Reply to comments by W. Haeberli

The authors would like to acknowledge the Reviewer for his constructive remarks and critics. Here we follow his text and react along it.

The term "glacier" as used already in the title of the paper may be inappropriate in view of the minimal size of the envisaged surface ice body (« 0.1 km2).

Our answer: According to this remark and to the whole review we will modify the title as follows: *"<u>Massive</u> ice in rock glaciers: a case study in the Vanoise Massif, Northern French Alps."* We present evidence for the existence of a massive ice body with structures similar to those found in glaciers. While we agree that this evidence is not unequivocal, it nonetheless suggests the possibility of a glacial origin for the Sachette rock glacier. We agree to focus more on the massive ice nature highlighted by the GPR results, and present the possible glacial origin as part of the discussion on the rock glacier genesis. However we question the relevance of the size threshold mentioned by the reviewer for defining a glacier, as this threshold does not appear in recently published glossaries and inventory guidelines. Thus this argument seems irrelevant to the discussion about the origin of the massive ice body. This point is discussed at length later in this document.

GPR soundings and rock glacier geophysics: Ice-rich material and lenses of massive ice are no exception but characteristic in creeping permafrost on mountain slopes, especially under conditions of compressing flow as in the investigated case. Complementary resistivity or seismic soundings could strongly improve the interpretation of the so far done GPR soundings. Comparison should at least be made with long-existing results from core drilling, borehole measurements and geophysical soundings reported from other rock glaciers. This type of information documents a typically layered vertical structure with large blocks at the surface (no or little ice in the pore volume), finer (silty/sandy) material with excess ice underneath, and a blocky layer at depth (from surface blocks which fell over the front of the creeping ice/rock-mixture and were subsequently overridden by it). The interpretation of the presented GPR soundings could make strong profit from such existing information about the internal structure of rock glaciers.

Our answer: Integration of geophysical methods, and particularly imaging techniques, is an extraordinary challenge in such environment. Concerning the present paper, it is practically impossible to envisage such seismic investigation as well as new drilling, in the short or even middle term. We still believe that the radargrams presented show significant and pertinent structural information, and moreover at a reasonable logistical and financial cost. Furthermore, although a general comparison between our results and other geophysical measurements made at other sites in the Alps is certainly valid, extrapolating the results from the few existing rock glacier boreholes to other sites/landforms is questionable. We certainly recognize the high value of these boreholes but nonetheless it cannot be assumed that the stratigraphy highlighted at the Sachette rock glacier will be the same as that observed at these boreholes/sites. We hence suggest emphasizing in the discussion the comparison between our GPR results and those from other sites in the Alps, as suggested, with mention of the existing knowledge of rock glacier stratigraphy derived from core drilling at other sites.

Thermal conditions and movements: Why were the temperature records interrupted in summertime? Completely measured annual cycles would provide important information about mean subsurface temperatures and the thickness of the investigated permafrost. Furthermore, information about energy fluxes through the surface could be obtained from more complete and systematically analysed records (thermal offsets, zero curtain, snow-cover duration, microclimate of the coarse blocks at the surface, etc.). Even with the presented incomplete records, better interpretation is possible: the recorded low temperatures during February and March reflect BTS-values (Bottom Temperature of the Winter Snow Cover – an often used method to map permafrost distribution in complex mountain topography), which clearly indicate permafrost conditions.

Our answer: The temperature records in the blocky layer were interrupted during summer 2006 to winter 2007 due to failure of the dataloggers, while battery failure caused the interruption during the summer of 2008. This will be specified in the paper. Due to both this incompleteness and the limited information provided by only 4 near-surface temperature records, we used these data only to describe the general ground thermal conditions on the rock glacier surface, as part of the site description section (and not in the results section). It is not the focus of this paper to study in details the microclimate and surface energy balance of the blocky layer. Nevertheless the limited data are useful to show that permafrost conditions are present at the site. As suggested by the Reviewer we will analyze in more details the potentially BTS-reflecting values in the records, as well as mention snow cover duration as derived from analysis of the temperature time series in the furrow sites. Figure 3 could be included within the site map (Fig. 2) in order to reduce its importance.

