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Discussions

A 240 year History of Avalanche Risk in the Vosges Mountains from Nonconventional Sources

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Abstract. Despite their strong societal impact, systematic documentation of mountain risks remains poor. Thus, snow avalanche chronologies exceeding several decades are exceptional, especially in medium-high mountain ranges where activity can still be significant. This article implements a combination of historical and geographical methods leading to the reconstruction, at the scale of the entire Vosges Massif (north-east of France), of more than seven hundred avalanches that have occurred since the late eighteenth century on 128 paths. The clearly episodic nature of the derived geo-chronology can be explained by three interrelated factors that have changed together over time: the body and reliability of sources, social practices conditioning the vulnerability, and the natural hazard itself. Finally, the geo-chronology primarily reflects the evolution of the meaning of the hazard in the social space. Specifically, the event which could be retrieved from the historical sources is an aspect of the interaction between society and its environment. These results confirm the role of the historian in contextualizing and evaluating such data, transforming them into information relevant for risk changes understanding and mitigation. They also highlight the importance of constructing an original database from a diverse suite of historical data, and testing its fidelity using field investigations at an appropriate spatial scale. This general approach is of great utility for investigating other risk phenomena in the frequent situation where conventional sources are sparse and problematic to assemble

1 Introduction

Databases of historical events play a crucial role in evaluating the expected frequency and severity of natural hazards. However, they are typically sparse in their coverage, with their comprehensiveness hampered by multiple factors including: i) a close link to vulnerability, especially events with human casualties results in an under-representation of geophysically significant events that did not cause damage or fatalities; ii) a relatively short duration; and, iii) incomplete spatial coverage that excludes large regions. Such factors are particularly prevalent in developing countries where there is often an absence of relevant records from the period. In view of the destructive nature of hydro-climatic phenomena and of their considerable socio-economic impact, these limitations of existing records are paradoxical (IPCC, 2012).

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Avalanche risk is a characteristic illustration of this situation. Snow avalanches strongly impact upon the permanent and temporary populations of mountain areas in winter (for example: McClung and Schearer, 1998; Schweizer *et al.*, 2003), causing deaths, destruction (buildings, tourism infrastructure, power lines, forest stands), severing communications by cutting-off roads, and also cause losses related to an indirect vulnerability of mountain societies (the impact of the negative image of disasters on tourism etc.). Databases concerning the hazard and/or the risk have been developed in many countries but they are heterogeneous in terms of information content (Laternser and Schneebeli, 2002; Borrel and Brunet, 2006; Bourova *et al*., 2016). In addition, avalanche chronologies exceeding a few decades remain exceptional (Corona *et al.*, 2013; Schläppy *et al.*, 2014), and those not biased towards the events causing damage, or those triggered artificially even more so (Schneebeli *et al.*, 1997; Eckert *et al*., 2013; Podolskiy *et al.*, 2014). These are even totally lacking in some mountain areas, especially in medium-high mountain ranges that are often neglected in favor of high mountains.[1] In France this is the situation for the Vosges Massif (medium-high mountain range located in north-eastern France), whose significance in term of avalanche risk is overshadowed by the Alps. Indeed, the latter has had systematic observation of avalanches since the late nineteenth century, and has been the focus of deep interest regarding snow avalanche science and risk engineering (Mougin, 1922 ; Giacona *et al*., submitted b).

A further desirable for researchers and risk managers is the existence of long data series for detecting changes in risk with time (due to both social and environmental factors) and estimating the relevant chance of event occurrence. That is, long data series allow to understand the dynamics of the phenomenon (return period), to define reference scenarios and to contextualize them. Historical analysis is now widely used to reconstruct chronologies and specify the characteristics of past events, particularly in terms of flood risk (Stedinger and Cohn, 1986). However, avalanche risk stands out as an exception to this pattern, with this phenomenon arousing the interest of only a few historians, such as Granet-Abisset and Brugnot (2002) in France, Bruno (2013) in the former Soviet Union, Laely (1984) in Switzerland and di Stefano (2013) in the eastern United States and Canada. In addition, these rare studies have frequently been conducted in a framework that mixes together snow avalanches with other types of gravitational hazards, and at the spatial scale of a village or of a mountain region, whereas the study of the evolution of avalanche activity would require a specific focus on snow avalanche risk at the scale of a mountain

[1] Just as no universal definition of mountains has been proposed to date, the concept of medium-high mountains remains highly subjective, especially in terms of physical and social criteria that remain unclear and vary according to latitude. In France, medium-high mountains refer to areas ranging from 600-700 to 2000 m. a.s.l. These are often presented in contrast to high mountain areas, in terms of altitude, topography (old *versus* young, rounded tops *versus* rugged peaks, etc.), natural processes (seasonal snow cover only *versus* glaciers) or practices (everyday living space *versus* marked seasonal rhythm associated with tourism). Medium-high mountains are finally characterized by the combination of a humanized mountain (everyday living space and possessing of a rich cultural heritage) and a preserved nature (Sgard *et al*., 2007 ; Giacona *et al*., submitted a).

area that is coherent in terms of climate and topography (Leone, 2006 ; Granet-Abisset and Montredon, 2007 ; Favier and Granet-Abisset, 2000 ; Favier and Remacle, 2007).

The contribution of risk historians to this research goes significantly beyond the simple ‘production’ of large data sets from a variety of disparate and, potentially, new sources. Their expertise is essential to place the spatial and temporal occurrence of a natural phenomenon and its societal interpretation in their socio-historical and geographical contexts, so as to elucidate their meaning (Cœur and Lang, 2011). More broadly, contextualization helps capturing the temporality and dynamics of the various components involved in the ‘Risk system’: biophysical factors (climate, hazard), practices and land use, vulnerability factors (stakeholder perceptions, representations of risk and the relation of societies to risk, as well as the capacity to deal with damageable phenomena and, for societies, to protect themselves). The historical approach is highly dependent on the existence of sources and, consequently, a long lasting occupation of the territory. In cases where ‘usual’ sources are deficient, geohistorical tools can also be utilised to complement traditional methods. The purpose of this article is to demonstrate the value of such an approach to the (re)construction of a geo-chronology of avalanches and damages of sufficient duration and temporal resolution to understand the different characteristics of the phenomenon in the context of global change.

For this purpose, the Vosges Massif is an ideal illustrative territory. Indeed, its topographical and snow features are *a priori* favorable to avalanche activity. Covering a compact area of 7300 km², it is a spatial scale that is topographically and climatically consistent. Moreover, the long duration of human occupation at relevant elevations ensures *a priori* the existence of appropriate data sources. The study can thereby examine avalanche risk from the turn of the nineteenth century to the present day.[2] Nevertheless, the local existing knowledge regarding the material reality of avalanche risk in the Vosges Massif is low (no systematic recording of activity exists in contrast to the French Alps). This limitation, combined with little information existing in institutional archives (at regional and municipal administrative scales) justifies the use of sources beyond the ‘classical’ corpus the historian is used to working with.

After a detailed description of the geographic and socio-historical contexts, the article describes the proposed methodology, which consists of an original combination of sources of different types: administrative, printed, graphical, verbal and those resulting from spatial analyses. Indeed, we have chosen to use a dual approach, integrating the analysis of traditional sources and field enquiries in their ‘social sense’ with physical analysis of topography, vegetation etc. Our social enquiries are based on surveys and interviews with people *a priori* concerned with avalanche risk: stakeholders in the Vosges massifs, mountain professionals, employees of resorts and ski schools, mountain practitioners and local history associations, plus various other

[2] The last two centuries are characterized by continuity / consistency in terms of production and conservation of archives, despite the successive changes of national sovereignty that Alsace has experienced over this period. Since the French Revolution departments indeed consistently had an archivist and the production of documents relating to land use continuously increased (Lang *et al*., 2003).

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users of the massif. The results provided by this approach are then presented, interpreted and discussed in light of the socio-historical, geographical and biophysical contexts of the region.

