debris	G	P	~~(?)~~ ?
53	Marderello torrent	Italy	Flow	Debris	G	P	~~(?)~~ ?
54	Acquabona torrent	Italy	Flow	Debris	G	P(?)	~~(??)~~ ??
55	Moscardo torrent	Italy	Flow	Debris	SP	P	~~(?)~~ ?
56	Gadria torrent	Italy	Flow	Debris	G	P	~~(?)~~ ?
57	Mt. Yakedake volcano - Kamikamihorizawa Creek	Japan	Flow	Debris			~~(?)~~ ?
58	Lattenbach torrent	Austria	Flow	Debris	G	P(?)	~~(??)~~ ??
59	Illgraben torrent	Switzerland	Flow	Debris	G	P	~~(??)~~ ??
60	Farstrine torrent	Austria	Flow	Debris	G	P(?)	~~(?)~~ ?
61	Wartschenbach torrent	Austria	Flow	Debris	G	P(?)	~~(?)~~ ?
62	Dristenau torrent	Austria	Flow	Debris	G	P(?)	~~(?)~~ ?
63	Shenmu creek	Taiwan	Flow	Debris	G	P	~~(?)~~ ?
64	Ai-Yu-Zi creek	Taiwan	Flow	Debris	G	P	~~(?)~~ ?
65	Fong-Ciou creek	Taiwan	Flow	Debris	G	P	~~(?)~~ ?
66	Chenyoulan creek	Taiwan	Flow	Debris	G	SC	~~(?)~~ ?
67	Mt. Sakurajima Volcano - Nojiri Torrent	Japan	Flow	Debris	G	P	~~(?)~~ ?
68	Mount Pinatubo	Philippines	Flow	Debris	G	P	~~(?)~~ ?

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Table 2. Characteristic of the seismic network for the 13 sites analyzed in the present parer. The landslide dimensions are given for the most active area of the slope instabilities (as presented in the published studies). The total number of the seismic network are given as well as its minimal and maximal inter-sensor distance and distance to the active zone. In the case a fewer number of the sensors have been investigated in the present study, we indicate the number of the sensors as well as the name of the use station in parenthesis.

Site	Sensor type	Network geom.	Number of sensors in tot.	Number of sensors analyzed	Inter-sensor distance min	Inter-sensor distance max	Distance to the landslide min	Distance to the landslide max	Landslide dim.
Séchlienne	SP	SA	41	11 (THE)	25 m	85 m	< 50 m	< 200 m	600 m $\times$ 200 m
La Clapière	SP	SN	18	9 (CL4)	30 m	77	0 m		900 m $\times$ 700 m
Aaknes	G	SN	8		< 50 m	250 m	0 m		1 km $\times$ 1 km
Aiguilles-Pas de l'Ours	BB	SN	4		205 m	690 m	0 m	200 m	500 m $\times$ 500 m
Super-Sauze	SP	SA	8		30 m	150 m	0 m	< 100 m	800 m $\times$ 150 m
Pont Bourquin	SP	SN	2		30 m		0 m		240 m $\times$ 35 m
Pechgraben	SP	SA + SS	5		5 m	40 m	0 m		500 m $\times$ 100 m
Slumgullion	SP	D-SN	88		11 m	450 m	0 m		1 km $\times$ 500 m
Chamousset	SP	SN	7		15 m	50 m	0 m	40 m	60 m $\times$ 30 m
St. Eynard	SP	SN	4	3*	500 m	1.7 km	0 m	500 m	7 km $\times$ 300 m
Riou Bourdoux	SP,BB	SA + SS	5		50 m	200 m	20 m	30 m	length: 200 m
Piton de la Fournaise	BB	SN	10	1 (BOR)	-	-	< 50 m		1 km $\times$ 300 m
Reibaxader	G	SN	9		< 20 m	200 m	0 m		700 m $\times$ 50 m

G: Geophone (f = [0.1-10] kHz); SP: Short-Period (f = [0.1-100] Hz); BB: Broad-Band (f = [10^{-2}-100] Hz);

SN: Seismic Network; D-SN: Dense-Seismic network;

SA: Seismic Array; L-SA: Linear-Seismic Array; SS: Single Sensor;

* investigated stations: FOR, MOL, GAR.

Table 1 – continued from previous page

Number	Site	Location	Type	Material	Sensor	Duration	Reference/Research Group
69	~~La~~ Colima volcano	Mexico	Flow	Debris	LP	P	~~(??)~~ ??
70	Merapi volcano ~~flanks~~	Indonesia	Flow	Debris	G	P	~~(?)~~ ?
71	Nevado del Huila volcano	Colombia	Flow	Debris	G	P?	?
72	Cotopaxi volcano	Ecuador	Flow	Debris	BB	P	?
73	Mount Ruapehu	New-Zeland	Flow	Debris	BB	P	?
74	Sawatch Range, Colorado	USA	Flow	Debris	G	P	?

