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Preliminary note on uplift rates gradient, seismic activity and possible implications for brittle tectonics and rockslide prone areas: The example of western Switzerland

by

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Abstract.–JABOYEDOFF M., BAILLIFARD F. and DERRON M.-H., 2003. Preliminary note on uplift rates gradient, seismic activity and possible implications for brittle tectonics and rockslide prone areas: The example of western Switzerland. *Bull. Soc. Vaud. Sc. nat. 88.3*: 401-420.
Current uplifts of Switzerland calculated from geodetic leveling are the results of the ongoing tectonic movements. The analysis of the uplift velocity values indicates that they are compatible with the global European tectonic stress field. The calculation of the gradient vector norm of uplift permits to locate the areas of the highest potential vertical shear strains. Results indicate that a correlation exists between higher values of uplift gradient and historical earthquake locations. Furthermore, fracturing as well as some landslide locations can be related to the zones of differential uplift, as in the case of the Randa rockslide.

Keywords: Uplift, gradient, earthquake, landslide, rockslide, brittle tectonics.

Résumé.– JABOYEDOFF M., BAILLIFARD F. et DERRON M.-H., 2003. Note préliminaire sur les taux de soulèvement, l'activité sismique et les implications possibles pour la tectonique cassante et les zones à glissements rocheux: l'exemple de la Suisse occidentale. *Bull. Soc. vaud. Sc. nat. 88.3*: 401-420.
Les soulèvements qui affectent la Suisse sont l'expression des mouvements tectoniques actuels. Ces mouvements sont estimés à partir de différents nivellements. La répartition des soulèvements est en accord avec les contraintes globales qui affectent les Alpes. Les normes des gradients permettent de délimiter les régions dans lesquelles les contraintes cisaillantes potentielles sont les plus élevées. Ces zones à fortes valeurs de normes de gradients peuvent être corrélées avec la localisation des activités sismiques historiques

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les plus élevées. Par ailleurs, on peut observer que les zones de fracturation importantes ainsi que la localisation de certains mouvements de versant comme l'éboulement de Randa peuvent être corrélées avec les zones de normes de gradient élevées.

Mots clés: Surrections, gradient, tremblement de terre, éboulement, tectonique cassante.

INTRODUCTION

Many data sets indicate that high topographical reliefs (e.g. Alps, Himalayan Ranges), like the Mt.-Blanc Massif (France) (SEWARD and MANCKTELOW 1994), are often affected by rapid and recent uplifts, which are correlated with high erosion rates (SCHLUNEGGER and HINDERER 2001, 2003; FINLAYSON *et al.* 2002). The relief height depends also on the erodability of the slope rock type (KHÜNI and PFIFFNER 2001a). Such high relief regions are also subject to medium to high seismic activity linked to recent tectonic (SCHLUNEGGER and HINDERER 2001).

The evolution of landscape depends on current and past uplifts (c.f. BURBANK and ANDERSON 2001), as it is illustrated by the Swiss Alps (SCHLUNEGGER and HINDERER 2001, 2003; KÜHNI and PFIFFNER 2001b). The differential uplift movements modify the relief by simple plastic or elastic deformations, and also by brittle deformations in the upper part of the crust, that results in movements along recent or ancient faults. Such deformations lead to seismic activity and landsliding, which depend mainly on fracturing of the brittle part of the upper Earth's crust (JABOYEDOFF *et al.* 2003a).

Uplift velocity values are controlled by the vertical component of the movement of the earth's crust and by erosion. A zone of low or zero uplift (i.e. no vertical component) can be considered stable since there is no horizontal movement. Zones of high uplift velocity can be considered stable if vertical movements uniformly affect these zones. Only the borders of areas of homogeneous uplifts are submitted to differential vertical movements. As a consequence the borders are submitted to intense erosion, which is driven by the high difference in topographic elevation; and by the climate, especially by very high and intense precipitations.

This paper presents the spatial correlation existing between differential uplifts and earthquakes in Switzerland. The impact of differential movements on fracturing and on landslide and more specifically rockslide is considered.

GEOLOGICAL SETTINGS

The Swiss Alps are made of stacks of several nappes that have thrust the foreland to the northwest (ESCHER *et al.* 1997, BURKHARD and SOMMARUGA 1998, STAMPFLI *et al.* 1998). The northwestern nappes are mostly cover nappes that where separated from their basements during alpine subduction, whereas the southeastern nappes are made of gneissic rock that are partly their basement (Fig. 1). The Alpine collision has led to a bulge of the Alpine chain in the SW-NE direction and to a subsequent transpression regime to the south-southwest (STECK 1984, MAURER *et al.* 1997, KÜHNI and PFIFFNER 2001a).

Current movements lead to a medium seismic activity (RÜTTENER 1995; GLOBAL SEISMIC HAZARD MAP 1999). The seismic activity is mainly located in the southwestern part of the Alps and in some other particular areas. For example earthquakes occur in Sierre in 1946 (MSK-Intensity VIII), an aftershock of which triggered the rockfall (6 millions m^3) of le «Six des Eaux-Froides» (MARIÉTAN 1946, F. Philippossian, pers. comm.) and in the context of the Rhine graben the Basel earthquake in 1356 (MSK-Intensity IX-X) (PAVONI 1977, MAYER-ROSA and CADIOT 1979) triggered several rockfalls (BECKER and DAVENPORT 2003). The greatest seismic activity is situated at the northern limit of the large transpression system of the Rhône-Simplon fault within the southwestern Swiss Alps (MAURER *et al.* 1997, STECK 1984, ESCHER *et al.* 1997). The presence of regional active strike-slip faults indicates that the transpression system is still active.

A large number of landslides have been noted in the Swiss Alps (EISBACHER and CLAGUE 1984). Slope instabilities are often induced by movements along faults, ground seismic activity, or by uplift movements. A typical example is Illgraben in Valais with its river catchment, submitted to intense erosion leading to frequent debris flows (M. Sartori pers. comm.).

DATA AND THEIR DESCRIPTIONS

The uplift data used for this study are given by changes in elevations between successive geodetic leveling surveys in the last century from KAHLE *et al.* (1997). The measures were collected along the main Alpine valleys (Fig. 1). The main current uplifts are located in the southeastern part of Switzerland (Fig. 1), whereas the northwestern displays a zero or negative uplift velocity values. The zero value is located in Aarau, NW Switzerland. Global Positioning System (GPS) data indicate that it is a quasi-static point (Dr. U. Marti, pers. comm.). These measurement points are not homogeneously distributed in Switzerland, thus the location of the maximum uplift values obtained by the geodetic leveling surveys does not correspond exactly to the true location of the maximum value of uplift velocities.

