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A NEW METHOD TO ESTIMATE THE INFILLING OF ALLUVIAL SEDIMENT OF GLACIAL VALLEYS USING A SLOPING LOCAL BASE LEVEL

ABSTRACT: JABOYEDOFF M. & DERRON M.-H., *A new method to estimate the infilling of alluvial sediment of glacial valleys using a sloping local base level*. (IT ISSN 1724-4757, 2005).

A new method is used to estimate the volumes of sediments of glacial valleys. This method is based on the concept of sloping local base level and requires only a digital terrain model and the limits of the alluvial valleys as input data. The bedrock surface of the glacial valley is estimated by a progressive excavation of the digital elevation model (DEM) of the filled valley area. This is performed using an iterative routine that replaces the altitude of a point of the DEM by the mean value of its neighbors minus a fixed value. The result is a curved surface, quadratic in 2D.

The bedrock surface of the Rhone Valley in Switzerland was estimated by this method using the free digital terrain model Shuttle Radar Topography Mission (SRTM) (~92 m resolution). The results obtained are in good agreement with the previous estimations based on seismic profiles and gravimetric modeling, with the exceptions of some particular locations. The results from the present method and those from the seismic interpretation are slightly different from the results of the gravimetric data. This discrepancy may result from the presence of large buried landslides in the bottom of the Rhone Valley.

KEY WORDS: Glacial valley, Infilling sediment, Volume estimation, Sloping base local base level, Digital terrain model.

INTRODUCTION

Sediment flux variations over time depend on climate (Harbor & Warburton, 1992), especially in Alpine areas where erosion by abrasion of weathered material, landslide areas and weak terrain is stronger during glacial periods (Augustinus, 1995; Harbor, 1995; Hinderer, 2001). High erosion rates during glacial periods are partly recorded in the sediment deposed in the glacial valleys (Hinderer, 2001). In the Swiss Alps, high alluvial sediment fluxes are known just after the Last Glacial Maximum (LGM) (Hinderer, 2001). After the glacial retreat, lakes created by over deepening of the valleys became sediment traps, reducing the sediment flux to areas down valley.

In the last 20 years many studies have attempted to estimate sediment volumes in Swiss glacial valleys (Wildi, 1984; Pugin, 1988; Finckh & Frei, 1991; Besson & *alii*, 1992, Pfiffner & *alii*, 1997; Rosselli & Olivier, 2003). These volume estimations indicate relatively high erosion rates of around 1 mm a^{-1} for the Rhine and Rhone valleys, contrasting with the present denudation rates of around 0.2 mm a^{-1} (Schlunegger & Hinderer, 2001).

The locations of glacial valleys are often linked to the occurrence of weak, highly erodible bedrock (Harbor, 1995) but also to highly strengthened areas leading to rock fracturing (Augustinus, 1995). Augustinus (1995) interprets glaciers as «removers of pre-fractured rock», indicating that glacial erosion is linked to a cycle of glacial and interglacial periods, the unbuttressed slopes being destabilized during the interglacial periods. This succession of glacial and interglacial period frequently leads to the formation of U-shape valleys. Nevertheless the absence of U-shape valley does not mean that no glacial erosion has affected the valley (Harbor, 1995).

Glacial valley cross-sections were studied by Weehler (1984) and Li & *alii* (2001) showing that a quadratic equation ($z = ax^2 + bx + c$) fits the U-shaped valley well. The quadratic equation is more robust to describe valley sections than a power law (Li & *alii*, 2001).

Usually, the volume estimations are based on longitudinal interpolation of seismic profiles across a valley, on drill holes and simple geometrical methods (Besson & *alii*, 1992, Pfiffner & *alii*, 1997; Aarseth, 1997). Such approaches are

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often time consuming and expensive, requiring several days of heavy field investigation and interpretation. The recent availability of digital elevation model (DEM) such as the global SRTM (Shuttle Radar Topography Mission) or the Swiss DHM25 (digital elevation model with a 25 m grid: www.swisstopo.ch) permits an estimation of sediment infilling volumes with a new and fast method based on the Sloping Local Base Level (SLBL) concept (Jaboyedoff & *alii*, 2004). We present the first results of this method for the upper Rhone valley between the Lake of Geneva and the city of Brig (Switzerland). The results are compared to previous studies using seismic and gravimetric interpretations. The great advantage of the present method is that only a few hours were required to obtain reliable results. We have chosen to work with the SRTM because of its worldwide availability.

MORPHOLOGICAL AND GEOLOGICAL SETTINGS

The Rhone Valley is located in the western Swiss Alps (fig. 1). This glacial valley was probably partly excavated during the LGM period. The glacial retreat took around one thousand years after the LGM 17,000 BP (Hinderer, 2001). The infilling of the valley was rapid after that period indicating a rapid erosion and high sediment fluxes within the basin. The interpretations of seismic sections across the Rhone Valley were performed by Besson & *alii*, (1992), Pfiffner & *alii*, (1997), and Finckh & Frei (1991). Rosselli & Olivier (2003) have used previous data (Besson & *alii*, 1992; Finckh & Klingele, 1991; Finger & Weidmann, 1988) to refine the interpretation of new gravimetric data. The Rhone Valley is mainly filled by a basal till deposit overlain by glacio-lacustrine sediments covered by deltaic sequences often interlaced or overlain by alluvial fans (Pfiffner & *alii*, 1997). The estimated maximum thickness of the Quaternary sediment is around 900 to 1000 m (Pfiffner & *alii*, 1997). The total volume of sediment in the Rhone Valley was estimated to be 80 to 100 km^3 by Rosselli & Olivier (2003) and to 106 km^3 by Hinderer (2001) based on seismic data.