2. Description of the territorial context

The Vosges Massif is located in the North-East of France, in the west part of the Rhine Valley. It is generally associated with an imagery and landscape that contrasts with the idea of massive avalanches: a mountain range having a 'human scale', described using a lexicon that conveys softness, accessibility and friendliness (Giacona et al., submitted a). Its dimensions are small (7300 square kilometers, 1423 meters at its highest point, 150 km long with a width varying between twenty and sixty km). However, the southern part of the range shows marked signs of Quaternary glaciation: U-shaped valleys, glacial cirques, moraine deposits and slopes greater than 30 ° (Flageollet, 2003). Oriented north-north-east – south-south-west, the range forms the first orographic barrier encountered by low pressure air flows coming from the Atlantic (Fig. 1). The main ridge stands perpendicular to the prevailing winds that sweep its flat and bald apical surface, loading snow on the eastern slopes, with impressive cornices forming at the break-of-slope (Fig. 1E), and wind slabs also commonly being produced.[3] The cold and humid climate permits the growth of a deep and long-lasting snow cover that persists in the form of snow patches until late spring and sometimes even until early summer in the glacial cirques located on the eastern slope. Due to its latitude and altitude, the proportion of snow precipitation to the total precipitation is respectively 20%, 30% and 60% at 700 meters, 1000 meters and 1350 meters (Wahl *et al*., 2009).

Even if the massif areas where avalanche activity is significant do not constitute permanent living spaces, human activity has been present in these areas for centuries (Kammerer, 2003). The Vosges Range has been occupied since the Middle Ages and several activities have left a durable imprint on the landscape, of which, perhaps the most significant is the agro-forestry-pastoral system that is a characteristic of the communities inhabiting the valleys. Livestock farming, as the main source of wealth, still holds a prominent place in the agricultural system. However, the harsh weather conditions and the seasonal snow cover limit the use of mountain pastures. The mountain farming has therefore two periods: summering at altitude, between late May and late September and wintering, in the valley, for the remainder of the year. The consequence of human pressures on the environment has been a development of human presence, economic activity (such as the farms at altitude, used for making cheese in summer) and an increasing land utilization owing to the use of slopes and summits for pasture. Furthermore, proto-industrial activities (mills, glass factories, mines, forges and metallurgy) that arose as a consequence of the presence of wood and ore, exerted significant pressure on the forest cover between the sixteenth and nineteenth centuries (Garnier, 2004). In addition, the eighteenth century saw the rise of summer tourism practices, associated with ideas regarding the recreational and contemplative benefits of the mountain environment. This was part of the hygienist discourse that highlighted at that time the benefits of mountain air and exercise in the form of walking (Moralès, 2007 ; Rauch, 1995 ;

[3] Cornices (Figure 1) are a characteristic feature of the avalanche dynamics in the Vosges Massif (Wahl *et al*., 2007).

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Vigarello, 2005 ; Laperche-Fournel, 2013). The turn of the twentieth century marked the development of winter recreational activities. All of these new uses resulted in a huge modification of the mountain calendar, with the human presence in the uplands now taking place throughout the year. This in turn had a concomitant impact on new processes of appropriation and mountain development, such as the extension of the network of trails for hiking, the construction of new buildings or the creation of ski resorts (Schwartz, 2001 and 2003).

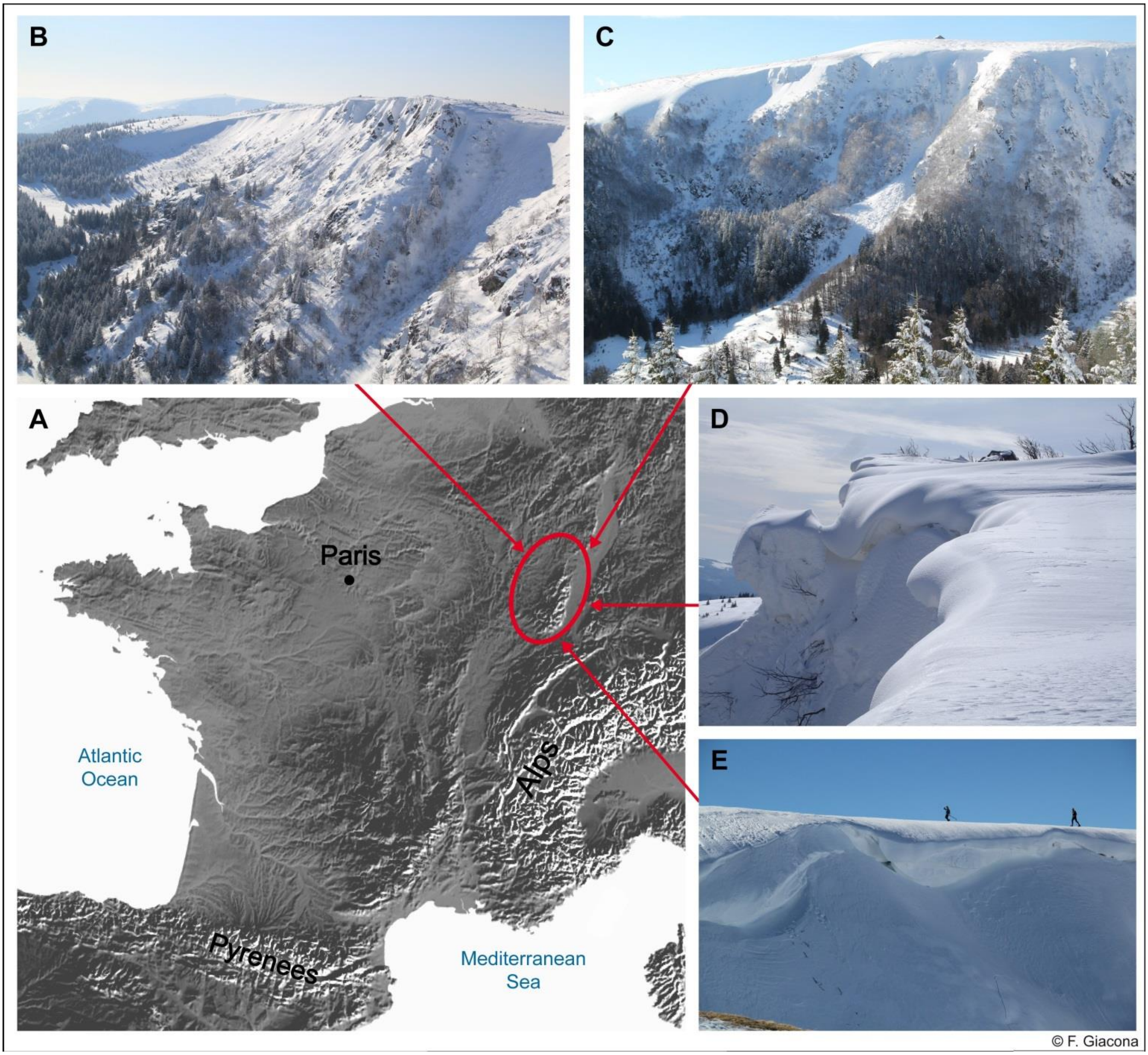

Figure 1: Location of the Vosges Massif in the North East of France (A, red circle). Avalanches occur mainly in former glacial cirques (B, C). At the top of these, huge cornices often develop during the winter season (D-E), and their fracture is the most common avalanche triggering factor.

Finally, even if the Vosges has never been, *a priori*, a 'barrier mountain',[4] its geographical location combined with its chaotic political history have been major obstacles to its perception as a complete and coherent entity and to the development of a real local memory and culture of natural hazards (Martin *et al*., 2015). This space has, in fact, been marked by several political breaks that have concerned the Alsace and Alsace-Lorraine region over the studied period. Between 1870 and 1918, the massif was partitioned at the main ridge of the massif in to two separate national territories. More generally, three Franco-German conflicts between 1870 and 1945 resulted in five changes of language, nationality and administration.

3. Geohistorical methodology

Only fifteen avalanches over the last two centuries are mentioned in church records, administrative documents, minute books of the municipal councils, etc. Because of the rarity of this information in the archives, the choice was made to expand the search to other sources, both written and oral. Figure 2 summarizes all geohistorical tools used to expand the corpus.

Browsing topographic maps of the French National Geographic Institute has helped to screen toponyms but few of them indicate the occurrence of avalanches. Similarly, scientific and regional literature provides little information on the occurrence of avalanches. Information, relating in particular to avalanche accidents that have required rescue missions, was more abundant in the regional media, especially the press. To this, was added the graphical material that could be collected – postcards and, for instance, photographs (Fig. 3). The number of photographs illustrating avalanches increased from the last decade of the nineteenth century and exploded in the 1990's. This was a consequence of the increased frequency of human activity in the Vosges, coupled to the development of information and communications technologies.

The choice was also made to use oral testimonies of stakeholders involved in the Vosges range and likely to be privy to pertinent information. These individuals made various contributions ranging, from bibliographic records to their own oral testimony of observed events. Finally, online forums and websites dedicated to the practice of backcountry activities in the Vosges were consulted, and a detailed enquiry was conducted. The latter focused on the risk cultures (knowledge and representations) of the main users potentially affected by the risk, namely the practitioners of winter activities.