G: Geophone (f = [0.1-10] kHz); SP: Short-Period (f = [0.1-100] Hz); BB: Broad-Band (f = [10^{-2}-100] Hz); A: Accelerometer;

P: Permanent monitoring; RC: Repetitive Campaigns; SC: Single Campaign.

OPVF/IPGP: Volcanological Observatory of the Piton de la Fournaise / Institut de Physique du Globe de Paris.

USGS: United States Geological Survey.

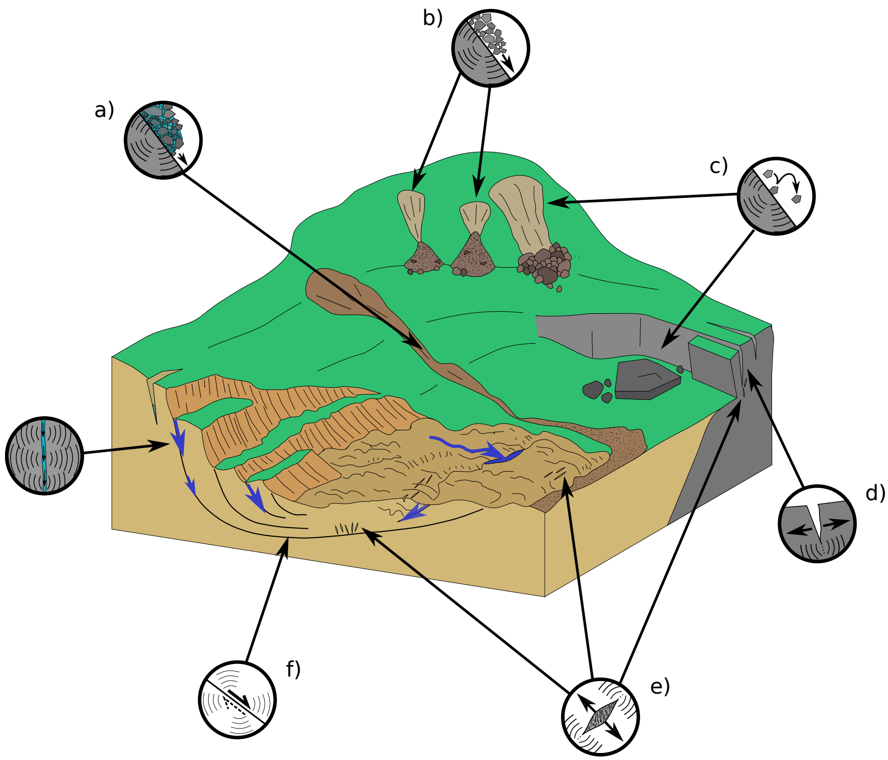

Figure 1. Conceptual scheme of the landslide endogenous seismic sources with a) wet granular flow, b) dry granular flow, c) rockfall, d) tensile fracture opening, e) tensile cracks opening, f) shearing and h) fluid migration in fracture.

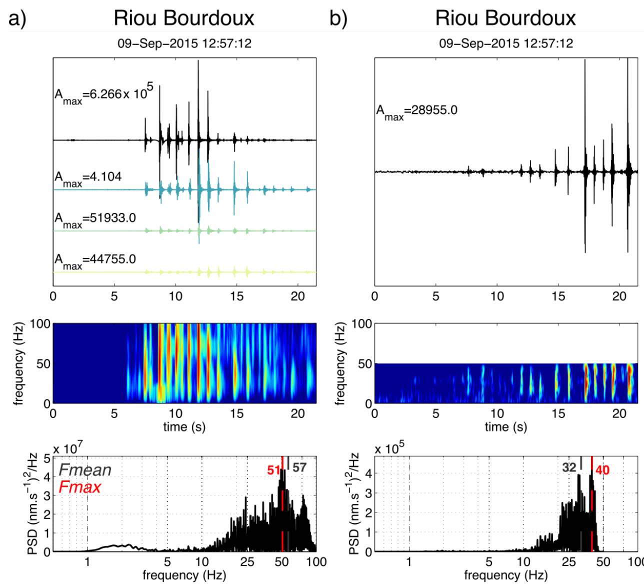

Figure 2. Example of one controlled rockfall (mass= 430kg) at the ~~Riou Bourdoux~~ Riou-Bourdoux catchment (**?**) recorded by SP seismometer located at 50 m of the rock departure (left) and recorded by BB seismometer near the rock arrival (right). The waveforms ~~is~~ of the vertical traces are plotted on the upper part of the figure. The amplitude are normalized on the trace with the maximal amplitude (black), the signal recorded by the other sensors (when available) are represented in color below. The maximal amplitudes (A_{max}) of all the traces are plotted on the sub-plot. The spectrogram is plotted on the middle part of the figure and normalized to the maximal energy. The lower part of the figure represents the PSD of the most energetic trace and the frequency corresponding to the maximum and the mean of the PSD are plotted in red and gray respectively.