METHOD

The Sloping Local Base Level (SLBL) is a generalization of the base level concept, traditionally defined in geomorphology as applied to rivers, but applied in this case to the study of landslides. Base level was first defined during the 19th century by J. W. Powell as the lower level that can be affected by land erosive processes. This means that after an infinite time, the relief is eroded to a land at the sea level altitude (Strahler & Strahler, 2002). The local base level is the same concept but applied to a restricted area, the lower limit being a lake or a basin floor (Ahnert, 1996; Burbank & Anderson, 2001). The SLBL is defined as a surface above which rocks are assumed to be erodible by landsliding (Jaboyedoff & *alii*, 2004). The SLBL can be determined either manually, or by using an iterative routine.

The SLBL routine was adapted to estimate the bedrock surface of filled glacial valley (fig. 2). The areas recognized as filled by sediments are deepened by an iterative routine applied to a DEM squared mesh with the following rules:

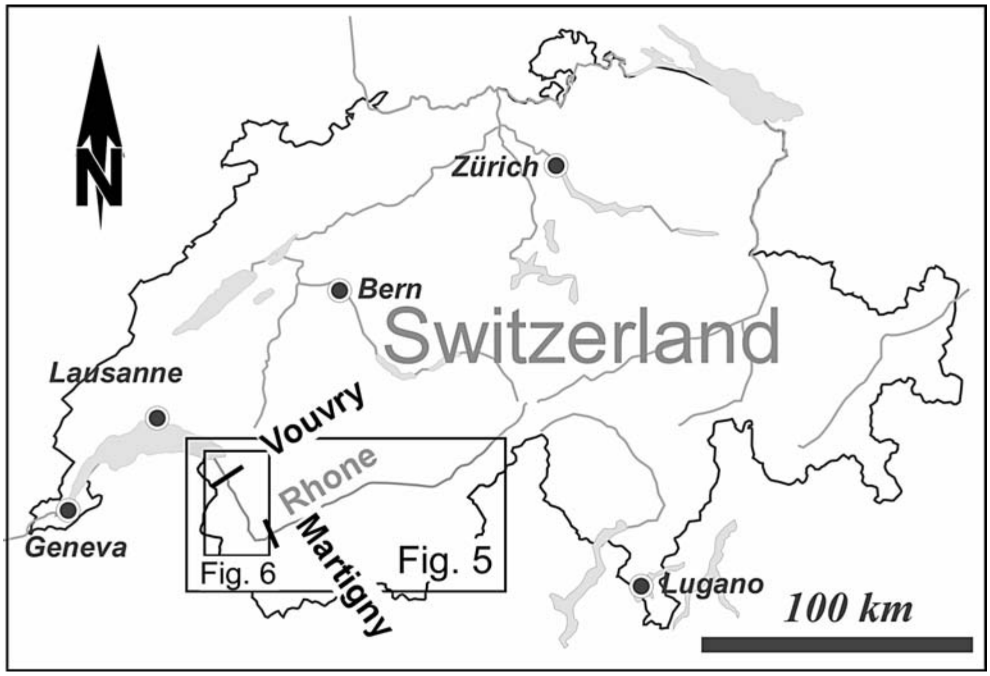


FIG. 1 - Location of the studied area and the profiles of Martigny and Vouvry.

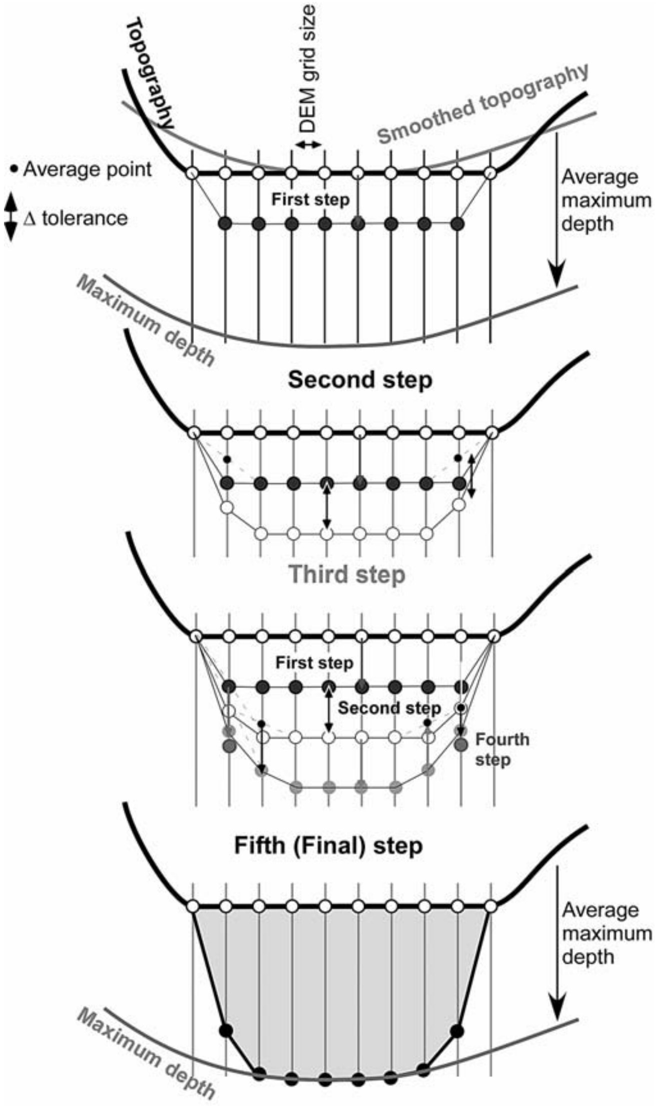


FIG. 2 - 2D representation of the SLBL method indicating intermediary steps of computation. At each step a point is replaced by the mean of its two neighbors minus the tolerance Δz. If the maximum depth is reached, it is replaced by the maximum depth value.