The uncertainty of 0.6 m/y in the movement determination for slowly creeping permafrost on slopes is very high, provides an extremely coarse image of the flow field, which probably exists in reality, and strongly limits possible interpretations. Much more sophisticated and detailed flow determinations have been accomplished on other rock glaciers. Such detailed flow measurements enable flow trajectories to be constructed, patterns of surface age to be estimated and relations between surface structures and extending/compressing flow to be analysed. The authors should at least refer to the corresponding studies, results and understanding. Even the limited information presented here appears to indicate that there is a transverse flow component in the upper and orographic left part of the feature from thick frozen debris underneath large rock walls to the west, while movement is weaker in the upper and orographic right (eastern) part with much smaller rock faces and thinner debris. This asymmetry may be related to the transverse deformational structure visible in the GPR soundings.

Our answer: As highlighted by the Reviewer, we presented admittedly low-resolution measurements of the horizontal (x, y) displacements of the rock glacier surface. We used the basic tracking feature method in GIS software (used, e.g., by Lugon and Stoffel, 2010). The resulting high uncertainty (0.6 m/yr), as pointed out by the Reviewer, is in part due to the initial 0.5 m pixel resolution of the images. The resolution and precision of these data do indeed contrast with the high resolution of our GPR results. Therefore, we will reduce the importance of these displacement measurements and present them only as evidence for the current activity of the rock glacier, within the site description section. We propose to overlay only the *measured* displacement vectors (larger than the error threshold) onto the actual Figure 2b. A shorter description of the tracking method employed, together with a brief interpretation of the measured displacements as an evidence for the active character of the rock glacier, will be made within the site description section (and taken off entirely from the result section).

On another hand, the Reviewer relates the asymmetry of the surface displacements in the upper part of the rock glacier to (1) a lateral change in the morphology of the upper rock faces, and (2) the transverse deformational structure visible in the GPR profiles. We are not convinced by this interpretation. First, the lateral (west-east) changes in the morphology of the rock walls are not really evident. Secondly, the typically synclinal, trough-shaped transverse structures observed in the GPR results (Fig. 9) are symmetric: why would the surface displacements therefore be asymmetric? We think that this asymmetry arises from the difference in height between the lateral ridges at the upper end of the rock glacier (the western ridge is 5-10 m higher than the eastern one) and to surface downwasting due to internal ice melting between those lateral ridges.

Geomorphology/paleoglaciology: The geomorphological interpretation should be essentially reconsidered with respect to (a) the highly questionable "push moraine" and its use for ELA reconstructions, (b) various possible origins of ice-rich frozen ground and subsurface massive ice, and (c) a correct use of the term "glacier" and an adequate physical understanding of minimal-size surface ice. The feature called "push moraine" is outside the investigated rock glacier and roughly parallel to its flow direction. It could represent a lateral moraine of a long vanished late glacial ice body in the cirque or possibly even be part of a separate and now inactive flow feature from the separate talus in the east of the rock glacier. Its use for paleoclimatic reconstructions and ELA estimates is highly questionable and should better be avoided. The speculative and vague age constraint envisaged is of limited interest anyway (cf. the much more informative direct age determinations for other rock glaciers in the Alps).

Our answer: We admit that the nature, disposition, and subsequent use for paleoclimatic estimations of what we called 'push moraine' at the immediate east of the rock glacier, is somewhat questionable. We admit that the information obtained is of low precision and does not help much in the interpretation of the internal structure of the rock glacier. We will remove this whole section from the manuscript. Regarding the statement: '*correct use of the term "glacier" and an adequate physical understanding of minimal-size surface ice.*': this point is addressed at length later in this document.

Deformational structures in subsurface ice are deformational structures in subsurface ice and nothing more. There is no straightforward or unique relation between such deformational structures and a "true glacier" (what is a "true" glacier? – better use scientific language). Deformational structures in a creeping permafrost body can develop in subsurface ice of various origins (this was already misunderstood in the cited paper by Fukui et al. 2008).