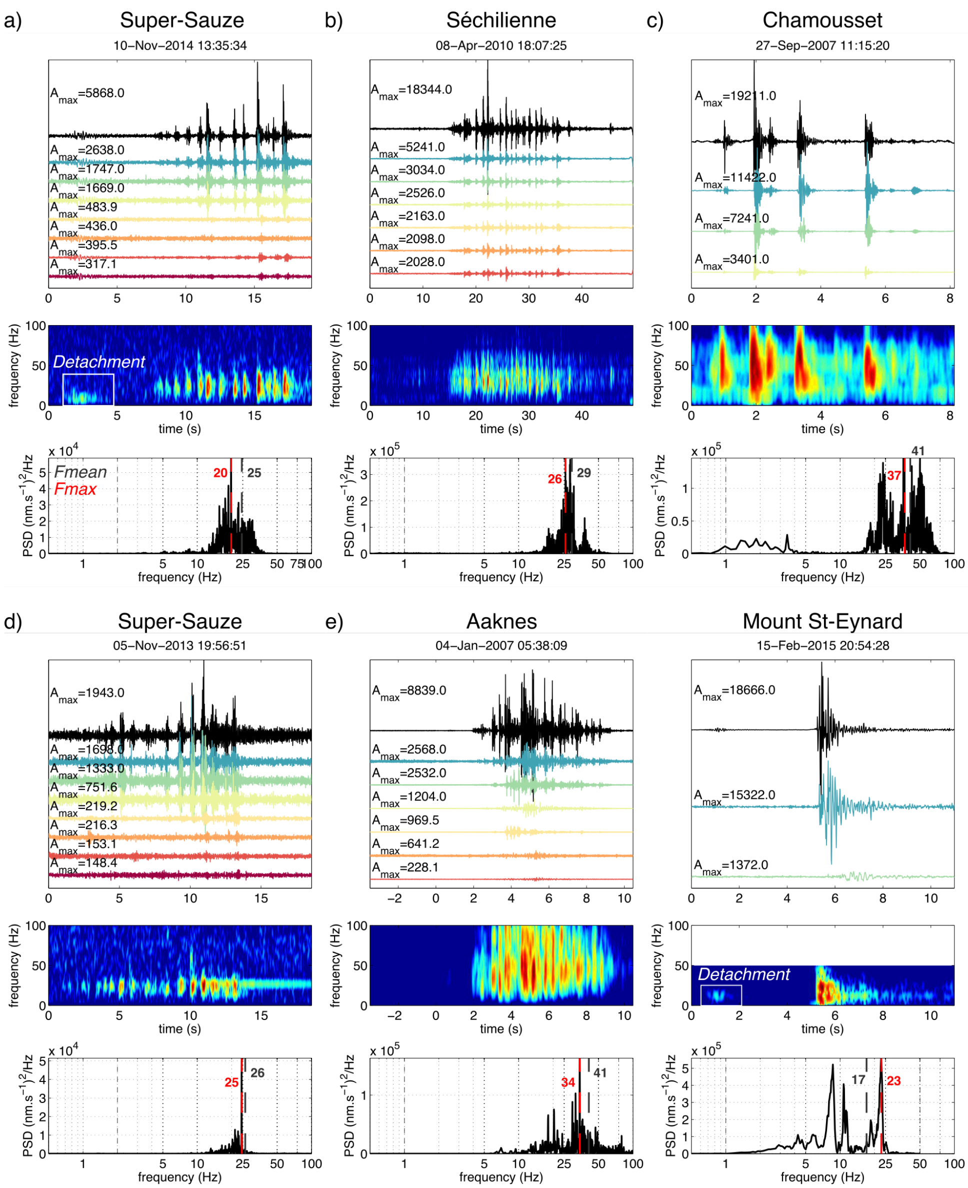

Figure 3. Rockfall events recorded at a) and d) Super-Sauze (France) (?), b) at the Séchilienne (France, ??), c) Chamousset (?), e) Aaknes and f) Mount Saint-Eynard slopes (?). See ~~Figure~~ Fig 2 for description of the figure.

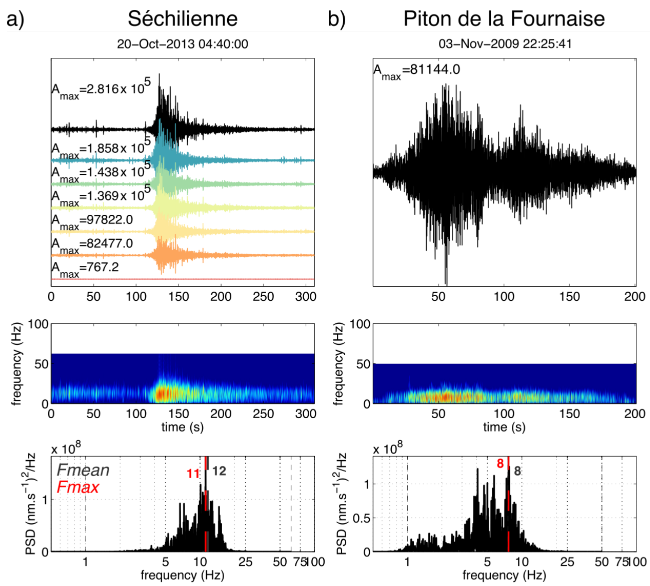

Figure 4. Dry granular flow events recorded at a) Séchilienne and b) the Piton de la Fournaise Caldera. See ~~Figure~~ Fig 2 for description of the figure.