A point (a pixel of the DEM) has four direct neighbors. Opposing neighbors having the greatest difference in altitude are chosen as elevational extremes. If a point is located above the mean of its two extreme neighbors minus a tolerance value Δz, its altitude is replaced by the mean value of the two extreme neighbors minus Δz. The routine is run until the surface stays unchanged between two iterations (fig. 2). The area of the DEM processed with the SLBL is defined by the contour of the sediment filling the valley. The routine can be also stopped before at an intermediate iteration.

Bedrock absolute value of curvature scales positively with greater Δz. High values of Δz lead to very steep flanks of the bedrock. The value of Δz can be estimated and chosen by inspecting the result in 2 dimensions, because in this case the shape is a parabola:

$$z = ax^2 \quad (1)$$

where a is a constant equal to half of the second derivative:

$$z'' = 2a = \frac{2 \times \Delta z}{(\Delta x)^2} \quad (2)$$

where Δx is the size of the grid mesh. The maximum depth of a valley of width L can be estimated using:

$$z(\max) = \frac{a}{4} L^2 \quad (3)$$

The above argument demonstrates that in 2D the results of the SLBL are parabolas in agreement with the quadratic profiles proposed by Weehler (1984) and Li & *alii* (2001) to describe glacial valley cross-sections.

A surface of maximum depth of the SLBL can be defined too. Here, a smoothed topography lowered by the maximum possible thickness known from seismic profiles has been used (fig. 2). A smoothed surface, calculated by a moving average, has been chosen because it is assumed that the more erodible the rocks are, the wider the valley and the deeper is the bedrock must be. A moving average performed with a range larger than the valley width generates a smoothed topography higher (less deep) in the narrow parts of the valley than in the wider parts. Using this topography lowered by the maximum expected depth of the bedrock, a limiting basal surface is created. It leads to a U-shaped valley for the SLBL surface.

The shape of the bedrock obtained by the present method is dependant on both Δz and Δx. A suitable Δz value can be chosen based on equation 2 and 3. Nevertheless in its present form the method is sensitive to the DEM grid orientation, because if the excavation is oblique to the grid the apparent Δz is smaller by a factor cos α, where a is the angle between the grid and the orientation of the limit of the valley (figs. 3 and 4). As a consequence a is given by:

$$a = \frac{2 \times \Delta z}{(\Delta x \times \cos \alpha)^2} \quad (4)$$

The comparison of computed results with the equation (4) shows a good agreement (figs. 3 and 4), but some differences appear, because the grid orientation makes the limit of the valley irregular, owing to the problem of lines transformed to pixels.

RESULTS

The method was applied using the SRTM DEM (NASA, 2000) with a grid mesh of 92 m. A mean filter over a square of 41 x 41 (~3666 x 3666 m) grid points has been used to create the smoothed topography. Based on seismic data near Martigny, we assume that the maximal

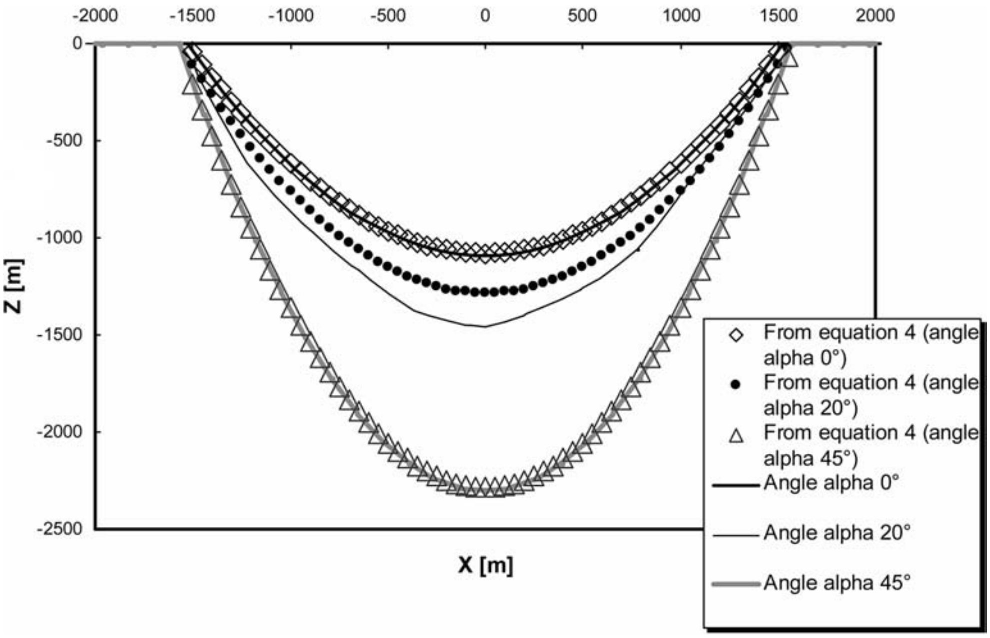


FIG. 3 - Profiles obtained with the SLBL, with different orientations of a 3000m wide valley, compared to the results from the equation 4. A discrepancy is visible for α=20°.