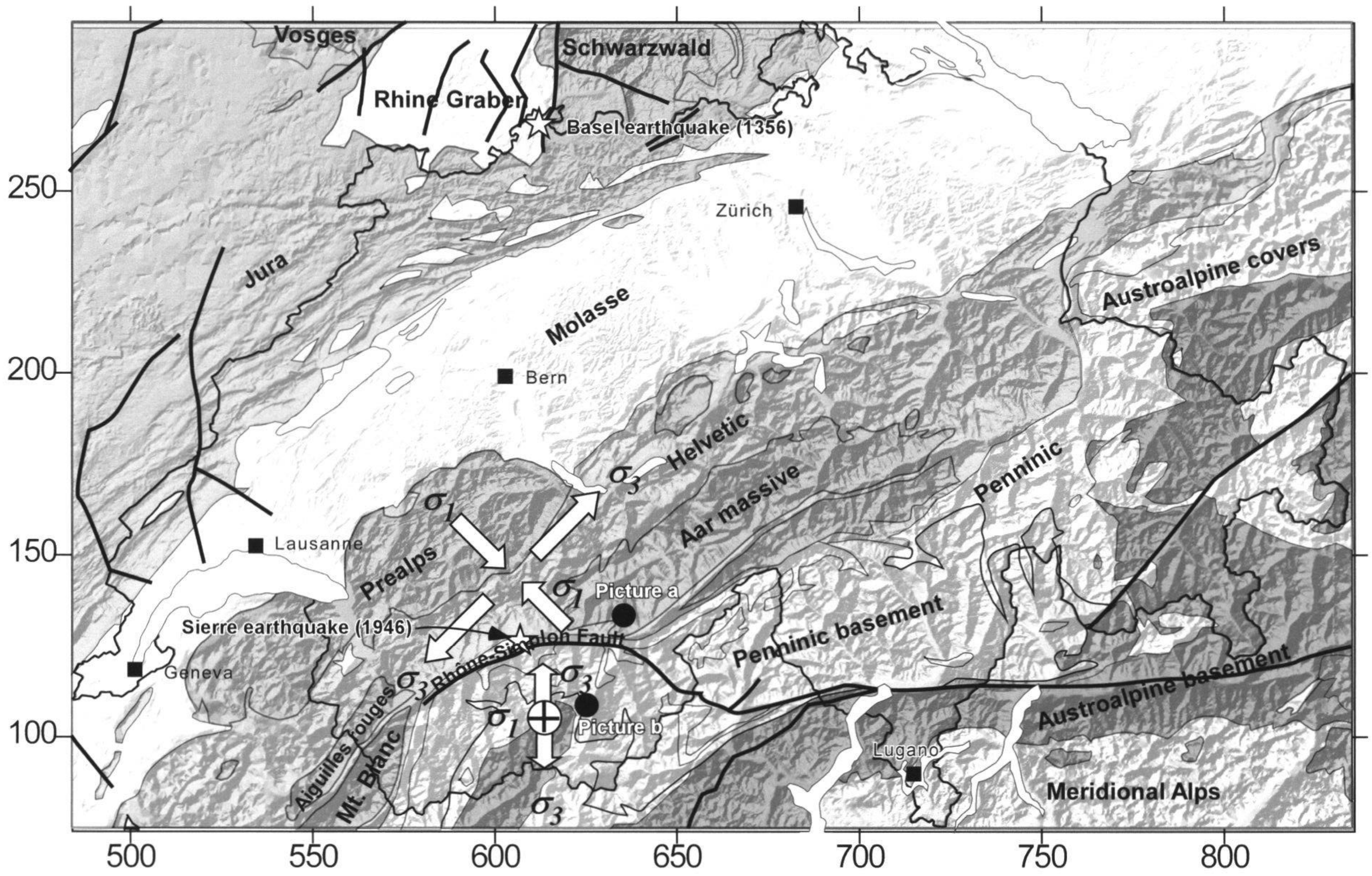

Figure 1A.– Geology (after Swiss tectonic map, http://www.bwg.admin.ch/) and global stress field from MAURER *et al.* (1997). DEM RIMINI Federal Office of Topography (DS 033032).

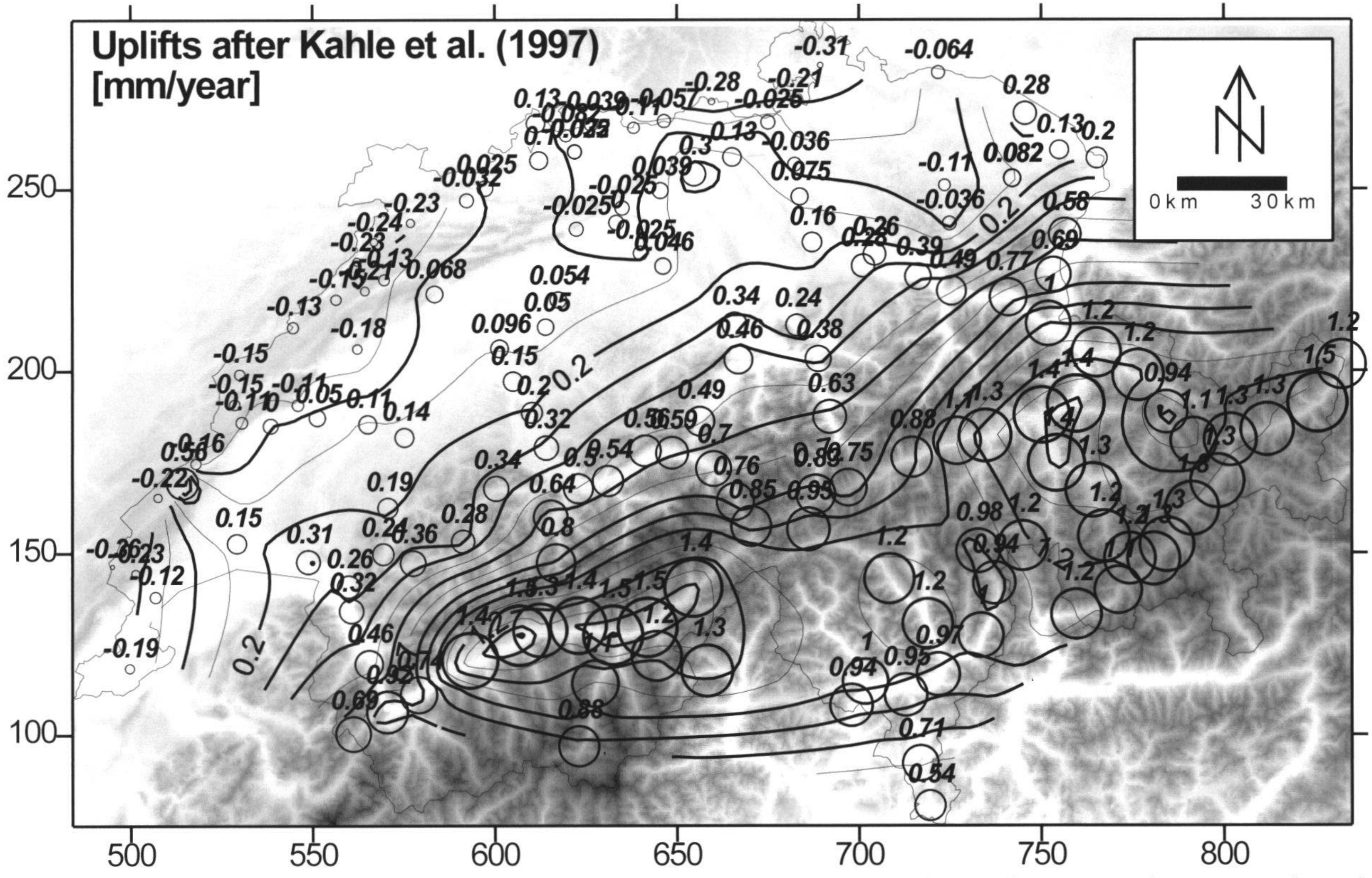

Figure 1B.–Maps of the uplifts calculated using the difference in altitude between the leveling surveys that were performed during 1903-1990 (KAHLE *et al.* 1997). Contouring of uplifts using natural neighbor SURFER(C) program. The background is a grayed elevation map (DEM RIMINI Federal Office of Topography (DS 033032)).