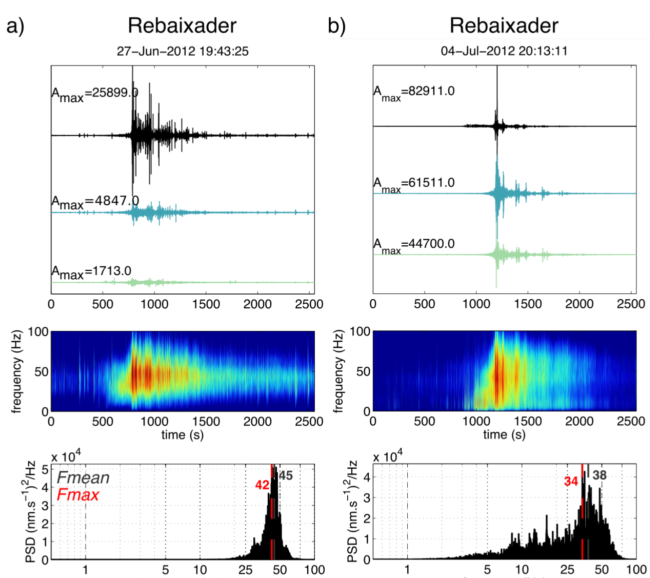

Figure 5. Wet granular flow events recorded at Rebaixader torrent (**???**). See ~~Figure~~ Fig 2 for description of the figure.

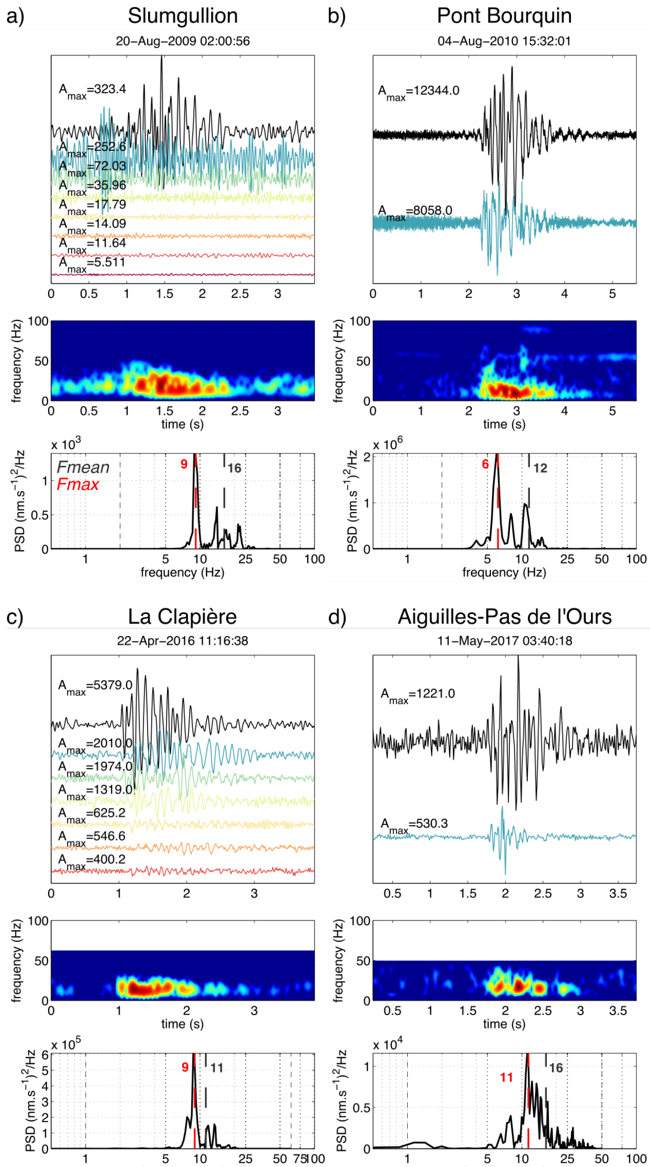

Figure 6. Low-Frequency Slopequakes recorded at the a) Slumgullion (?), b) Pont-Bourquin, c) La Clapière and d) Aiguilles-Pas de l'Ours slopes. See ~~Figure~~ Fig 2 for description of the figure.