These different approaches allowed us to retrieve data on avalanches not mentioned in institutional archives. It is important to note the contribution of photographs, regional media, Internet sites and forums, as well as of oral memory that aided in the reconstruction of a history of avalanches and enhanced their contextualization (Table 1). Iconographic documents represent almost two-fifths of the total of resources used. The proportion is slightly less than a fifth for oral testimonies and is the same for regional media. A given source may refer to, from one to upward of hundred and eighteen avalanches. However, four fifths of the sources refer only to a single avalanche. Moreover, a source may be contemporary with the avalanche or be produced later. Therefore, an avalanche may be identified by one or different sources (up to more than sixty), possibly of different age.

[4] That is, a mountain range with little communication across it, isolating one side from the other.

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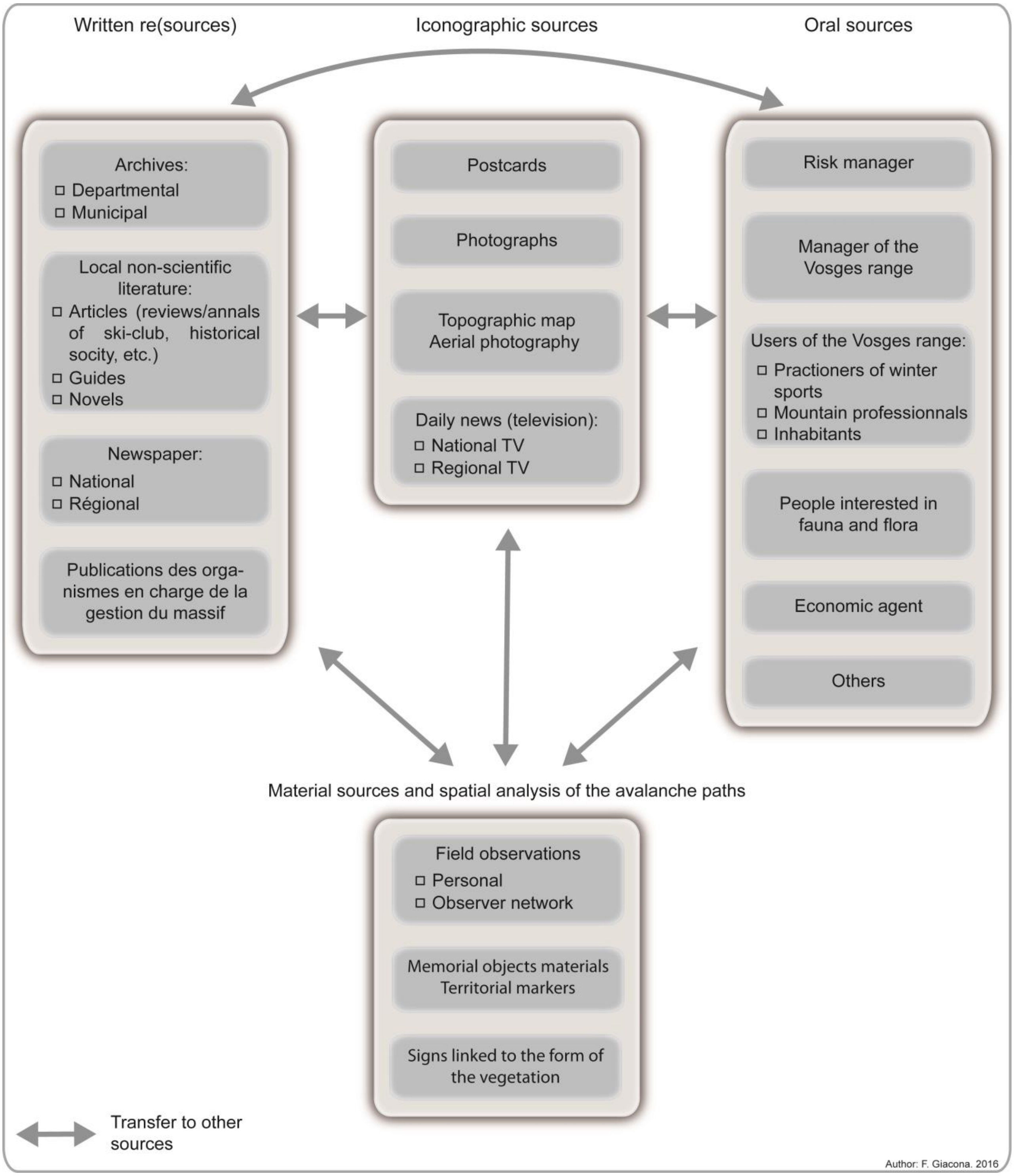

Figure 2: Set of geohistorical resources used for this study.

Figure 3: Postcard of Wildenstein (township in the Vosges Range) that shows (bottom left) an avalanche that occurred in February 1895, *Lawine* meaning avalanche in German (Alsace was part of the 2nd Reich at that time). The card was circulated in 1897. Private Collection: J.-M. Ernst, Consultation through T. Meyer.

Type of (res)sources	Number of documents / persons making references to one or more events
Toponyms	1
Scientific literature	9
National media (newspaper and news programs)	10
Nonscientific and local literature	34
Departmental and municipal archives	58
Forums and web sites	135
Oral memory (testimonies, written correspondence, survey, field observation)	189
Of which survey	*84*
Regional and local media	198
Of which television (news programs and television magazines)	*19*
Of which newspaper	*178*
Images (postcard, photo)	417

Table 1: Number of references to one or more events by type of source.

These data were supplemented by diachronic spatial studies of avalanche paths. Ground observations and discussions with observers (mountain professionals or practitioners of winter activities) allowed us to locate the cornice formation areas, make a list of avalanche paths and collect information on past avalanche activity or on areas were past activity was likely. Direct field investigations and observations including avalanche deposits and memorial objects (in particular, the presence of crosses commemorating a tragic avalanche) were used to confirm the occurrence and location of avalanches.

Finally, the (re)sources are indeed sufficiently abundant and exploitable to reconstruct a geo-chronology including a time series of past avalanches, a precise mapping of these, and comprehensive information allowing the social and spatio-temporal contextualization of the risk. In addition, the combination of questions, methods and tools from the fields of history and geography, and of diachronic and multiscale approaches, facilitated the critical analysis of data and sources, and, more generally, the verification and cross-checking of all information. Three-fifths of the avalanches have been corroborated by several sources. Among these, nearly two thirds are known by two sources, and the remainder by at least three sources. Of course, it was not, however, always possible to cross-check sources, in particular oral testimonies.

4. Results: a spatially and temporally non homogeneous geo-chronology

The reconstructed geo-chronology includes 730 avalanches that occurred between the winters of 1783/84 and 2013/14 on 128 paths. They have generated all kinds of damage: human, material, functional and environmental. Avalanches are therefore a common phenomenon in the Vosges range. The geo-historical approach also allows us to characterize their spatial and temporal distribution.

Over the entire period covered by this study, ninety four avalanches caused one or more casualties, among which sixteen were fatal to at least one person. Seventeen avalanches have caused material damage, among which eleven led to the total destruction of one or several buildings (Table 2). In addition, fifty seven avalanches have caused functional damage, mostly to road cuttings. Of these, sixteen required the use of plowing machines. Finally, eighty avalanches damaged forest stands, among which twelve have destroyed several hectares of forests. This typology of avalanches may contain some uncertainty. Indeed, the sources only contain information about the harmful nature of the event for half of the recorded avalanches only. Nevertheless, it is reasonable to assume that most of the avalanches whose detailed impact is not known did not cause significant damage. Moreover, the data were used to classify nearly half of the avalanches according to their intensity.[5] More than nine tenths of the latter are of low to medium intensity, and less than a tenth of them therefore correspond to high to exceptional intensity.

[5] An intensity scale (from one: very low intensity to five: exceptional intensity), adapted to the available data and to the physical characteristics of avalanche activity in the Vosges Massif, has been specifically elaborated.

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Over the whole period, more than 90% of the avalanches identified (682) could be specifically related to a given cold season (Table 2). It is on these that the geo-chronology described below is based. The primary dating problem concerns recent decades, for which the information relates mainly to non-damaging and *a posteriori* observed avalanches, which are often dated approximately (the uncertainty range is then a few years). By contrast, sources generally mention at least the year of occurrence (sometimes the exact day) for avalanches that have caused damage, and even more data are available when they cause serious damage.