Our answer: We agree that deformational structures can develop in subsurface ice of various origins in permafrost creeping bodies. The most frequently observed stratigraphies in rock glaciers are reflectors roughly mirroring the surface topography, straight or more or less undulating, with local toplapping events (Berthling et al., 2000; Isaksen et al., 2000; Lehmann and Green, 2000; Degenhardt et al., 2003; Monnier et al., 2008 and 2009; Degenhardt, 2009; Leopold et al., 2011). These structures have been related to the deformation of the permafrost body during compressive flow. The structures highlighted in the Sachette rock glacier are strikingly different. Except on the uppermost part, they are always truncated by the topography. They are assembled in unique patterns: in the upper part of the rock glacier, where information is available both in transverse and longitudinal directions, the structures can be described as embedded spoons (or trough-shaped, as suggested by the other Reviewer); further down the rock glacier, the reflectors are up-rock glacier-dipping. In addition, we observed shallow exposures of massive ice at the root of the rock glacier and highlighted the widespread distribution of high radar wave velocities (>0.15 m/ns) in the upper half of the rock glacier. Consequently, the main result of our contribution is the identification of a core of massive ice in the rock glacier.

It is worth to note the geometrical reminiscence of the stratigraphy we observe with the typical englacial arcuate structures: primary stratification structures (e.g., Roberson, 2008), foliation structures (e.g., Allen et al., 1960, first authors to used the term "nested spoons", p. 607), as well as shear planes (e.g., Benn and Evans, 1998; Roberson, 2008). In several glaciological studies, these structures have been highlighted by GPR: e.g. Hambrey et al. (2005) described series of up-glacier-dipping reflectors from a glacier in Svalbard and interpreted them as stratification features. In New-Zealand, in a profile acquired in the terminal part of a glacier, Appleby et al. (2010) related concave, up-glacier-dipping events to arcuate shear planes observed on the surface. Moreover, recently, similar GPR structures were highlighted in rock glaciers by studies putting the emphasis on the possible incorporation of massive ice inherited from former glaciers into rock glaciers (Fukui et al., 2008; Krainer et al., 2010; Monnier et al., 2011). The latter studies reported exposures of massive ice and high measured radar wave velocities (>0.15 m/ns, typical of massive, buried, and/or glacial ice) within the rock glaciers. Fukui et al. (2008) and Krainer et al. (2010) related the GPR reflectors to debris bands visible along the massive exposures and suggested that they represented shear planes. Using historical maps and pictures, Krainer et al. (2010) and Monnier et al. (2011) showed that their studied rock glacier areas were occupied by glaciers in their upper part at the end of the LIA – and that, therefore, the observed massive ice was glacial in origin.

Finally, whereas our observations do not constitute indisputable evidences for the existence of glacial ice, they do point in that direction. It is difficult to conclude definitely on the exact nature of the spoon-shaped or up-rock glacier-dipping events: their geometry expresses deformation; therefore they may indicate foliation as well as shear planes. Their high density (higher than the ones reported by Fukui et al. 2008, Krainer et al. 2010, and Appleby et al. 2010), strong bending and dip (especially in LP#1) suggest a rotation during flow, which would imply that they are foliation features.

Massive subsurface ice can form by ice segregation at a stable freezing front in fine material, reflect injection ice or originate from burial of former surface ice (see below).

Our answer: We agree: massive subsurface ice is not necessarily of glacial origin. However, in the studied case, the thickness of the massive ice body is estimated to be up to 20-25 m (the Reviewer insists on the thinness of the ice body; however our GPR results highlight a much greater thickness). While theoretically possible, in the alpine context considered here, where debris supplies primarily originate from rockfalls from the surrounding steep cirque walls, the development of the type of highly frost-susceptible soils that would allow the formation of such a massive ice body by ice segregation or injection is less likely. However this argument is conjectural since we do not have direct information on grain size below the blocky surface. However, the GPR signature, like we demonstrate, is distinct from most of those previously published for rock glaciers, and is rather characteristic of glacial facies. Nor do we think that burying of a perennial avalanche-derived superimposed ice body, usually thin as the Reviewer mentions later, could explain the occurrence of such a tick and apparently homogeneous massive body as highlighted here. Therefore the massive ice body is considered as a buried one.

Electrical resistivity provides the most reliable information about different formation processes (sedimentary, congelation and metamorphic ice with characteristic ion contents). Even buried ice, which originally built up at the surface, is not necessarily "glacier ice" (a term without precise scientific content anyway).