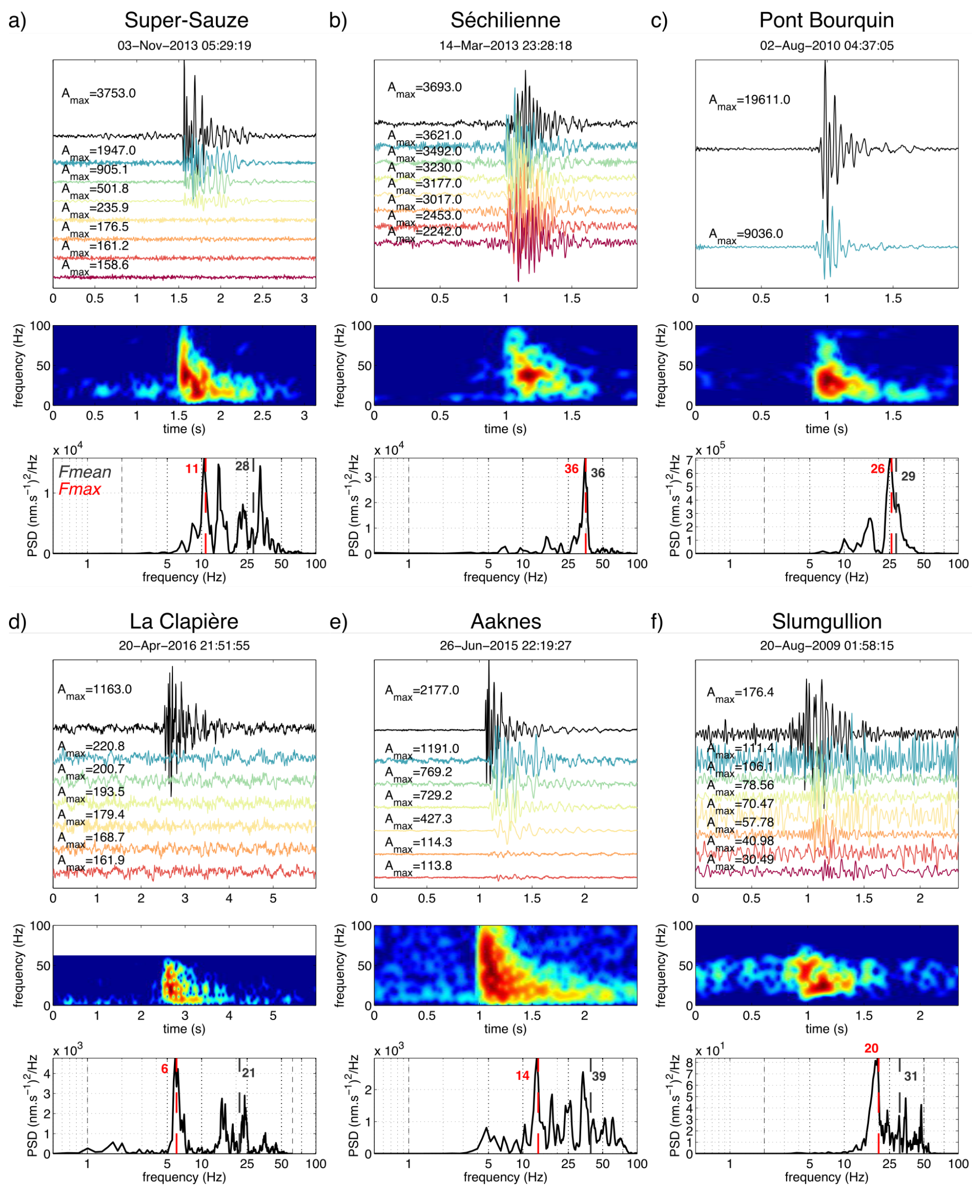

Figure 7. High-Frequency Slopequakes recorded at the a) Super-Sauze (?), b) Séchilienne (??), c) Pont-Bourquin, d) La Clapière, e) Aaknes, and f) Slumgullion (?) slopes. See ~~Figure~~ Fig 2 for description of the figure.

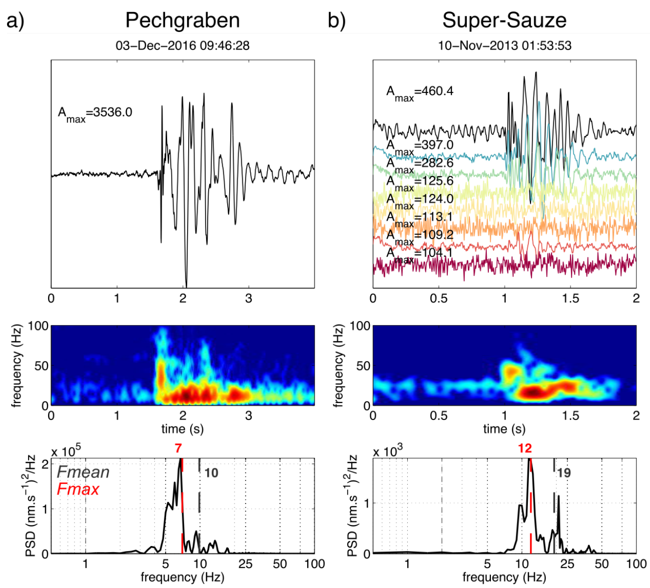

Figure 8. ~~Mix-Slopequake~~ Hybrid-Slopequake recorded at the a) Pechgraben and b) Super-Sauze landslide. See ~~Figure~~ Fig 2 for description of the figure.