Examination of the variograms (ISAAKS and SRIVASTAVA 1989, PANNATIER 1996) shows a spatial correlation of the uplifts. The variograms indicate that uplifts change more rapidly transversally to the Alpine chain than along the Alpine chain. This is consistent with the Alpine bulge, which is orientated perpendicularly to the principal stress fields affecting the Alps, (MUELLER and KAHLE 1993, KASTRUP 2002.), indicating that current uplift movements have most likely a tectonic origin and are not caused by the postglacial rebound. An additional argument against postglacial rebound is the low uplift velocity values observed in the foreland basin, i.e. the Molasse (Fig. 1), which was completely covered by an icecap during last ice age (JÄCKLI 1962). At the regional scale of Switzerland, the uplift field displays a non-stationary spatial structure (Fig. 2). Thus, the use of a simple kriging method is not relevant for interpolating uplift data. Considering the current data set, the appropriate method is the natural neighbor method, which takes into account of the areas of influence of the neighbors (SURFER 1999).

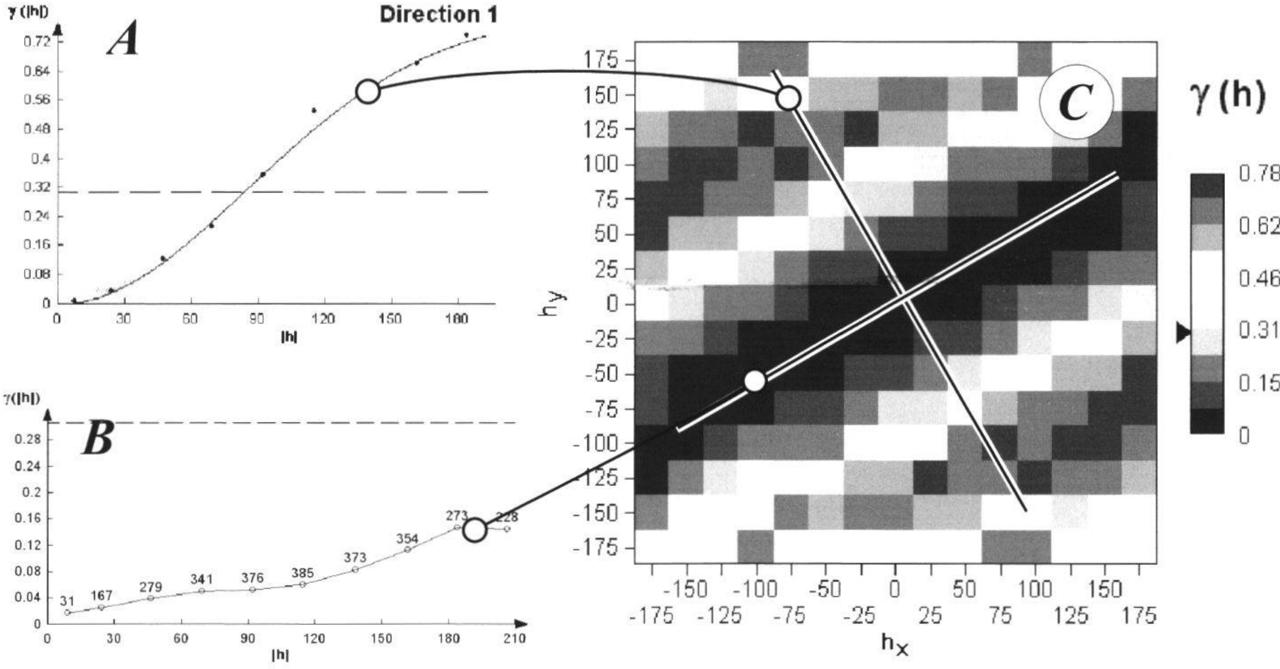

Figure 2.–(A) Variogramm for 150° direction displaying the greatest variability and model using two Gaussian components. (B) Variogramm perpendicular to A indicating the smallest variability. (C) Variographic surface of the uplift showing the great variability across the chain.

The seismological data are extracted from PAVONI (1977) by digitization. This data set reflects the historical data, including the main events. This data set is more reliable to uplift data than more recent data sets (DEICHMAN *et al.* 2002) because it reveals high active zones for a longer period of time. The current regional tectonic stress regime of the western Swiss Alps is extracted from MAURER *et al.* (1997) using earthquakes fault solutions. Based on analysis of recent earthquakes, MAURER *et al.* (1997) show that:

a) The south of the Rhône-Simplon (SW-NE) fault is in extension in the direction N-S (σ_3) with a vertical σ_1.

b) The northern part is in compression leading to a strike-slip regime with a σ_1 NW-SE and a horizontal σ_3 (REINECKER *et al.* 2003).

c) The general regime is a NW-SE compression (MUELLER and KAHLE 1993), which is underlined by the high uplift rates in the region of the Rhône-Simplon fault.

ANALYSES OF UPLIFTS GRADIENT VECTOR NORM

The magnitude of gradient vector norm of displacement velocity is a good indicator of zones submitted to high deformation. For example, the horizontal displacement gradient near the fault of San Andreas indicates that the fault is located at the place of the highest value of the norm of the gradient (SHEN *et al.* 1996).

Basically, uplifts are indicators of the movements and/or erosion in the vertical direction. They do not give any information about the relative movements. That is why the analysis of gradient of the uplifts is more reliable to detect the strained zone. For a given gradient of a surface f(x, y, z) = C, where x, y and z are the spatial coordinates and C a constant, the norm of the gradient is equal to the tangent of the slope of the surface. Assuming z the uplift velocity, the gradient vector norm (G) is given by (KREYSIG 1999, SURFER 1999):

$$\left|\vec{G}\right| = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}$$

Regions where the potential vertical shear strain are the highest are given by the highest value of the uplift gradient This implies that the upper brittle crust has to be adjusted by faulting if uplift velocities are high enough, or by reactivation of pre-existing faults. In other words, this implies that areas with uniform uplift velocities are not subject to differential movements, but areas showing differences in movements are the locations in which deformation is concentrated.

RESULTS FOR EARTHQUAKES

The map in Figure 3 displays gradient vector norms, which are compared to the uplifts velocity mapping. The map shows that the highest gradient vector norm values are located where the uplift isolines are the closest together, in other words where the slope of the uplift values is the highest. The main areas of differential uplifts are located in the southwest of Switzerland, near Zürich and in the northeast.

The comparison of uplift gradient with historical earthquakes indicates that the areas with a gradient above 0.03×10^{-6} mm km^{-1} $year^{-1}$ are correlated with a high density of historical earthquakes (Fig. 3).

The greatest values of gradient vector norms are linked to faults (e.g. Simplon fault zone in the Alps or known fault systems within the Jura range). For other locations with high uplift gradients, no fault data are reported. However, the Rhine graben may have an important impact on the uplift in the northwest part of Switzerland, because of the ongoing subsidence. In the eastern part of Switzerland, the gradient of uplifts and the seismic activity are smaller. The correlation between uplifts and earthquakes is in general less well-defined than in the southwestern part. The seismic activity in the central Swiss Alps is probably linked to the transpressive system.