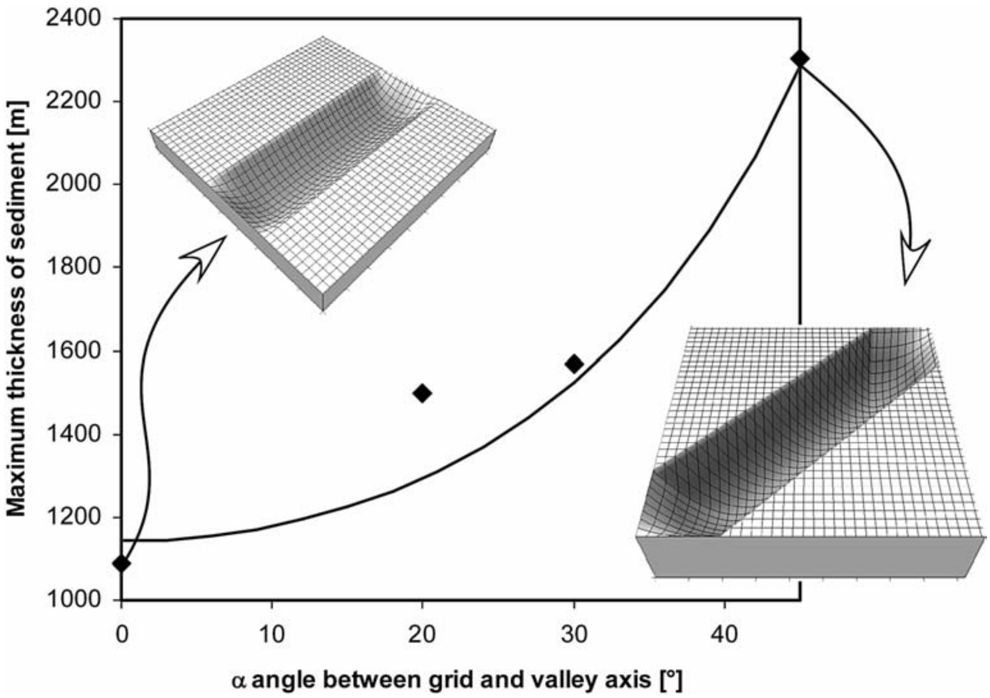


FIG. 4 - Relationship between the orientation of the valley relatively to the DEM grid and the greatest depth of the valley. The line is the theoretical value for a 3000 m width valley assuming a quadratic profile (equation 4). The points indicate the results from the SLBL showing some discrepancies caused by the numerical method applied to a grid. Examples are displayed as blocks diagrams for α = 0° and 45°. See also figure 3.

thickness of sediment is about 900 m. Note that we use only one punctual estimation (not all the seismic data) that could also have been a borehole data. As a consequence the smoothed topography was lowered by 900 m to get the limiting basal surface. To compute the bedrock surface we used $\Delta z = -4$ m in the SLBL calculation (figs. 3, 5, 6 and 7). The choice of $\Delta z = -4$ is based on the fact that assuming a 3 km wide valley the expected depth of excavation will be around 1000 m (eq. 3). Moreover, the angle of the valley axis with the grid being about 20° in a large part of the area of interest, increases slightly the deepening. This leads to a U-shaped valley because the SLBL procedure excavates below the 900 m lowered smoothed topography used for the lower limit of the