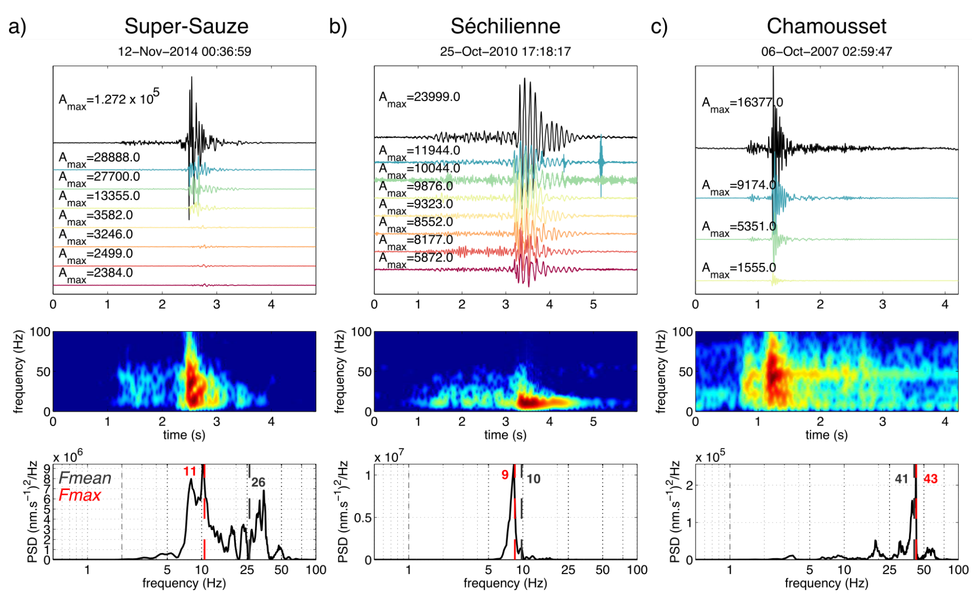

Figure 9. Examples of ~~slopequakes~~ Slopequakes with ~~resonance in the coda~~ presursory event recorded at ~~a) Chamousset and b) Super-Sauze slopes. See Figure 2 for description of~~ the ~~figure.Examples of Slopequakes recorded at the~~ a) Super-Sauze, b) Séchilienne and c) Chamousset slopes. See ~~Figure~~ Fig 2 for description of the figure.

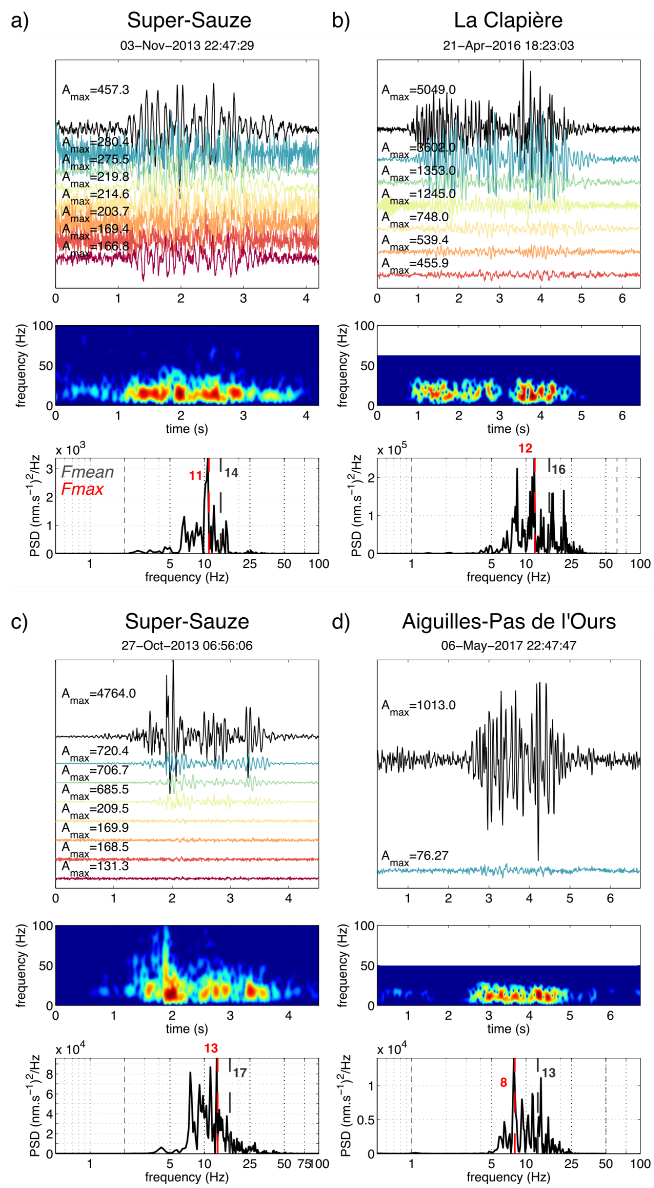

Figure 10. Examples of repetitive Slopequakes recorded at the a),c) Super-Sauze, b) La Clapière and d) Aiguilles-Pas de l'Ours slopes. See ~~Figure~~ Fig 2 for description of the figure.