Locating the path of origin for an avalanche was possible for 520 of the 730 avalanches. All others, except one, have been associated with a sector, a geographical area slightly wider – a few square kilometers – where a few avalanche paths are located. This allowed us to determine the characteristics of the typical path where avalanches occurred (Table 3): its length is close to 600 meters, its average altitude 1100 meters, its mean slope twenty nine degrees and vertical drop 240 meters. However, the variability around these values is important, the path length varying, for example, from forty meters to more than 1350 meters among the 128 paths of the massif. Also, the average altitude of the lowest path of the massif is 441 meters whereas the maximum vertical drop in the massif is close to 580 meters.

	Number of avalanches	**Number of avalanches with known winter**	**%**
Total number of avalanches	730	682	93%
Large avalanches (intensity class > 3)		26	93%
Small avalanches (intensity class ≤ 3)	328	321	98%
Unknown size	374	335	90%
With causalities	94	72	77%
With dead people	16	16	100%
With injured people	23	23	100%
With material damages	17	17	100%
With functional damages	57	54	95%
With environmental damages	80	77	96%

Table 2: Typology of avalanche events

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	Mean	Minimum	Maximum
Length (m)	592	38	1351
Vertical drop (m)	241	5	576
Mean altitude (m)	1112	441	1336
Mean slope (deg.)	29	16	42

Table 3: Topography of the avalanche paths where the 520 events that could be precisely located occurred. The statistics take into account the specific activity of each path (when several avalanches, say *N*, occurred in the same path, the path's characteristics are weighted by a factor *N*.

Avalanches occur preferentially in the southern part of the massif: the High Vosges mountains (where more than 95% of all avalanches occurred). Starting zones are mainly oriented between the north east and the south east and, to a lesser extent, in the south. Very few are oriented to the west (Fig. 4). This is explained by the combination of factors favorable to the development of cornices and avalanche mentioned above.

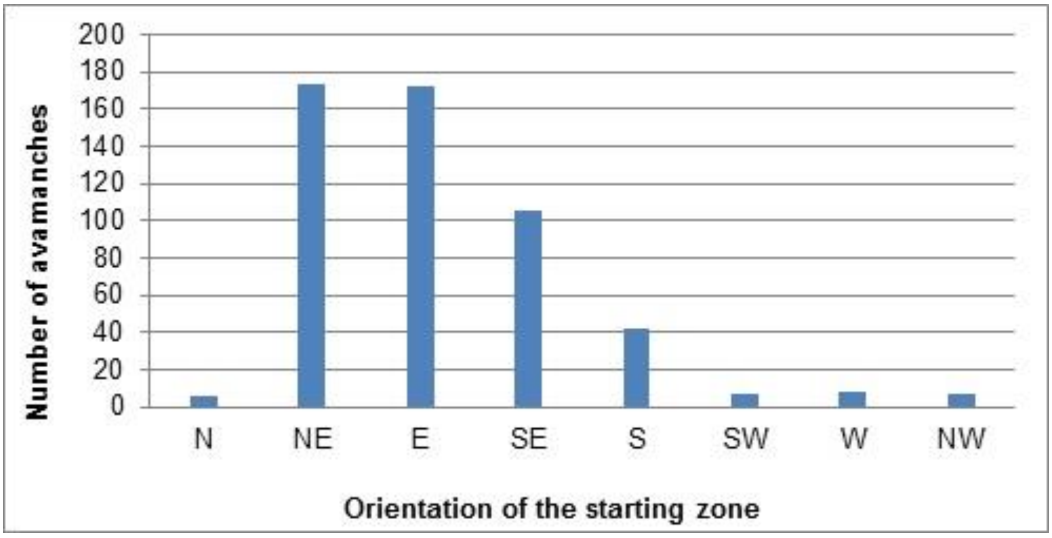

Figure 4: Number of avalanches as function of orientation of the starting zone. Only the 520 avalanches that could be precisely attributed to their path are considered.

The inventory clearly reveals specific temporal dynamics and singular rhythmicities. Thus, the raw chronology is marked by a strong temporal variability: the recorded avalanches remain sporadic until the mid-twentieth century (about 5% of the total avalanche number of the chronology occurred *prior* to that date), with many winters without any avalanche. Winter avalanche numbers rise sharply in the 1960s, and even more in the 1990s (Fig. 5A). Nearly nine-tenths of the recorded avalanches occurred between the winters of 1989/90 and 2012/13, corresponding to the recent period during which there are no longer winters without any avalanches recorded.

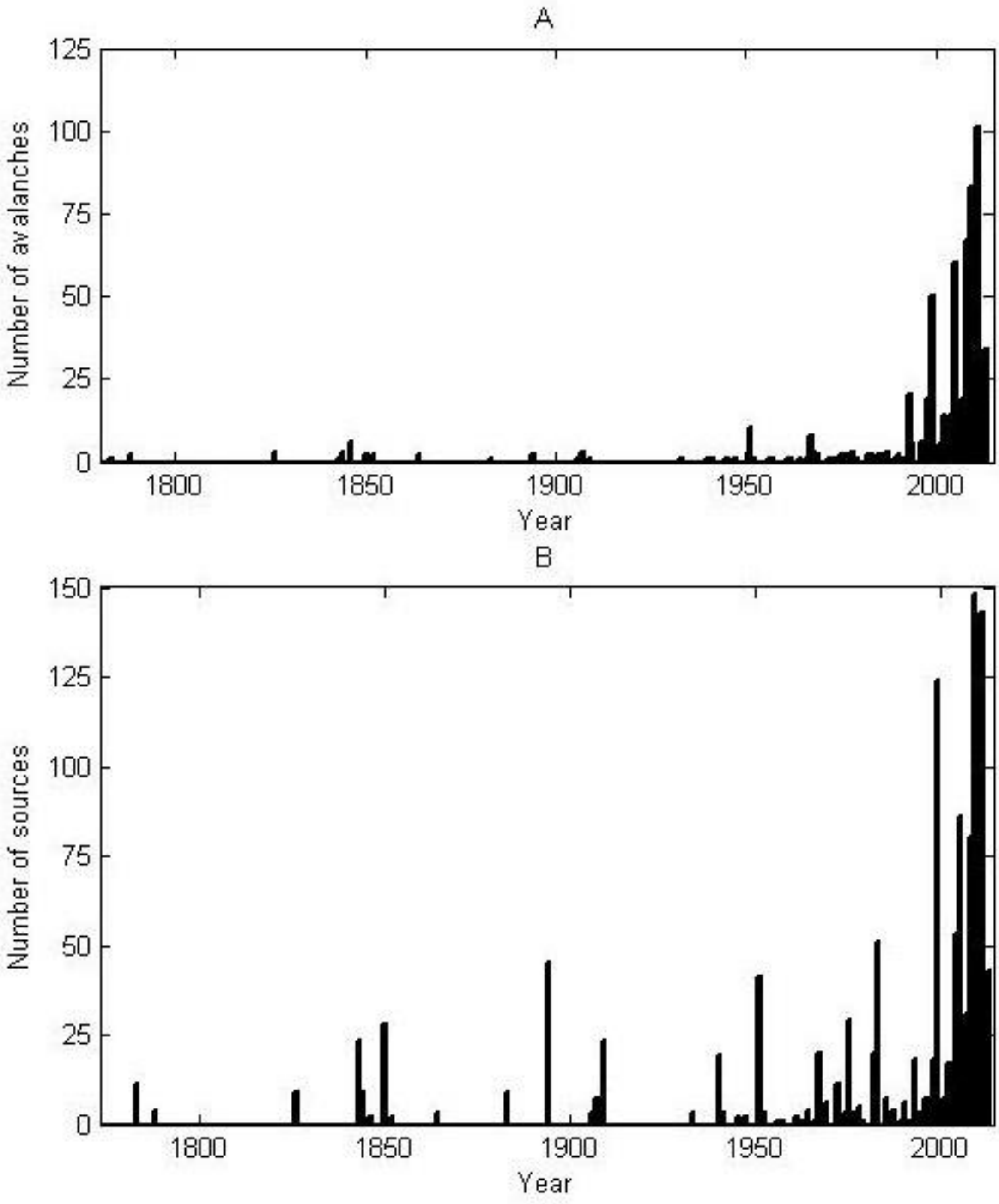

Figure 5: Number of avalanches (A) and number of distinct sources (B) as function of time. In A, only the 682 avalanches with known year (winter) are considered.