POSSIBLE TECTONIC CONTEXT LEADING TO UPLIFT

The uplift velocities change more rapidly transversally to the Alpine chain than along the chain. Three different tectonic settings can be proposed for high uplift gradient:

a) Extension faults that lead to a differential movement introducing a strong uplift gradient;

b) Thrust ramp or reverse fault with a vertical component;

c) Uplift caused by bulging, or backfolding, or extrusion (ESCHER and BEAUMONT 1997, CHEMENDA *et al.* 1996)

The gradient vector norm does not give any information about the movement direction (up or down). Thus the gradient vector norm must be coupled with uplift values to determine whether the vertical movement inducing a gradient vector norm is upward or downward. The tectonic setting comprising extension faults (a) is compatible with the tectonic setting of the north of Switzerland, including the Rhine graben, and partly of the southern central part of Switzerland. The second tectonic setting (b) illustrates the western bipolar anomaly in the Jura range, northwest of Lausanne, which is situated at the intersection of conjugated faults, and where vertical movements is the result of movements along near-vertical faults used to adjust the shortening of the earth's crust.

The third tectonic setting (c) is certainly the most probable cause of the Swiss uplifts since the general regime strength is compressive and the complete Swiss Alpine relief is uplifted. Furthermore, the anisotropy of the spatial correlation in Figure 2 indicates that the intensity of deformation varies parallel to the greatest shortening axis, which is the direction of compression σ_1 (NW-SE).

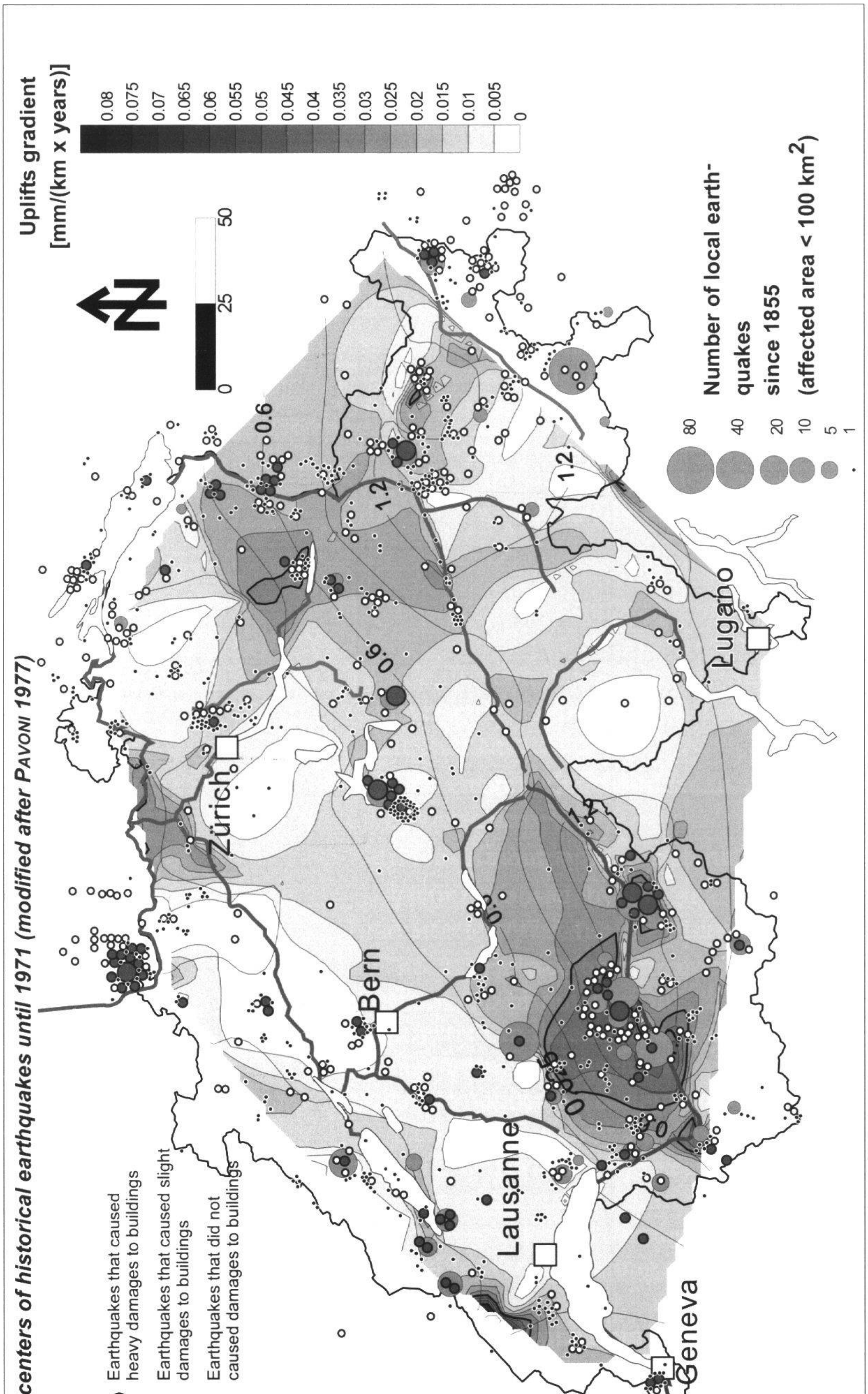

Figure 3.–Map of uplift gradient in Switzerland and historical earthquakes with the legend on map.

The Alpine bulging and backfolding have been active for the last 30 million years (ESCHER *et al.* 1997, ESCHER and BEAUMONT 1997). In the Alpine compression context, the earthquakes are often found as signature of extension. However, the tectonic stress deduced from earthquakes gives orientations of the local fault but not the complete global field stress (KASTRUP 2002). Despite the existing extension towards south and southwest, the uplifts remain active, indicating that the global stress regime is compressive (MUELLER and KAHLE 1993, REINECKER *et al.* 2003).

PROPOSED GEOMETRICAL MODELS

A brittle upper crust submitted to differential uplift change its geometry by changing its length. It is achieved by movements along faults generating earthquakes (SIBSON 1983). In this proposed 2D model (Fig. 4), the upper crust is considered fractured and the horizontal length of the uplifted zone is maintained constant during the uplift. Therefore, shortening and extension of the basal limit of the brittle crust are necessary to maintain geometrical continuity (no holes) in the upper crust. Such a model indicates also that the fracturing direction and location of faults can be controlled by the thickness of the upper brittle crust (Fig. 4).