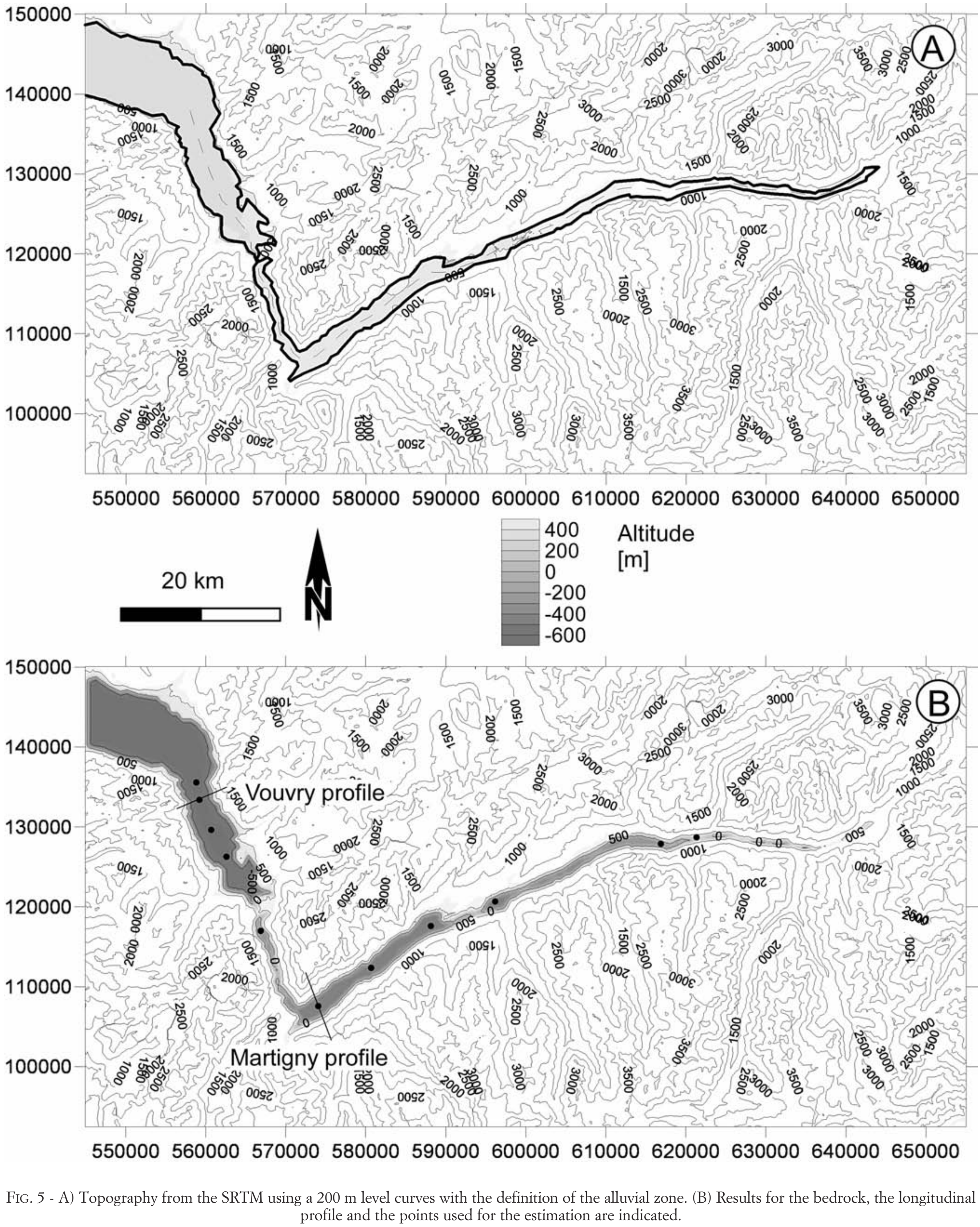


FIG. 5 - A) Topography from the SRTM using a 200 m level curves with the definition of the alluvial zone. (B) Results for the bedrock, the longitudinal profile and the points used for the estimation are indicated.

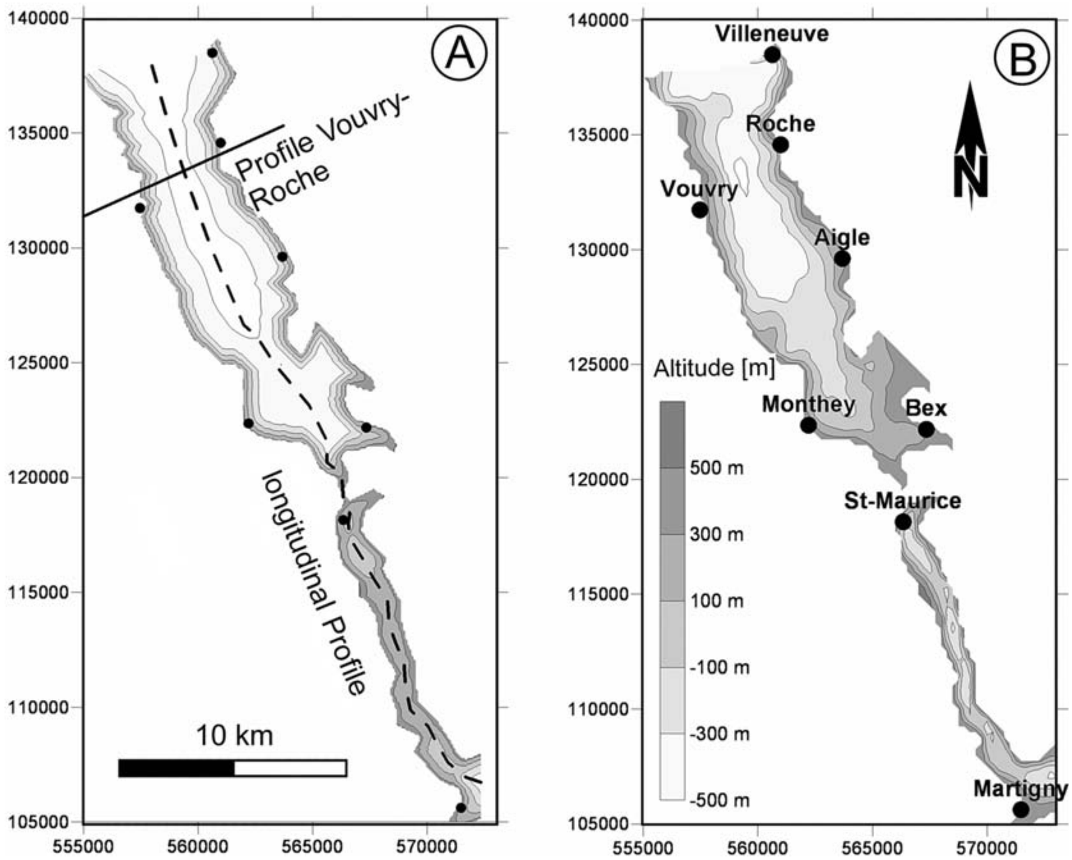


FIG. 6 - Comparisons of the isohypses of the bedrock deduced from the present method (A) and the gravimetric data (B) (Modified from Rosselli & Olivier, 2003).