Until the mid-twentieth century and even as late as the early 1990s, known avalanches were almost always high intensity (greater than 3 on the scale previously introduced). These high intensity avalanches are the exceptional cases, and the crucial difference with the more complete recent records is that the number of low intensity recorded avalanches (intensity less than or equal to three) explodes in the latter case (Fig. 6A). This evolution is confirmed by the negative correlation between avalanches intensity and cold season (-0.33, significant at the 5% significance level).[6]

The nature of the damage caused by avalanches has also changed (Fig. 6 B- G). The relative proportion of the types of avalanches over time shows that a few avalanches that resulted in significant damage are progressively outnumbered by more avalanches without significant consequences. Thus, in the nineteenth century and the first half of the twentieth century, fifteen avalanches which damaged or destroyed buildings were identified. Since then, no altitude farm or house located in valley has been impacted. Some of these destructive avalanches have also led to a significant number of deaths: up to ten during the destruction of a single building. However, almost two-thirds of recorded avalanches that have caused injuries (seventy one avalanches in total)[7] have occurred since the early 1990s. It is the same for the total number of victims: 188 in total have been counted and these include thirty four fatalities, as well as injured and unscathed people, and half of these has been recorded since the early 1990s. The increase of known human damage is concomitant with a change in the nature of the victims impacted. During the eighteenth and nineteenth centuries, the human damage mainly concerned people who were in their impacted homes, while in the twentieth century it concerns exclusively practitioners of backcountry activities. The mid-twentieth century also saw the emergence of a register of injured victims whereas, before, information was only retained, in general, for events that resulted in fatalities. Functional damage to transportation routes (fifty events have affected road cuttings) emerged in the middle of the twentieth century as mountain roads were used increasingly in winter. Finally, the number of avalanches that have caused damages to forests has also increased since the mid-twentieth century, and their relative proportion with regards to all recorded avalanches has decreased. However, the difference compared to other damage types such as the functional cases is that damage to forests by avalanches could be identified from the mid-nineteenth century.

[6] The Pearson correlation coefficient is used. It is calculated from all avalanches for which cold season and intensity are both available. Its significance is assessed by a Student test for which a correlation is significant at the 0.05 significance level when the *p*-value of the test is less than 0.05 (here it is even lower than 0.0001). This means that we are at least 95% sure that the avalanches were on average larger in the past.

[7] These numbers may seem relatively low, especially compared to the damage caused by avalanches in high mountain ranges. While there has been a total of ten avalanche deaths in the Vosges range due to recreational activities since the winter of 1971/72, the national average is around thirty deaths per year in the Alps and Pyrenees (Jarry, 2011). However, at the regional level, these ten deaths are far from negligible. Moreover, such ‘raw’ comparisons are to be handled with caution as frequency of occurrence and the extent of spatial areas concerned with the risk of avalanches are very different between the Vosges range and high mountains, especially the Alps. Also, as the physical characteristics of avalanche activity (altitude, soil type in the avalanche path, snow climatology, size, intensity and frequency of events, etc.) and vulnerability are undoubtedly different in the two types of mountain areas, it is not certain that, at the individual level of the skier or the mountain hiker, the risk is significantly lower in the Vosges Massif than in the high mountain ranges.

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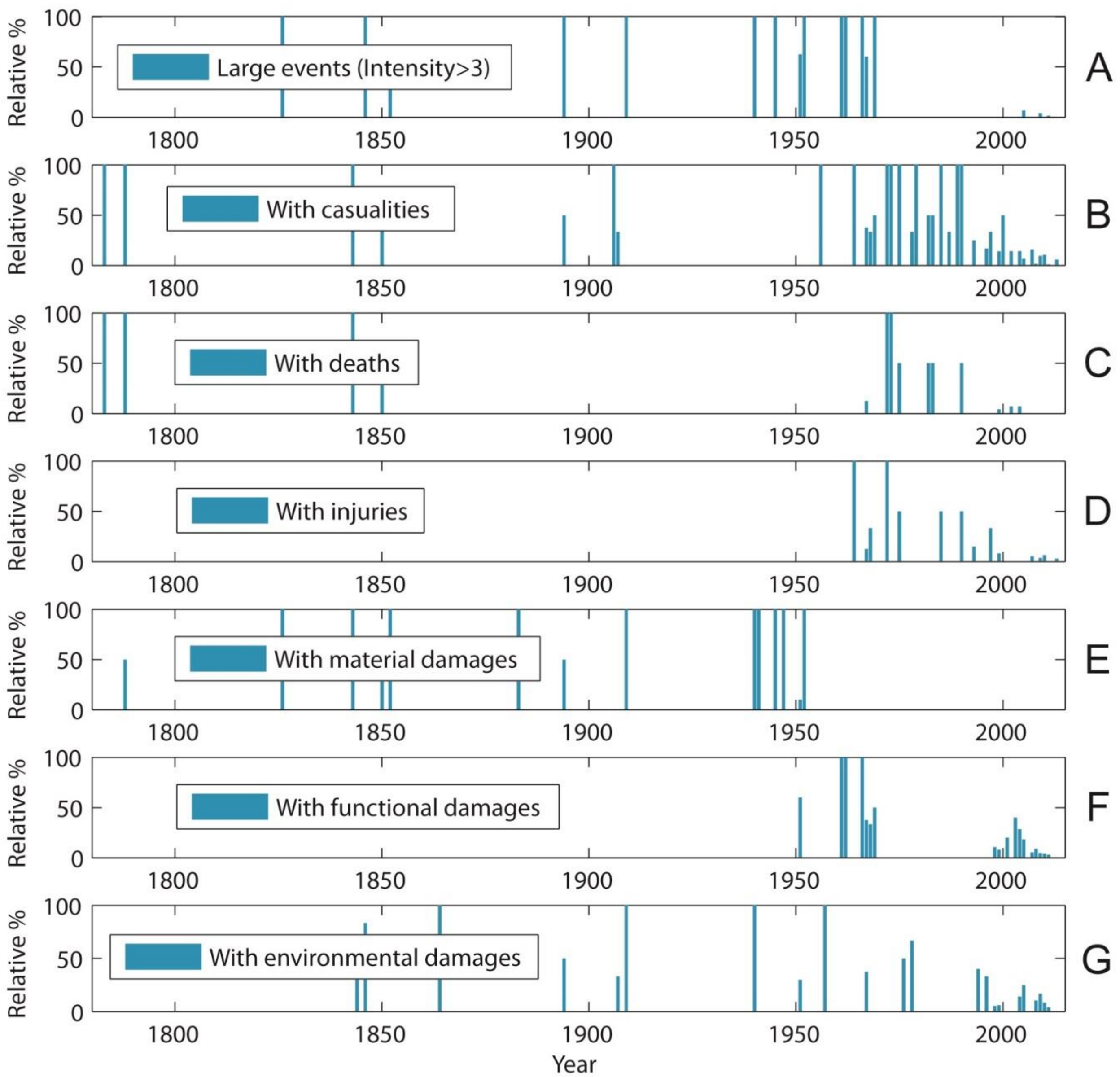

Figure 6: relative chronology of the types of recorded avalanches. A: large avalanches with regards to all avalanches with a known size. B- F: avalanches that have caused damages, respectively deaths, injuries, material damage, functional damage and environmental damage, with regards to all avalanches. All percentages (A -E) refer to avalanches for which the year is known with certainty (Table 2, left column).

Finally, throughout the study period, there were twenty winters remarkable by the number of victims and/or the extent of material or environmental damages: 1826/27, 1844/45, 1846/47, 1850/51, 1852/53, 1894/95, 1909/10, 1940/41, 1951/52, 2009/10 and to a lesser extent 1907/08 1942/43,1947/48, 1952/53 , 1957/58, 1967/68, 1977/78, 1994/95, 1999/00, 2005/06, and 2009/10. For example, it was in February 1844, in Sainte-Marie-aux-Mines (Alsatian town located in a valley) that an avalanche occurred that caused the destruction of a house and led to the death of the ten people previously mentioned. In February 1895, an avalanche starting from the Rothenbachkopf summit (located in the southern part of the Vosges range) and flowing down in the valley, was sufficiently striking to be recorded on a postcard (Fig. 3). More recently, at the beginning of February 1952, three avalanches in the Rothenbachkopf-Rainkopf sector damaged twenty hectares of forest, leaving within its deposit just over 3000 cubic meters of dead wood.