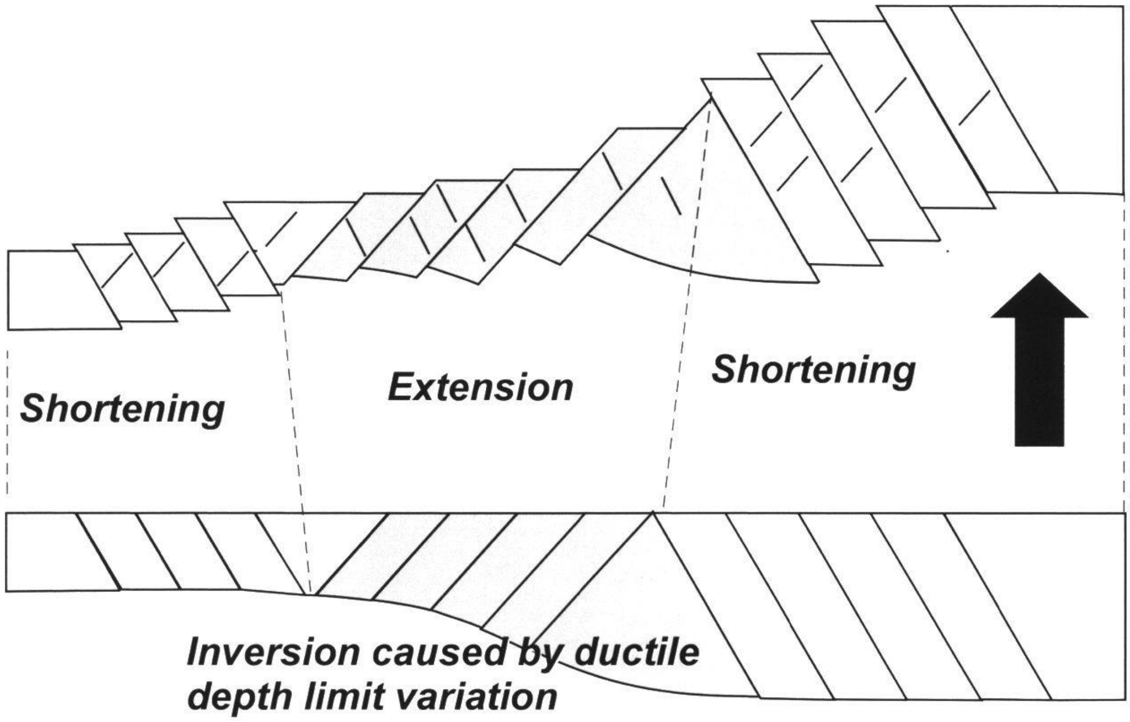

Figure 4.–Vertical uplift and surface adjustment explanation (the vertical scale is exaggerated): Adjustment to uplift without horizontal global variation in length. Note that the possibilities of faulting orientations are controlled by the thickness of the brittle crust (not to scale).

If the crust is shortened, then the number and total length of extension zones are reduced (Fig. 5). Considering the global tectonic movement of shortening affecting the Alps (MUELLER and KAHLE 1993, REINECKER *et al.* 2003), the observed uplifts found their origin in the deep ductile crust beneath the Alps. Such a situation promotes extrusion of ductile material (ESCHER and BEAUMONT 1997), which leads to a bulge that facilitates an extension in the upper crust (CHEMENDA *et al.* (1996), MAURER *et al.* 1997). The CHEMENDA extension model is very similar to the one proposed in Figure 4, but both do not take into account the possibility of movement along pre-existing faults.

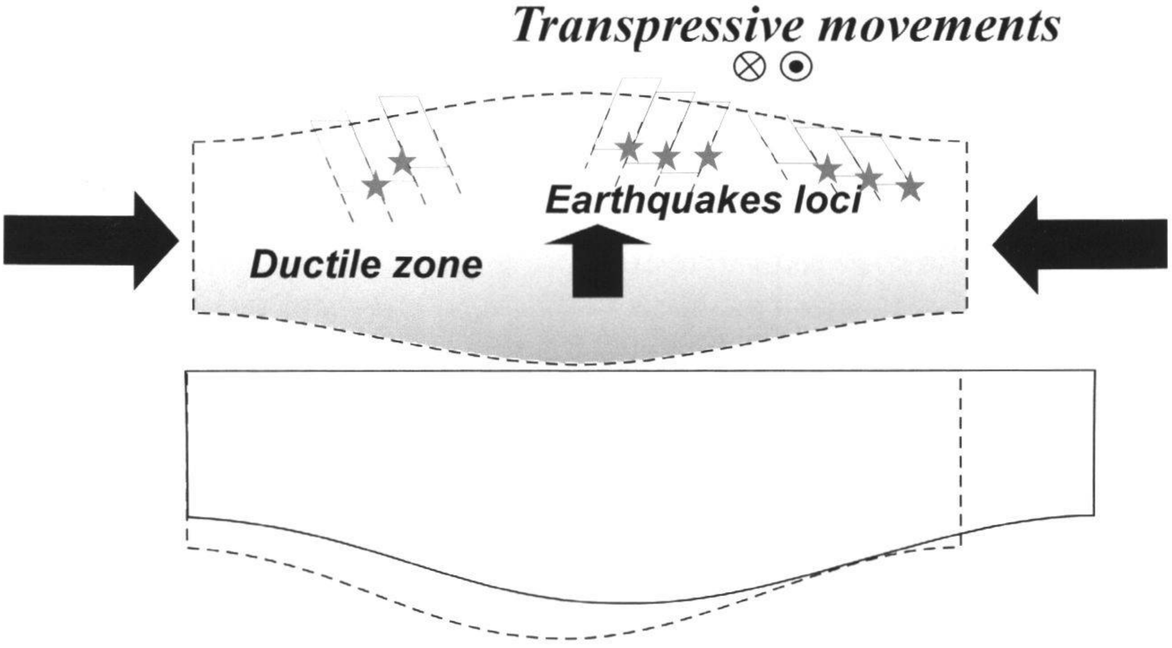

Figure 5.–Vertical uplift and surface adjustment explanation (the vertical scale is exaggerated): Global compressional regime where shortening adjustment is performed by brittle tectonic in the upper crust. The extension and shortening locations and ratio may depend on the position in the bulge. Transversal movements are also possible. The earthquakes can be located along the fracturing produced by uplift and shortening (not to scale).

Following the above hypothesis concerning the deep origin of uplifts, it can be assumed that shortening increases with depth, then the lower ductile zone is bulged by the large scale shortening that pushes the upper brittle curst upward (Fig. 6) and downward in the roots. This mechanism leads to an extension of the topographic surface. The upper part of the bulge (mostly deformed area) can undergo shortening depending on the material flux distribution. This shortening deformation on the right side of the model induced upward movements on the other side, which is limited by a vertical non-moving side of the model corresponding to the central part of the Alpine bulge. The entire Alpine bulge can be illustrated by duplicating symmetrically this proposed model (Fig. 6) around the non-moving zone.

This 2D model (Fig. 6) implies that the earthquakes are only associated to reverse and normal faults sensu stricto. In three dimensions, lateral movements are expected and transpression mechanism is possible. Then, faults can display relative reverse or normal movements but also strike-slip movements.

The Alpine framework is of course more complex. Uplifts and transpression mechanism are possible along pre-existing faults. Thus, fault orientations as well as earthquakes reveal only partially the uplifts. The presence of a bulge and strike-slip movements in the western Swiss Alps are compatible with the definition of transpression (SANDERSON and MARCHINI 1984) that can contain flower structure, i.e. vertical and lateral expulsion of the crust caused by shortening.

As shown by DEICHMANN (1993), most of the earthquakes in the Alps are located in the first 15 km beneath the ground surface. This is in agreement with the assumption of SISBSON (1983) that earthquakes are linked to the regional fracturing or to the reactivation of pre-existing faults caused by the 15 km upper crust adjustment of the brittle zone. In such a compressive regime, faulting occurs principally on reverse faults, but normal faults can be activated as well. This is the case in the southern part of the Rhône-Simplon zone where movements are compatible with the proposed model shown in Figure 6 (MAURER *et al.* 1997).