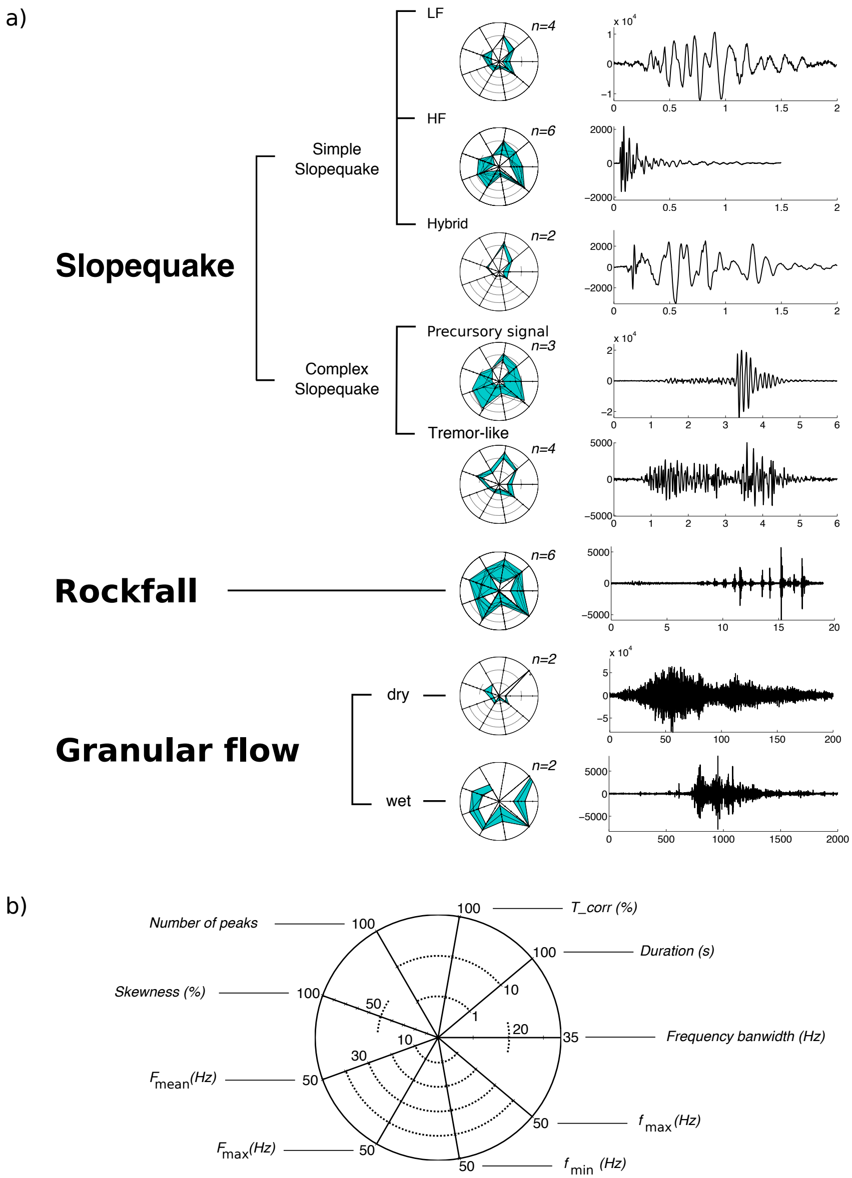

Figure 11. a) Summary of the proposed classification with plot of the attributes for the examples presented in the precedent figures and an example of waveform for each class. The convention for the attribute plot is presented in b).