Finally, a temporal evolution of the spatial distribution of avalanches is noticeable. Until the 1940s, the data relate mainly to paths located in valleys (Sainte Marie aux Mines, for example) and on the main ridges of the mountains. From the mid-twentieth century and especially since 1993/94, the information concern mostly paths located near or just below the summits (Rothenbachkopf-Rainkopf for example) and there is a real spatial extension of the information with the appearance of new avalanche paths in the geo-chronology. In addition, apart from a few exceptions, there is no longer a record of avalanches in the valley for this most recent period. The positive correlations between cold season and the average altitude of the path, and, even more, between cold season and the altitude of the starting zones (0.46 and 0.52, respectively, values both significant at a significance level of 5%)[8] corroborate this hypothesis: recent avalanches have occurred commonly in paths that are, in the mean, located at higher elevations, and, even more significantly, have been triggered from starting zones located, on average, at greater elevations.

5. Discussion

Even if they are significant, these results and the spatial and temporal development cannot be interpreted directly in terms of avalanche activity phases. First, information must be more precisely contextualized in order to explain the shape of the geo-chronology. We consider that three factors, sometimes interdependent, can contribute to the interpretation of the periodicities highlighted:

- The sources, which are dependent on vulnerability and on avalanche observations/traces, leading or not to an 'event building' from the facts, and to their transmission;
- The land use, conditioning vulnerability, from which the production of sources is partially dependent;
- Avalanche activity, which results from a combination of meteorological and topographical characteristics with triggering factors.

5.1 'Sources effect' and 'event'

Quantitatively, the written and oral documentary mass related to avalanches is characterized by a net increase (almost exponential) during the studied period. A first evolution takes place at the middle of the twentieth century, when the number

[8] Student's test performed on the set of available pairs, *p*-value <0.0001 in both cases.

of sources becomes multiplied by three. They are then multiplied by nearly nine between the period from the 1940s to the early 1990s to the period covering the 1990s to today (Fig. 5B). The increasing contribution of the regional daily press, and of direct observation testimonies, photographs and information sharing via forums and websites should be noted (Table 1).

In addition to the non-homogeneity of the mass of documentation, a diversification of the nature of sources throughout the period also exists. Thus, five periods were identified based on the different types of (re)sources available during the studied period (Fig. 7). It should be noted that no source type really disappeared. Whereas some of them did not continuously provide information, mentioning the occurrence of avalanches only occasionally, they have nevertheless been considered as having been continuous from their appearance until today since their contribution could have been possible at any time. As available resources progressively became more numerous, one may have thought that this would have lead to a diversification of information. However, in practice, this is not really the case, since each period is characterized by one or two main source(s):

- 1783/84 – 1842/43: essential contribution of administrative records;
- 1843/44 – 1869/70: first diversification, with contributions from local literature and the regional press;
- 1870/71 – 1939/40: major contribution of the regional press and, to a lesser extent, of the articles / scientific books and graphical materials that make their appearance. However, this period has to be considered in its political context. Several political breaks occurred: the annexation of Alsace-Lorraine to the German Reich in 1871, the First World War, the return of Alsace-Lorraine to France in 1918 and the beginning of World War II. These historical events had an impact on archives since those of 1871-1918 and 1919-1945 are subject to a specific classification by the authorities (and some archival collections are incomplete, or even have disappeared);
- 1940/41 – 1992/93: predominance of the regional press, complemented by municipal archives, the local non-scientific literature, iconographic documents and news from the regional television;
- 1992/93 – 2013/14: exponential contribution of graphic materials, followed by oral testimonies, forums and websites as well as the regional press. This period is an exception, since all the different types of sources are represented.

These changes to the body of available (re)sources are visible in the shape of the geo-chronology. The number of recorded avalanches follows more or less the same trend as the number of sources. This is especially true from the mid-twentieth century, from when the registering of avalanches becomes more regular, a change linked to the regional daily press which relates accidents more frequently consecutive to the practice of winter recreational activities (Fig. 5). Moreover, the net increase in avalanches by cold season identified since 1993/94 is related to the contribution of the 'diary' of a backcountry skier who records regularly, since that season, his field and weather condition observations. A last significant development occurred in 2003/04 because since this data, at least ten avalanches a winter season have occurred (Fig. 5A). This also marks the beginning of our own observations, supplemented by those of the observer network, and information from forums and websites. The average increase in avalanche records, however, is not constant over the whole study period, with some years with very few avalanches. These irregularities can be partly explained by the irregularity of sources, combined or not (depending on the cold season) with snow and meteorological conditions more or less favorable to avalanche activity.

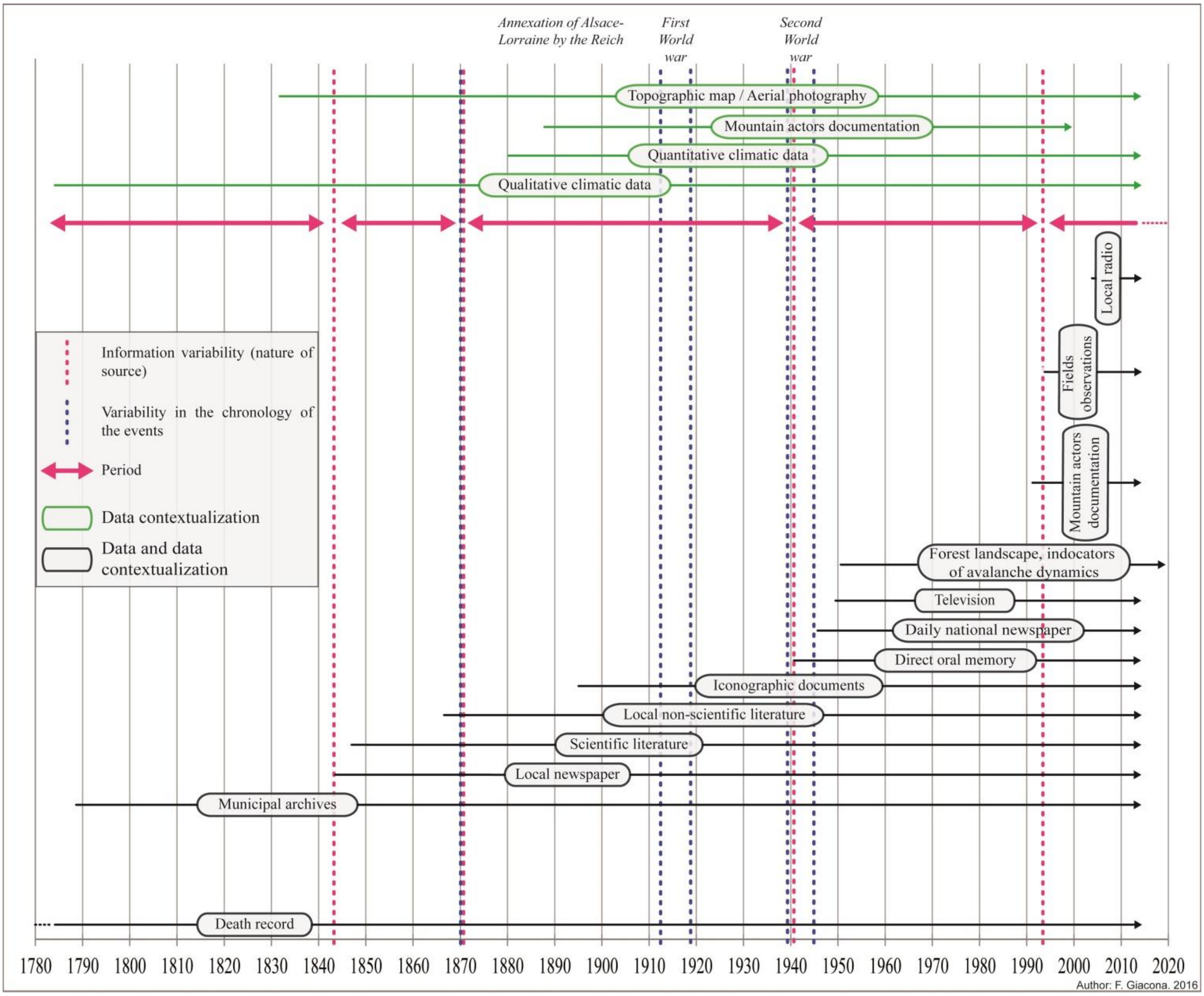

Figure 7: Source availability as function of time. Sub-periods are delimited according to the predominance of a given type of source.