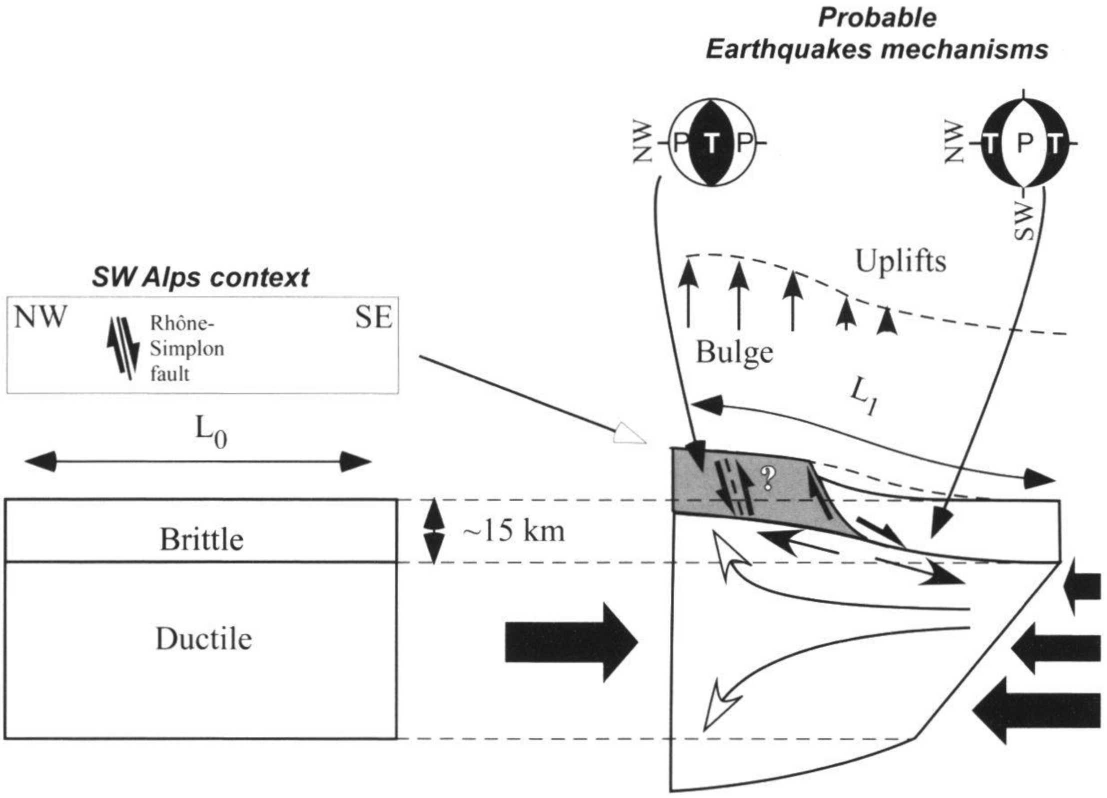

Figure 6.–Schematic illustration of a possible explanation (the vertical scale is exaggerated). L_0 being less long than L_1 the upper brittle crust must be adjusted mainly by extension but also by shortening (Fig. 4). The large black arrows are the possible strain components. Because no horizontal movement are recorded by earthquakes the transition between ductile to brittle is probably continue. White arrows are the potential ductile material paths, but note that it is a model for half space. Vertical arrows indicate the uplifts. The potential earthquake mechanisms are indicted P: Pression, T: Tension (not to scale).

ROCKFALLS AND UPLIFTS

It is clear that rockfalls triggered by earthquakes can be linked to uplifts in Valais or in Basel (BECKER and DAVENPORT 2003, MARIÉTAN 1946). In Valais most of the important historic rockfalls reported by various authors (Table 1) are located within areas with gradient vector norm of uplifts above 0.015 mm km^{-1} years^{-1} (Tab. 1; Fig. 7). The values go up to up to above 0.04 mm km^{-1} years^{-1} for the Six des Eaux-Froides rock avalanches triggered by an earthquake. The lowest value is obtained for the Illgraben catchment producing frequent rockfalls (E. Bardou, pers. comm.), but in that case the strike-slip movement is certainly dominant.

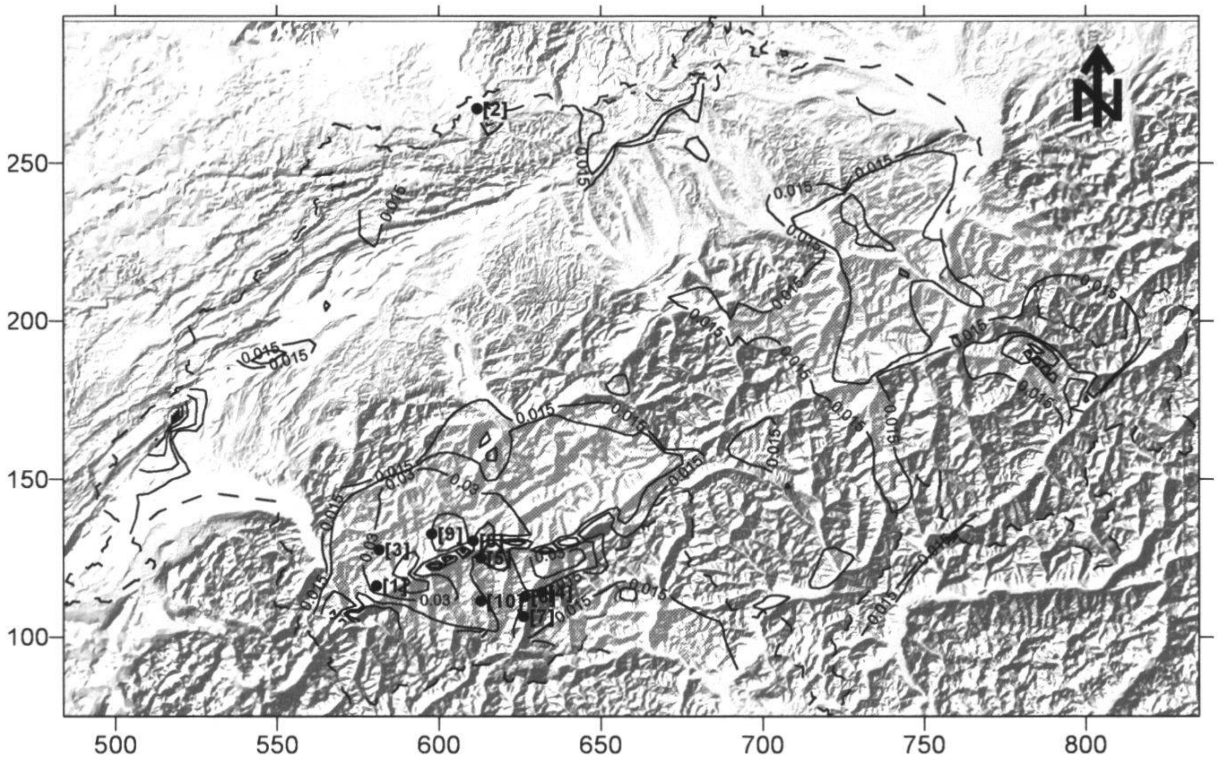

Figure 7.–Contouring of the gradient vector norm above 0.015 mm km^{-1} years^{-1} and rockslide location in Valais (black points). The numbers in bracket indicate the related lines in Table 1. The point in Basel is not a particular location of one rockfall but indicate that many rockfalls are reported for the 1356 earthquake. (DEM RIMINI Federal Office of Topography (DS 033032)).