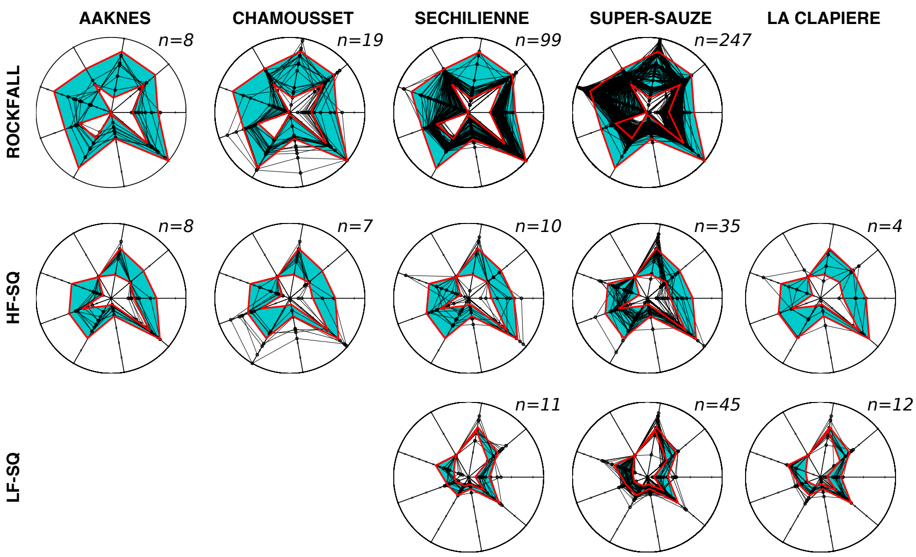

Figure 12. Variability of the signal features of classes “Rockfall”, “HF-slopequake” and “LF-slopequake” for five different sites: Aaknes, Chamousset, Séchilienne, Super-Sauze and La Clapière.

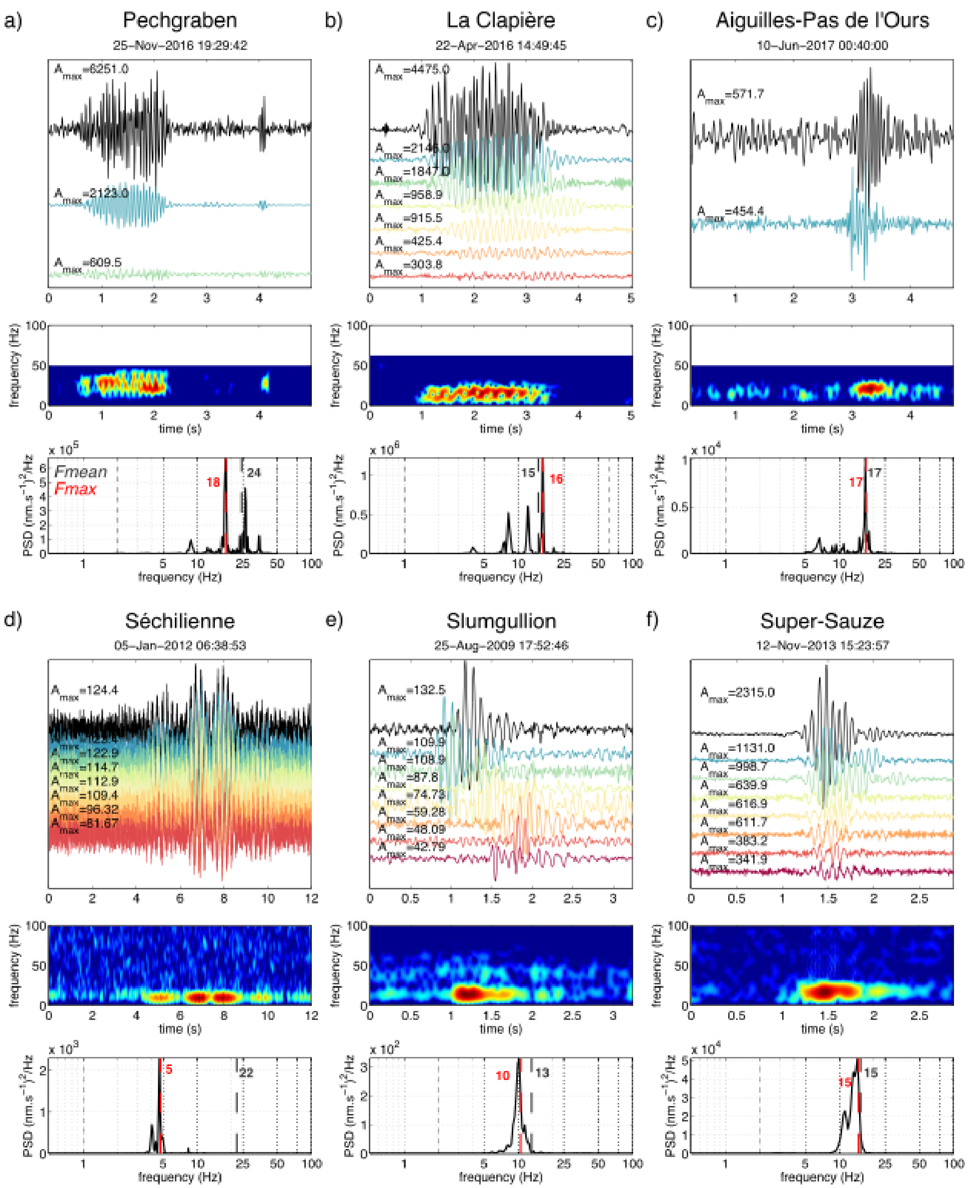

Figure 13. Examples of pure harmonic signals recorded at the a) Pechgraben, b) La Clapière and c) Aiguilles-Pas de l'Ours, d) Séchilienne, e) Slumgullion (?) and f) Super-Sauze slopes. See ~~Figure~~ Fig 2 for description of the figure.