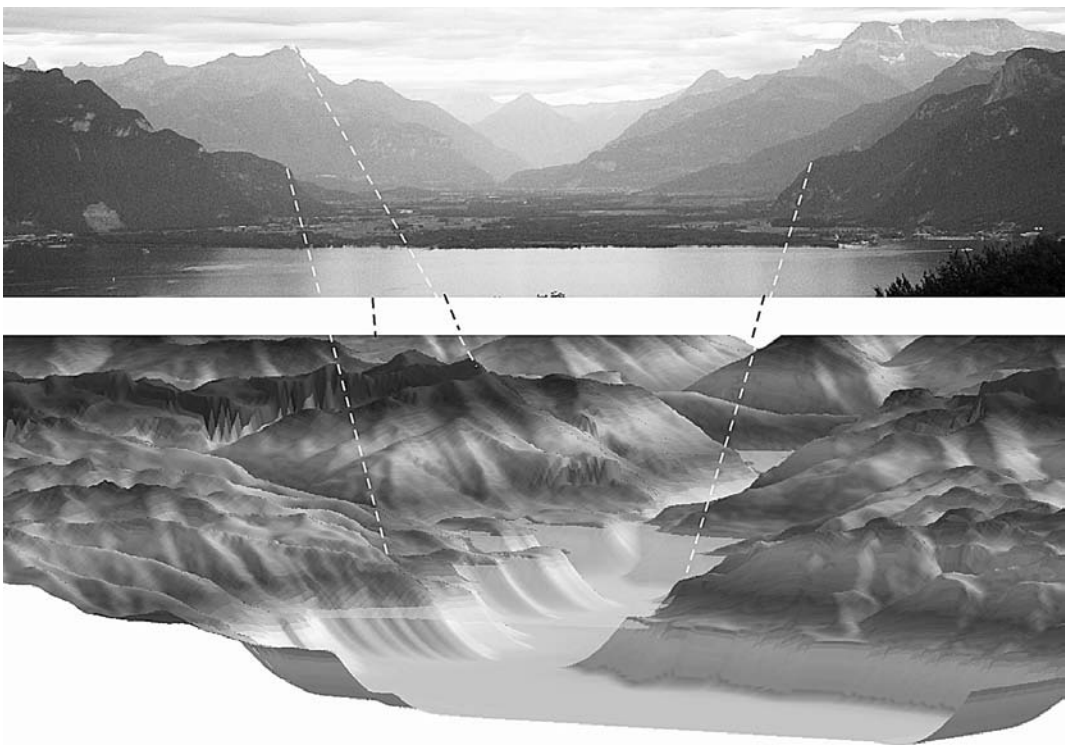


FIG. 7 - View of the Rhone valley down towards the southeast. On the bottom the results with the present valley level and top a picture of the Rhone valley.

bedrock. Nevertheless, depending on the width of the valley, the depth reached by the SLBL estimation does not always reach the limiting basal surface defined by the smoothed topography minus 900 m.

The comparison of the SLBL longitudinal profile with the seismic and gravimetric interpretations indicates that the three models provide similar results (figs. 8, 9 and 10). The correlation between the deepest point locations of the eleven seismic profiles with results given by gravimetric interpretation are good, but the gravimetric results have been calibrated with the seismic data (Rosselli & Olivier 2003). The results of the SLBL method are well correlated with the results of the two other methods except for two points that show an over-deepening near shallow bedrock in the Sion and Bex areas (figs. 8 and 9). The differences between each of these profiles are of the same magnitude except in some areas where the valley is narrow like between Martigny and St. Maurice and probably near Sion. In these areas the SLBL method does not deepen the valley enough (fig. 8). In the region of Bex the SLBL model deepens too rapidly, parallel to the valley, right after the outcropping bedrock which can lead up to 400 m difference in these particular cases. Usually disagreements with the seismic profile do not exceed 150 to 200 m in depth and is usually closer to 100 m. A similar discrepancy exists with the gravimetric data too, but this can be explained because the seismic profile has been used for the gravimetric interpretation. Even if the gravimetric longitudinal profile presents some differences up to 400 m with the SLBL model, the major tendencies are similar.

The models for the western part of the Rhone Valley, between Martigny and the Lake of Geneva, shows the same tendency as observed along the longitudinal profile of the eastern part. Nevertheless, the bedrock valley from the SLBL method has steeper flanks than the other models (fig. 5).

The transversal profile near Martigny gives a symmetrical U-shaped valley (fig. 10A). The two other interpretations are slightly asymmetric, but the overall shapes are very similar. In this case the lowered smoothed topography limits the vertical extent of the digging by the SLBL routine.

For the profile Roche -Vouvry, the SLBL model matches very well the interpretation of Finckh & Frei (1991) based on seismic data (fig. 7B). The gravimetric model shows a more complicated shape. Here also, the maximum depth defined by a lowered smoothed topography is a good solution to obtain a sensible morphology of the bedrock.

Comparing the present SRTM DEM and the results of the SLBL model, the volume of sediment is estimated to 118 km^3. This estimation is close to the 106 km^3 of Hinderer (2001) based on seismic results (Pfiffner & *alii*, 1997) and of the same order of magnitude as the 80-100 km^3 obtained by Rosselli & Olivier (2003).