The value for Basel is estimated from the nearest value gradient vector norm of the map, because Basel is situated at the border of Switzerland. No direct gradient data are available, but it is probably higher taking into account the values observed 40 km westward Basel, the effect of the 1356 earthquakes induced a lot of small rockfalls (BECKER and DAVENPORT 2003).

The 1991 Randa rockslide (volume: 30 × 10^6 m^3, SARTORI *et al.* 2003) and the recent 2002 St. Niklaus rockfall (Medji, volume ~100’000 m^3) are situated near the isoline 0.015 mm km^{-1} years^{-1} (Fig. 7), weather the cross-section of Figure 8 indicate 0.022 mm km^{-1} years^{-1}. This underlines the problem of

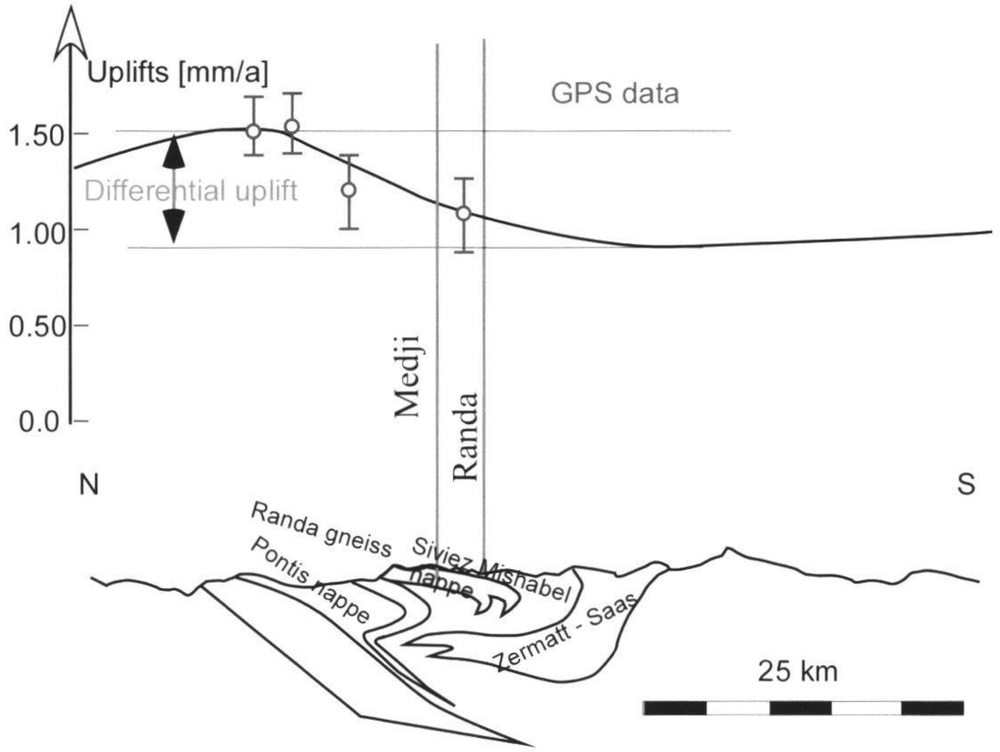

Figure 8.–Rockslide of Randa and Medji and uplifts along the Matter valley (after KAHLE *et al.* 1997).

interpolating data. Those two rockfalls belong to an area crossed by at least two sets of regional fault sets, which are expressed by ledges on the fields (JABOYEDOFF *et al.* 2003b; SARTORI *et al.* 2003). The development of those fault sets can be attributed to the proposed above model (Fig. 9).

Alpine landscapes often display large ledges, one hundred meters thick, with very small-observed displacements. For instance, vertical measurements in the Swiss Alps indicate a differential uplift of 0.6 mm/year for a 20 km section of the Mattertal (KAHLE *et al.* 1997). Assuming a theoretical 100 m-spaced vertical discontinuity pattern, the vertical displacement along each discontinuity would be equal to 30 cm for a period of 100’000 years, which is compatible with our field observations of fault displacements of repeating regional faults system in the vicinity of the Randa rockfall (Fig. 9a) (GIROD 1999).

These vertical displacements induce fracturing and movements along existing faults. Such movements can generate earthquakes along these faults, whereas potential unstable rock slopes can be located within those fractured areas. The fracturing or fault reactivation induces large faults that can be the location of rockslides as in Randa. Thus, the fracturing or the movements on pre-existing faults are sources of destabilization of slopes as the result of rock strength weakening which can lead to landslides.