Our answer: The value of electrical resistivity methods is a minor issue here. However, some studies have yet admitted the challenges and difficulties related to the application and interpretation of geoelectrical data in permafrost environments (Hilbich et al., 2009; Hausmann et al., 2010). In general the results of electrical resistivity studies are far from being unambiguous: the resistivity values are inverted resistivities and, thus, naturally not 'true' resistivities and can significantly differ from the latter due to many factors (inversion method-related problems, non-uniqueness of the results because of possible equivalences, sensibility of the results to the initial model…). For stratigraphic investigations, GPR is irreplaceable and absolutely without any concurrence. In our and previous (Monnier et al., 2011) papers it is also shown that it yield valuable information related to the constitutive materials.

The length of the investigated rock glacier is some 300 m and its width about half of this if not less. The dimension of the surface-ice feature inferred by the authors is thus « 0.1 km2. Because of this minimal size, the term "glacier" is inadequate and should be replaced by a term like "perennial snowbank" or "glacieret". Such surface ice of minimal size can be a former avalanche cone, which formed at the foot of the steep slopes at the head of the rock glaciers (such snow patches are visible on Fig. 5 and high-resolution Google Earth images of the investigated rock glacier) and would probably not even be included into glacier inventories. Perennial surface ice bodies with the dimensions « 0.1 km2 are indeed often encountered near the head and on the surface of rock glaciers. They are usually thin (metres, cf. Fig. 4), predominantly consist of refrozen snow (superimposed ice) and do not really move from an accumulation (firn) area to an ablation (ice) area. Instead, they are ablation areas in some years and accumulation areas in others. Their ice is commonly cold and frozen to the underlying ground, because ice temperature cannot rise above zero during summer yet cool far below zero during winter. As a consequence, such small bodies of perennial surface ice from avalanche deposits, wind drift, etc., are – by definition – related to negative ground temperatures throughout the year (= permafrost); they often participate in the building-up of deeply frozen talus, which then starts creeping, and they are best preserved under conditions of compressing flow due to dynamic thickening of the insulating blocky surface layer.

Our answer: The calculated area of the assumed former exposed ice surface that extended down from the uppermost part of rock glacier is exactly ~0.12 km^2. The debate about terminology is rather semantic, but we agree that the proper terminology should be clarified and employed. The Reviewer mentioned several times the concept of minimum size for glacier definition, advocating 'a *correct use of the term "glacier" and an adequate physical understanding of minimal-size surface ice.*' We would appreciate from the Reviewer a clarification and references to recent publications about this size threshold and its physical meaning. We could not find it from recently published glossaries and glacier inventory guidelines or from published inventories.

We would like to draw to the attention of the Reviewer the recently accepted definitions for *glaciers* and *glacierets*. In the *Glossary of Glacier Mass Balance and Related Term* quoted by the Reviewer (Cogley et al., 2011), and referenced by the World Glacier Monitoring Service (http://www.wgms.ch/guidelines.html), the following definitions are found:

- **Glacier:** *'A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of* *past or present flow.'* (Cogley et al., 2011, p.45)

- **Glacieret:** *'A very small glacier, typically less than 0.25 km2 in extent, with no marked flow pattern visible at the surface. To qualify as a glacieret, an ice body must persist for at least two consecutive years. Glacierets can be of any shape, and usually occupy sheltered parts of the landscape. Windborne snow and avalanches can be dominant contributors to the accumulation of glacierets.'* (Cogley et al., 2011, p.46).

There is no size threshold involved in the latest accepted definition of a glacier. The 0.1 km^2 threshold size appears to have arisen from a remote-sensing classification requirement: ice masses less than 0.1 km^2 were difficultly classified from filtered Landsat TM imagery in the original Swiss Glacier inventory (Paul et al, 2002a) and this minimum glacier size was later recommended for comparing TM-derived areas with glacier inventory data derived from aerial photography (Paul et al, 2002b). While the 0.1 km^2 size still appears to be used in order to compare glacier inventories between each others, no specific size threshold for defining a glacier appears in recent glacier inventory guidelines (Raup and Khalsa, 2010). Paul et al (2010), which include the Reviewer as co-author, advice that glaciers less than 0.01 km^2 (and not 0.1km^2) should not been included in inventories[1]. Recently published inventories (e.g. Andreassen et al, 2008; Nicholson et al, 2009) include glaciers smaller than 0.1 km^2.