Beyond the question of the existence of potential occurrences, it is also necessary that any observations have left a trace as a written or/and oral documentary source, and the potential for this has also varied over the studied period. Until the mid-twentieth century, the historical event is conditioned by the occurrence of damaging events and is therefore closely linked to vulnerability. Only avalanches that disturbed directly the lives of men in their occupations have left a mark. From the second half of the twentieth century, recorded observations concern damaging avalanches as well as non-damaging ones, especially for the most recent period (from 1993/94). This development is particularly related to guidance given to the observers' network to take into account all avalanches whatever their consequence or their intensity. The fact that practitioners of winter sports that feed the forums and websites are interested by the phenomenon itself as much as by its impacts also plays a role. The observation of any avalanche activity is indeed synonymous with instability in the snowpack, critical information for practicing winter sports. Furthermore, an ever-increasing number of observations are recorded on an increasingly diverse range of media. The extension of the spatial coverage of information (with the registration of avalanches in paths located below the summits where no permanent material or functional items at risk exist), observed since the mid-twentieth century, and even more from 1993 to 1994, is therefore the consequence of an evolution of the living space within the massif. This involves a new spatial distribution of avalanche accidents and, more widely, observations of natural avalanches that were missed before. Thus, in terms of the language of risk analysis, rather than an emergence of a natural hazard in areas where it did not exist before, there has been an evolution of the exposure of individuals to the natural hazard itself, which in turn, resulted in a greater visibility of the natural phenomenon.

Finally, the corpus of sources combines three types of information variability: the quantity of documentation, the type of available (re)sources and the nature of identified avalanches, which together constitute 'the source effect' that has a profound influence on the nature of the geochronology. Moreover, the physical occurrence of the avalanche is not always synonymous with an *event*, taken as a sign of the past reality of a phenomenon that has left traces[9]. In other words, it is not because an avalanche occurs that the event exists. The event is defined as 'that which introduces a cut, a discontinuity (...)', in the 'everyday life' of individuals but also as what is 'interesting', seems sufficiently 'important' or 'new' to be 'told or put into action' (Dosse, 2010 ; Bertrand, 2010).[10] Production of a narrative (written, oral), and therefore of a source, following the observation of an avalanche and its potential damage defines an 'event building', which is effective for a fraction of avalanches that actually occurred, according to criteria relating to the context. The 'building' of the event is the result of a social construction whose terms and rules have varied widely over the study period. In addition, of course, only part of the avalanches that have led to an event building appear in the geochronology, because some sources may have been missed by the historical investigation, while other events have been 'lost' as a result of a lack of transmission (end of oral memory, for example).

In view of the large proportion of non-damaging avalanches recorded since 1993/94, as well as of the concomitant increase in recorded small-sized avalanches, we believe that avalanches recorded in earlier periods, that were generally harmful and often large, represent only a small part of the avalanches that actually occurred. In the geo-chronology, damaging and large

[9] The notion of trace refers to 'everything a phenomenon, in itself impossible to grasp [for past events], left' (Dosse, 2010).

[10] This study focuses on all events that left a trace in the Vosges range, in order to get as close as possible to the material reality of the avalanche phenomenon. In this sense, we see as 'event' all spatio-temporal occurrences of the avalanche phenomenon. We therefore consider avalanching as a non-ordinary phenomnenon, normality being the non-occurrence of an avalanche.

avalanches are thus over-represented before 1993/94 (Fig. 6).[11] Moreover, the emergence of 'injured people' in the second half of the twentieth century is probably linked to the development of new winter activities, but also to the fact that, earlier, accidents that did not require rescue operations did not necessarily lead to the production of a source.

This gap between the reconstruction of avalanche activity from historical sources on the one hand, and field observations on the other hand, is illustrated by the comparison between the events of 1951/52 and 2009/10 in the Hohneck-Rothenbachkopf sector (Fig. 8). For the winter 1951/52, we retrieved medium to exceptional intensity avalanches that had functional impacts, and that caused environmental and material damages, while no mention is made of smaller avalanches. On the other hand, for the 2009/10 winter, there is knowledge of many lesser intensity events, and of a few large-scale events with damage/size levels equivalent to those of 1951/52, and therefore likely to be retrieved from historical sources even decades later. By analogy, one may postulate that the events mentioned in historical sources for the winter 1951/52 constitute part of the physical reality only, and that the actual situation of the winter 1951/52 was similar to the winter of 2009/10.

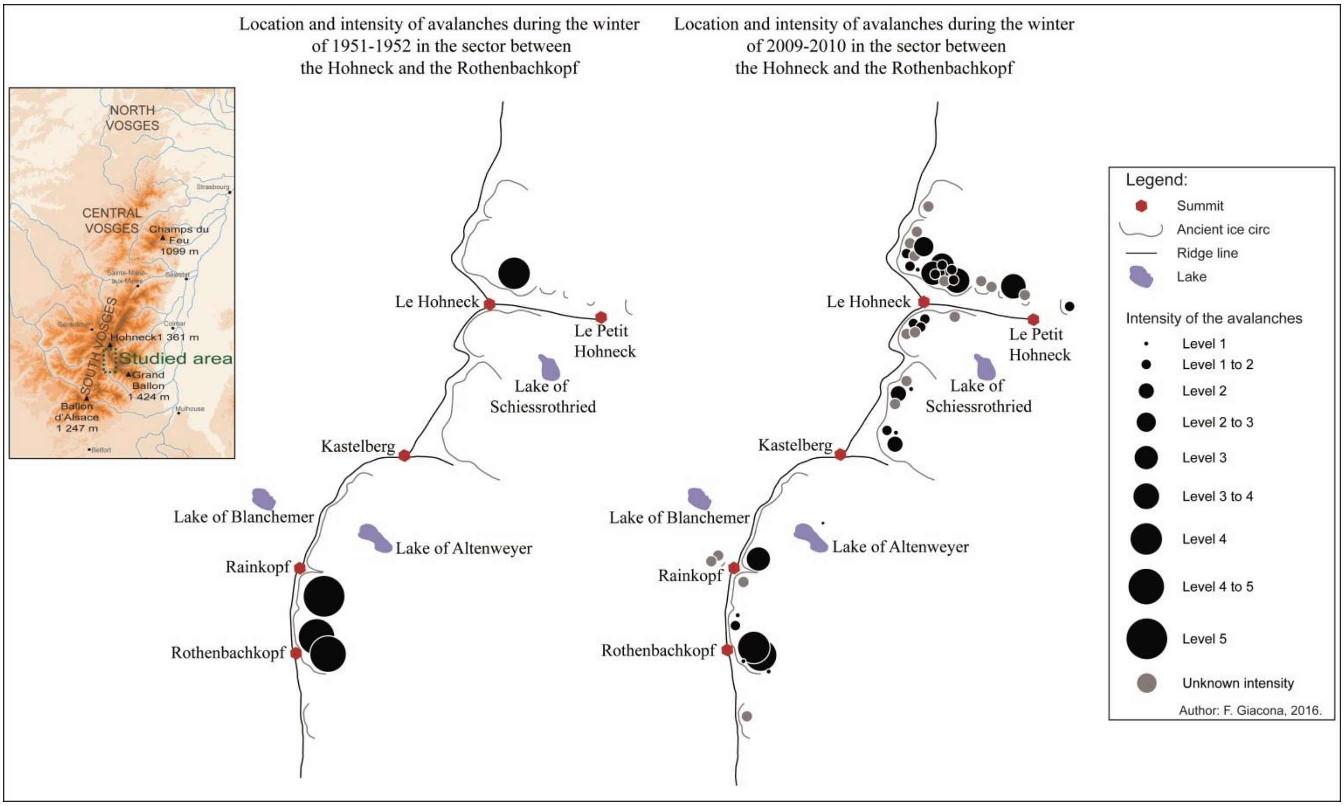

Figure 8: Location and intensity of the avalanches occurring in the Honneck-Rothenbachkopf sector during the winters 1951/52 and 2009/10, respectively, obtained from the geochronology developed in this study.

[11] Avalanche size and resulting damages are not synonymous, since few small avalanches may have had important consequences, but they are still closely linked. For example, major destruction of forest stands are always due to large avalanches.

5.2 Land use changes

The study period is marked by qualitative and quantitative evolutions linked to a profound change in function of the studied mountain area, in terms of practices and land cover. In the past, it was a living and resources area, where economic and political issues were very local. It has now become an area mainly dedicated to leisure for a wider population, although it can still be an area for local economic production.