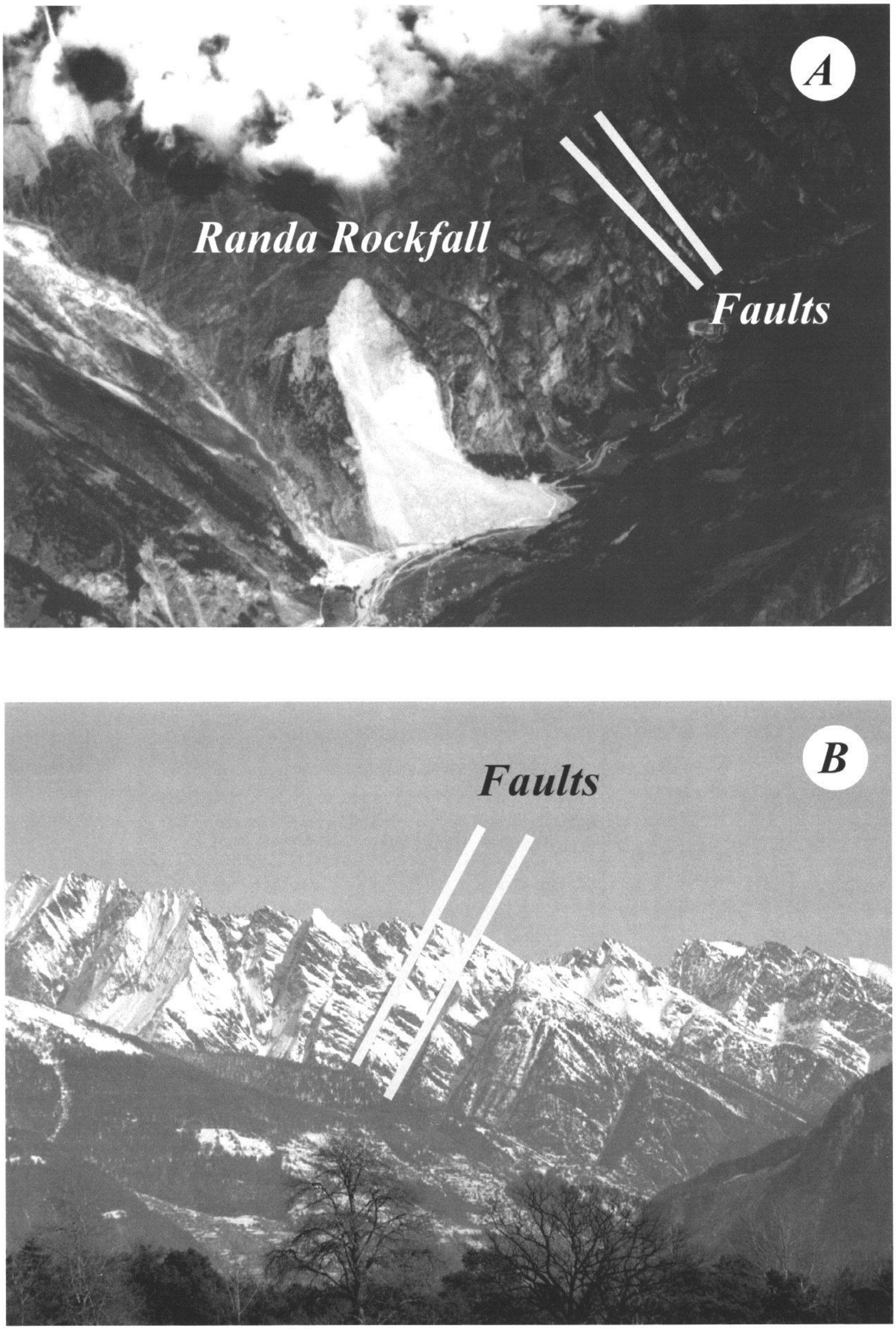

Figure 9.–Pictures showing (A) the highly-fractured zone in the northern part of the Randa rockslide in Mattertal and (B) in the Bitschhorn the fracturing is probably linked to Figures 4 and 5 explanations (source picture CREALP). See Figure 1 for location.

Table 1.–List of rockfalls which are presumably linked to differential uplift movements or fault movements. (From [1] EISBACHER and CLAGUE (1984), [2] BECKER and DAVENPORT (2003), [3] SARTORI et al. (2003), [4] BURRI (1997), [5] www.crealp.ch and MARIÉTAN 1946).

Num.	Location	Year	mm years^{-1} km^{-1}	Description
1	Ardève [1]	1570	0.035	Rock fall and large slump 5 × 10^6 m^3 of rock and deposit
2	Basel [2]	1356	0.020	Earthquake
3	Diableret [1]	1714, 1749	0.033	Rock-ice avalanches (~50 × 10^6 m^3)
4	Grächen [1]	1855	0.018	Rock avalanche
5	Illgraben [1]	Frequent	0.015	Debris flow and rock falls
6	Medji [1]	2002	0.015 (0.022)	Rock fall 100'000 m^3
7	Randa [3]	1991	0.014 (0.022)	30 × 10^6 m^3 rockfall
8	Sierre [4]	1946	0.035	~1 km^3 of rock
9	Six des Eaux-Froides [5]	1946	0.040	6 × 10^6 m^3 rock avalanches triggered by an earthquake
10	Val d'Anniviers [1]	13th century	0.022	Rock avalanche 2 × 10^6 m^2

DISCUSSION AND CONCLUSIONS

In the Swiss Alps, uplifts contribute to the fracturing of the earth's crust and to the reactivation of pre-existing faults of the upper crust as it is illustrated by the link between the gradient vector norm of uplifts and the earthquakes activity. The fracturing of the Alps is partly caused by the recent differential uplifts even if many faults were developed before the present stress field. Since the existing stress field is inherited from the late Alpine collision, and considering the extension regime occurring near the Simplon Pass along the eastern part of the Rhône-Simplon line, then the global stress fields would not have varied much during the last million years (STECK and HUNZIKER 1994). In Figure 10, the uplift gradient vector norm values are superimposed to the Rhône-Simplon line movements, which imply movements to the south being the result of the southeast uplift «extension» (Fig. 1) and of the southwestern strike-slip. Thus the adjustment of the upper crust by large, non-deformed (i.e. approximately planar), and newly or pre-existing faults (reverse and normal) is a good working hypothesis that can be compared to a transpressive system with flower structure.

Consequently the important fracturing and uplift movements can promote slope instabilities as it is highly suspected in the Mattertal. This hypothesis is important for slope hazard assessment because it induces progressive

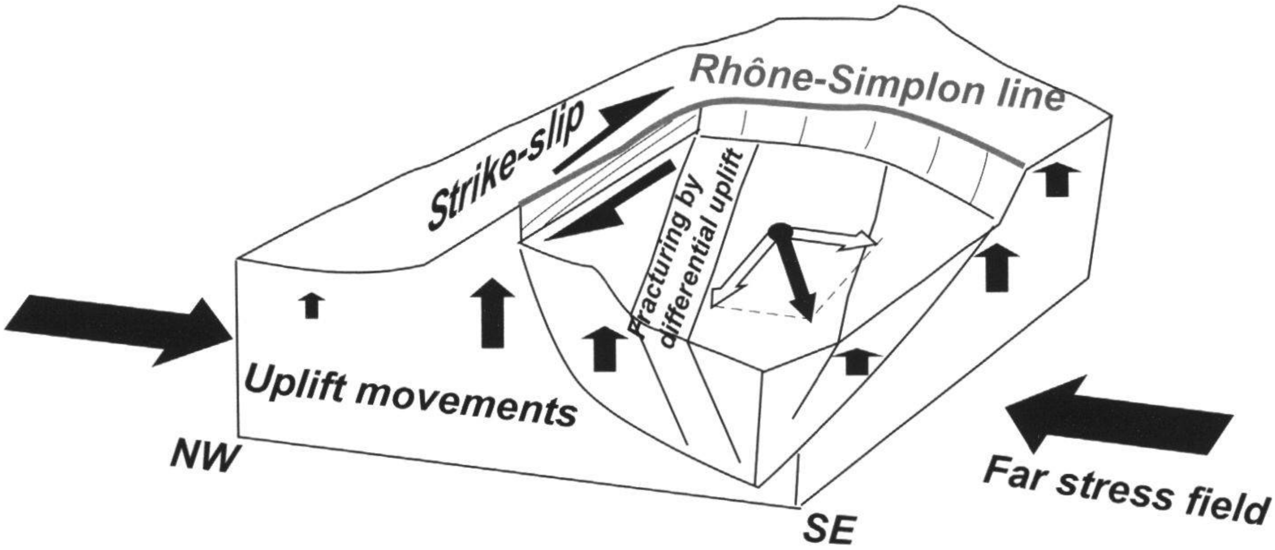

Figure 10.–(A) Schematic illustration of the Rhône-Simplon line system and the uplift movements.

movements along local preexisting faults, joint schistosity and stratification that progressively break up the rock slopes that lead to slope destabilization and in special cases to suitable material for debris flow. Quantification of the differential movements, such as uplift or fault movements and the effects they produce on the geometry of a slope with time (i.e. 100’000 years) is an access to time dependency of slope stability and thus to hazard assessment. The tectonic active zones are suspected to be the location of higher density of large volume landslide.

Furthermore, the possibility to predict zones of higher seismic activity using gradient vector norm of uplifts is promising. Zones with no record of historical earthquakes and submitted to high differential uplifts have to be inspected very carefully, since they can be the source of strong earthquakes if the energy is not released.

The rapid earth surface movements are now monitored by GPS techniques or radar interferometry (DZURISIN 2003). But at present the network of GPS data points is not sufficiently dense to provide detailed information on a large territory. Furthermore data obtained from regions with low velocity movements, such as the Alps compared for instance to the Himalaya, need time to produce accurate results for GPS and radar techniques. That is why classical geodetic data is still useful to develop new methods to characterize a tectonically active region with respect to earthquakes, geological structures and landslides, and why it becomes an interesting tool for earthquakes hazard assessment. Further developments of the proposed method (norm of the gradient of uplift velocities) adapted to 3D data are promising.

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