Our interpretation of the GPR reflectors as deformational structures characteristic of glacier facies may be taken as evidence of past movement. Hence according to accepted definitions (Unesco, 2011) the massive ice could originate from a former *glacier*. On the other hand it is quite possible that upon becoming progressively buried, the downwasting glacier had at some point become a glacieret, i.e. was smaller than 0.25 km^2 and was essentially a stagnant ice body (little or no movement).

In the discussion about the possible genesis of the Sachette rock glacier we proposed that glacial ice became progressively buried during glacial decay. In this conceptual genesis model, the decaying glacier progressively becomes buried by debris originating from rockfall and melting out of englacial debris. The precise climatic conditions that would have caused the glacier to recede and become buried is unknown, but must necessarily involve a prolonged period of negative mass-balance, with sustained or increased debris supply from surrounding rock walls. The thin perennial surface ice bodies that the Reviewer is referring to, which have no clear-cut accumulation and ablation areas, are, according to accepted definitions, glaciers or glacierets (if less than 0.25 km^2 and without apparent movement pattern). These ice bodies have also been observed by the authors, in the Alps and the Andes. While in some cases they do seem to results from accumulation by avalanching, in other cases they originate from small, decaying cirque glaciers (or glacierets) which progressively becoming buried.

Conclusion: The reported observations confirm our understanding of permafrost creep and periglacial rock glaciers. These observations are interesting but provide no evidence of anything extraordinary or unusual. It is unnecessary to warm up long out- dated speculations about "glacial origins" of morphological features and occurrences of surface ice, which – for simple reasons of size – are not called glaciers in inter- national programmes of glacier monitoring and inventory (cf.

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[1] *From Paul et al, 2010, p.2*: 'On the other hand, a size of 0.01km^2 could be seen as a practical lower limit, as entities smaller than this can be very numerous and their status as glaciers is likely to be doubtful. This is also the minimum size that can be identified with certainty under good conditions from satellite sensors operating at 15–30m spatial resolution (e.g. Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), SPOT High Resolution Visible (HRV), Landsat Thematic Mapper (TM)/ Enhanced TM Plus (ETM+)). It is thus recommended that 0.01km^2 be used as the minimum size to be registered when conditions permit.'

http://www.wgms.ch/ or Cogley, J. G., R. Hock, L. A. Rasmussen, A. A. Arendt, A. Bauder, R. J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson, and M. Zemp (2011). Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, 114 pp.). The authors may consider to either reduce their paper to an objective description of the measured information or to add further, complementary and better field measurements. With the latter, a much more solid paper on the internal structure, thermal condition and creep behavior of mountain permafrost in the studied region could then be submitted.

Our answer: The reported observations and their analysis extend our understanding of permafrost creep and rock glaciers. The investigated structure showed the existence of a well-identifiable type of inner stratigraphy, consisting of concave, spoon-shaped, syncline reflectors reminiscent of glacial inner structures, and associated with high radar wave velocities and exposures of massive ice on the surface. This type of rock glacier structure has only been highlighted in a few publications and differs from others GPR works on rock glaciers (see references previously cited). While the Reviewer may advocate that rock glaciers do not form from former glaciers, previous work, some long-dated (e.g., Potter, 1972; Johnson, 1980) but also more recent studies (e.g., Whalley and Azizi, 2003; Krainer, 2010) propose different views. We are of the opinion that rock glaciers have polygenetic origins, and while our data does not allow concluding with certitude on the glacial origin of the ice body, we nonetheless present strong evidence for it. Hence we do think that our study is a valuable contribution toward understanding the genesis and development of rock glaciers.

The Reviewer advices us to either reduce our paper to an objective description of the collected information or to add further complementary field measurements.The latter option is unfortunately logistically and financially impossible. We will therefore choose the former option. The new version of our manuscript will organize itself as follows: (1) study site description, including the presentation and interpretation of ground thermal conditions and rock glacier activity; (2) GPR methods; (3) presentation of the GPR results; (4) discussion, focusing on the significance of the high radar wave velocities and peculiar deformational structures. The latter discussion will consider – and select among – every plausible option for the genesis of the rock glacier, i.e. both periglacial and glacial origins for the depicted internal structure.

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