DISCUSSION

Compared to the seismic and gravimetric estimations, the SLBL approach is faster. The results from the SLBL model are roughly in agreement with the two other interpretations; nevertheless some systematic errors can be noticed. The SLBL method produces quite symmetrical valley shapes, in most cases U-shaped if a basal limit is added, which is in agreement with many observations from bedrock profiles across glaciated valleys (Anhert, 1996). Even if in the present case we have used the only estimate of the maximum thickness of sediment from the seismic data to deduce the maximum sediment thickness, it is usually possible to assume a reasonable value for this parameter. This can lead to rapid results without any deep knowledge of the area, the only condition being to delineate the area of the valley filling on the DEM.

The parameter Δz modifies the curvature of the bedrock morphology. This value was set in the case of the Rhone Valley to produce very steep sides of the bedrock valley. Generally, the obtained bedrock profile is wider than for seismic or gravimetric interpretations. If this artifact is quantified, a correction factor can be applied to avoid the overestimation of the volumes. The transversal profiles indicate that the present method produces U-shaped valleys while the seismic and gravimetric interpretations are more V-shaped and irregular. Sometimes the deepening with the SLBL method is too strong

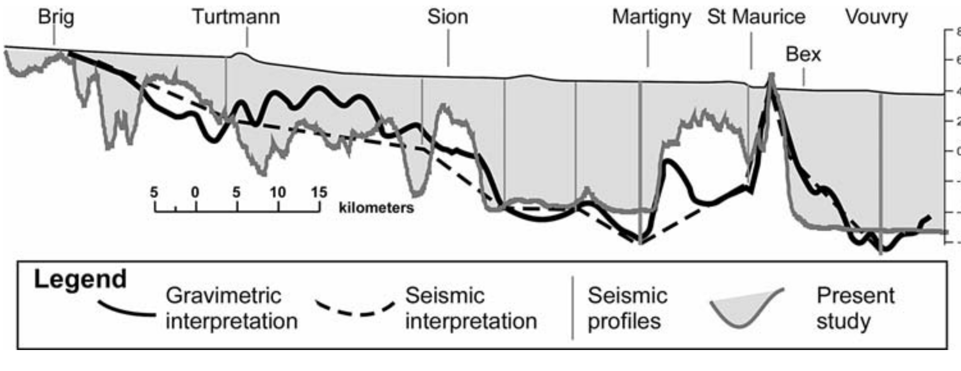


FIG. 8 - Longitudinal profile of the bedrock surface along the Rhone Valley. The results are compared to the seismic interpretation (Besson & *alii*, 1992) and with the gravimetric interpretation (Rosselli & Olivier, 2003).

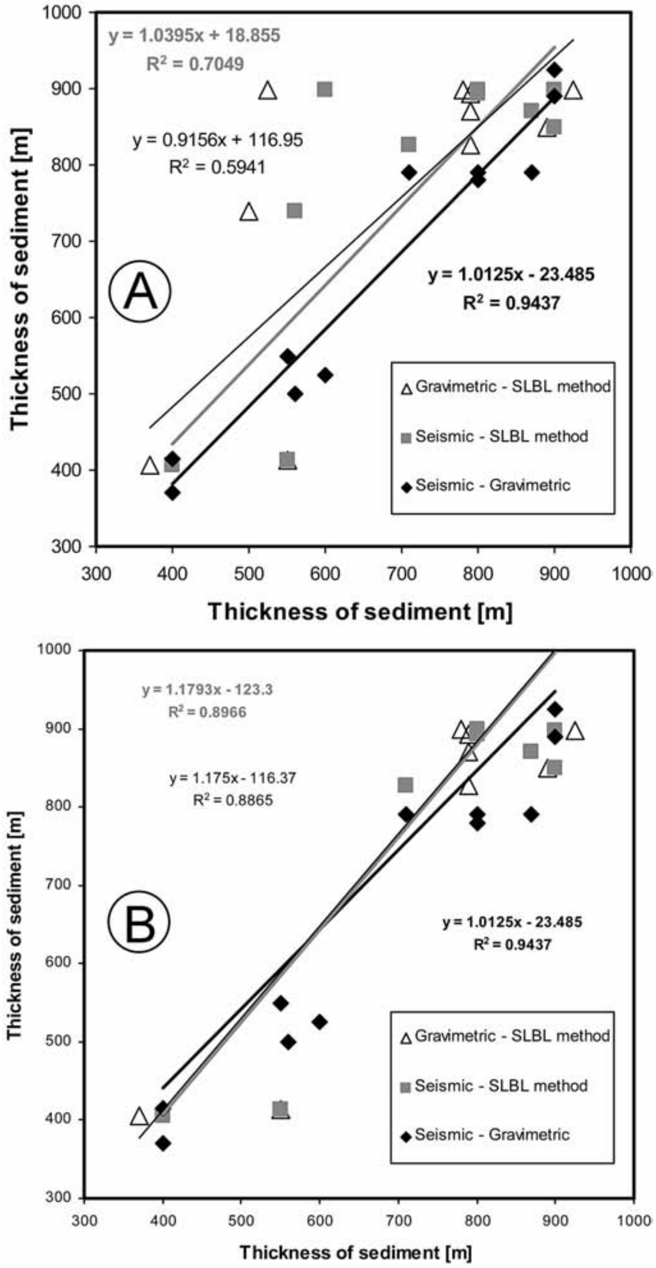


FIG. 9 - Correlations between results obtained from the different methods at the deepest location of all the 11 recorded seismic profiles. The comparison between seismic and gravimetric interpretations is good because the second one takes into account the first one. The comparison between SLBL method and the two others is bad if two points obtained near high level of the bedrock topography are taken into account (A). If those erroneous points are not taken into account the results are similar to the other methods (B).

in comparison to the two other interpretations. This is caused by the occurrence of the bedrock very close to the surface, as near Bex (fig. 6). A systematic error of the SLBL method is the estimation of the slope angle of the bedrock along a longitudinal profile of the valley, because in reality this angle can be the same, more gentle, or more steep. For a future interpretation, such an area must be removed from the zone of sediment filling or different conditions of maximum depth must be set in this location. One possibility is to take into account the slope angle and the curvature of the present relief of the valley flanks to induce automatically local Δz values. This would introduce an implicit characterization of the geomechanical properties of the rocks in the model (Rouiller & *alii*, 1997; Locat & *alii*, 2000). In this case, the region section Martigny - St- Maurice would be steeper than the presented results, because the steep valley flanks would induce a steeper bedrock valley.

The routine must also be improved because now the amount of deepening is dependent on the orientation of the grid relatively to the valley. Actually, because we have used a limiting basal surface, this problem represents only a small percent of error in the profile surface area.

The SLBL profiles are more U-shaped, symmetrical and smooth than the profiles from the seismic and gravimetric interpretations. It is interesting to notice that profiles resulting from gravimetric data can indicate bumps in the bottom of the valley. These bumps don't appear in the seismic and SLBL profiles. These differences can be explained by large landslides and rockfalls which would have occurred immediately after the LGM. The seismic data would not distinguish a mass of loose rock blocks from the other sediments, while the gravimetric data would consider the rock blocks as a higher density material.

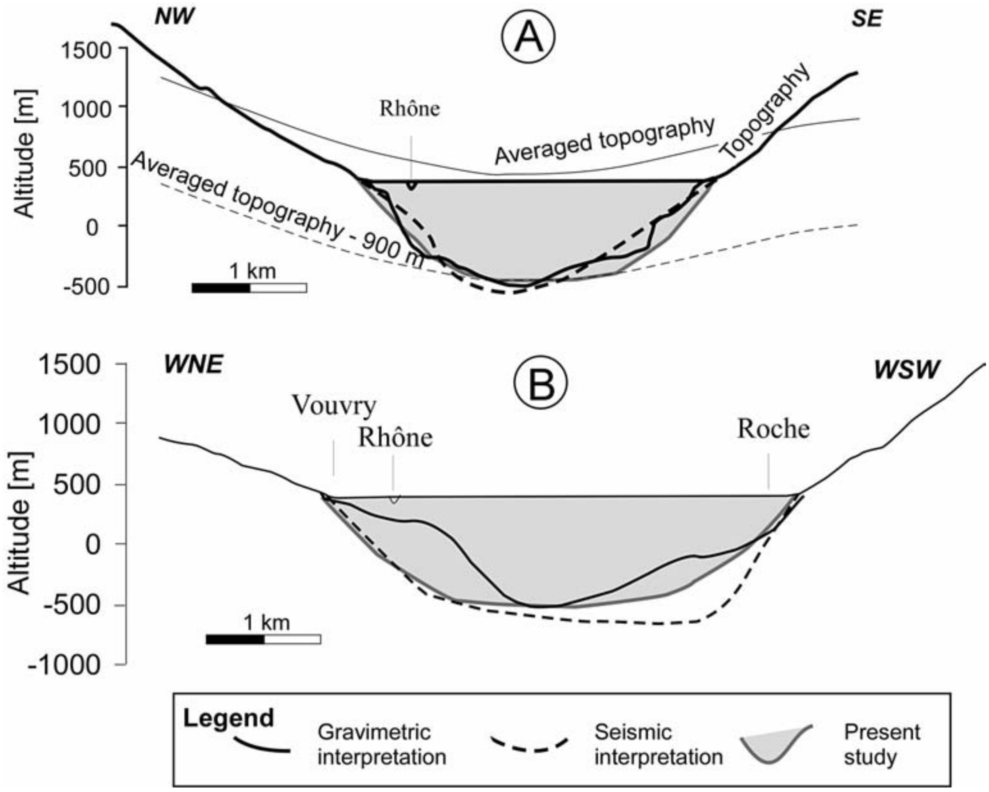
CONCLUSION

The results are surprisingly good when compared to the volume estimations from former studies based on seismic and gravimetric surveys. The SLBL volume is slightly overestimated but this discrepancy can be explained. Further evolutions of the method will lead to a better integration of the available information.

It appears that, with some improvements, the SLBL method should be able to provide more accurate estimations than those obtained in the present study. But even this simple model allows an estimate of the sediment volume of the Rhone glacial valley with a difference of about 10% with the interpretation based on several seismic profiles and a difference of about 30% with the gravimetric interpretation, because the latter produces a less deep bedrock surface. Taking into account other available information (geology, profiles by seismic, etc.), an improved version of the present method should permit the users to perform rapid assessments of sediment volumes based on a free DEM.

Our results point to a discrepancy between the gravimetric and seismic interpretations. To reconcile both, the possibility of landslides and rockfalls lying on the bottom the filling of valley is suggested.

FIG. 10 - A) comparison of interpretations on the Martigny profile. B) Idem for the Roche - Vouvry profile. The grayed area (with black line as border) represents the results of the SLBL method; the large gray lines represent the interpretation from gravimetric data and the large gray dashed lines represents the interpretation based on seismic.



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