In the past, the frequentation of the massif was mostly related to economic or family activities and exchanges, through the network of roads and paths connecting its various valleys. Some of these roads crossed avalanche prone areas. Merchants, smugglers, hawkers, hunters and poachers were their main users, without forgetting the loggers and 'schlitteurs', for whom the snow was useful for the transportation of felled trees.[12] Archival documents also attest to the visit of altitude farms in the winter season by farmers.[13] It is very difficult to evaluate precisely which routes were used in the past and, especially, to assess the traffic rates for each of them, even if it is clear that differences are noticeable with the current period, both in terms of traffic volumes and itineraries.[14]

Today, in the winter season, the Vosges range, including avalanche prone areas, is frequented entirely, for recreational purposes. If it is difficult to assess the evolution of the frequentation of backcountry sectors, it is certain that it is growing, as

[12] 'Schlitteurs' are the people who transported felled wood to the village with a 'schlitte' (a kind of sledge transport).

[13] Farmers were interested in checking the status of their farms before the spring because, if a damaged building was located less than a French "half mile" from the forest, they had an obligation to ask the prefect permission to rebuild or repair it. A farmer, for example, mentions that his farm was destroyed in March by an avalanche. If this indication is accurate we can hypothesize that: either the avalanche and the destruction were actually observed, either the farmer went to his farm before and after the avalanche and was able to date its destruction, or he attached it retrospectively to specific snow and weather conditions. Letter of M. Mathias Guthleben to the prefect of the 'Haut-Rhin', 24 March 1853, Record Group 7P, Box 638, Departmental archives of the 'Haut-Rhin'.

[14] Accidents that occurred on tracks are an indicator of winter use of the Vosges range. Accidents and losses were not rare, as arguably confirmed by an archival document that relates that Mr. Dominique de Bussang, said the 'Lonely', 'has already received an aid for good deeds, risked his life to rescue the lost travelers in Bussang pass and this in seasons when snow was abundant' (Aid granted by the Emperor, 24 March 1853, Record Group 21P, Box 34, Departmental archives of the 'Vosges'). Such tragedies are indeed frequently related, for example an accident in March 1841, where a brother and his sister were killed in a snowstorm on the stubble field of the Tanet while returning from an agriculture fair in Munster (Bresch, 1871). E. Garnier (2004) notices also two deaths on the same stubble field in March 1762. The Journal of Sainte-Marie-aux-Mines recounts two other accidents. The edition of the 23 January 1859 reports that two young people were 'lost in the snow' on the crest of the Ballon d'Alsace. One died, the other was in a very poor state. On the 26 December 1859 two people were surprised by a winter storm on the heights of the Schlucht. One of them disappeared and his body was not found until the following 10 April.

attested by the increasing number of avalanche accidents in these areas. This increase in visitation partly explains the increase of avalanches recorded from the mid-twentieth century and, to a greater extent, since 1990 (Fig. 5A). Thus, there is an increase of vulnerability linked to an increase in the number of visits and of certain modalities of winter activities (such as off-track skiing and hiking). As a consequence of these factors, there is an increase in artificially triggered avalanches (as opposed to spontaneous avalanches) resulting from a punctual overload, such as the passage of an individual. Consequently, people are playing a more active role in triggering avalanches, directly exacerbating the hazard. Meanwhile, unlike the human and functional vulnerabilities, the material investment in mountain areas (altitude farms in particular) has decreased significantly following the progressive abandonment of agricultural activities.

Hence, the low abundance of sources up to the mid-twentieth century is not explained by the absence of stakeholder activity in these regions, since accidents, deaths, damages to fields or properties have occurred. Is it due to a special link to avalanches marked by the acceptance of risk? Have farmers taken measures to face the reality of the threat? What was their understanding of the phenomenon? In detail, the connections that previous societies had to the hazard and to the risk in the Vosges range remains difficult to grasp, due to incomplete sources, and more generally because mountain people were characterized by an oral culture rather than written culture.[15] What is known is that the upland farmers certainly identified an avalanche risk, at least as early as the nineteenth century.[16] Having traveled, mapped and modified this territory, they undoubtedly developed a knowledge resulting from their experience of this space, and perhaps also, transmitted knowledge and know-how. However, it is not certain that the phenomenon has fundamentally influenced the practices and techniques, or has induced particularly elaborate precautionary principles, or, even that there was real comprehension of the threat. Moreover, were avalanches really perceived as a significant threat? It is not sure since the chronology is not very rich in avalanches that caused material or human damage. In fact, the phenomenon only rarely affected permanent living places. Even for upland farmers, the choice to spend the entire year in the Massif is a relatively new way of life. Moreover, it appears that there was at the opposite extreme, a tradition of temporary implantation of uplands farms, which constitute the main material stakes potentially affected by the risk (Matter, 2010). Hence, avalanches have in fact not induced structural damages to the mechanisms of the territorial system – physical or socioeconomic.

All in all, because the risk was not part of everyday life, upland farmers did not have to really learn to live with it, and had probably not developed specific territorialized knowledge 'with meter-accuracy', as it may be the case in the Alpine and Pyrenean mountains (Barrué-Pastor, 2014 ; Granet-Abisset, 2012). The constraints for the society due to avalanches were

[15] This situation exists in other mountain areas. M. Barrué-Pastor (2014) notes the existence of a mountain risk culture in the "Pays Toy" (French Pyrenees), including avalanches, but one that has left no written record. The risk was in fact apprehended through stories, architecture and toponyms.

[16] A regional book mentions the need to repair upland farms in the spring season 'if the farm or the barn is exposed to winds from the west or to the devastation of avalanches, the roof needs to be repaired, the overthought risen, the mountain path repaired and cleared from the stones that have rolled onto it' (Abel, 1913).

therefore different in the Vosges than in high mountain areas. The threat of avalanches must also be placed in a broader context, where 'social risks' such as epidemics or armed conflict had far greater consequences and, as a result, presumably structured the history and life of mountain societies in a much significant manner.

This context helps to explain that the records do not show an attention to avalanches 'sufficient to include them regularly in newspapers, private and local archives' (Granet-Abisset, 2012), so that the occurrence of damaging avalanches has lead only to mandatory documents required by the administration. It also explains why references to the phenomenon are limited to a few facts, without further detailed explanation or descriptive indication. Finally, it implies that the memory of the risk is in the 'short time of the event, experienced during a lifetime' (Barrué-Pastor, 2014). All in all, current knowledge does not therefore result from an inheritance or an oral transmission of experience, but from persona; experiences and observations.

5.3 Changes in avalanche activity

It is important to note that this study takes place in a well-defined climatic context, the end of the Little Ice Age in the second half of the nineteenth century[17] and the recent anthropogenic warming over the last decades. These changes already affect avalanche activity which is directly controlled by the amount and quality of the snow, thus by the climate (Eckert *et al.*, 2010). The exact effect of climate on the spatiotemporal distribution of recorded events is difficult to determine (Castebrunet *et al.*, 2012). However, the end of the Little Ice Age had an undeniable impact on the snowpack at low and medium altitudes. Cool winter temperatures until the middle of the nineteenth century enabled the development of an important snowpack at medium (900 meters) and low (600 meters) altitudes, which has become exceptional today due to warming. It is therefore *a priori* reasonable that natural avalanche activity has generally declined over the study period, at least on the global scale of the Vosges Massif.[18] This evolution, which is in contradiction with the overall shape of the geo-chronology, confirms the preponderance of the social significance of the event.

The climate also indirectly impacts avalanche activity through its effect on afforestation and practices. The climatic context has favored forest recolonization, which should *a priori* influence avalanche activity in the direction of a reduction of the hazard. The effect of climate is then combined with the abandonment of pastures and proto-industrial activities which also involve a reforestation. These interrelated changes explain, at least partially, the 'disappearance' of some paths in the valley areas, where in the nineteenth century destructive avalanches occurred. These paths are now fully re-colonized by forest, and do not show any visible sign of avalanche activity.

More broadly, strong interactions between avalanches, forest and society exist (Bebi *et al.*, 2009; Feistl *et al.*, 2015). Pressure on wood resources, remained strong until the nineteenth century, leading to the extension of deforested areas (including pastures) at the expense of forested areas, and therefore, presumably, to an intensification of avalanche activity, followed by a reduction or even by a disappearance in the context of forest recolonization linked to agricultural decline,

[17] The definition of the Little Ice Age is largely based on historical sources (Grove, 1988 and 2001), especially in France (grape harvest dates analyses, etc.).
[18] At the local level, examples of paths were activity has risen may be found due to the specificity of each path.

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global warming and man-made reforestation from the early nineteenth century.[19] Hence, it is possible to link the destruction by avalanches in the nineteenth century or early twentieth century, of upland farms (that existed a long time before) or houses located in valley, with deforestation carried out, especially for grazing, combined with exceptionally harsh winter conditions.

Finally, recreational activities, and therefore winter use of the Vosges range, are partly based on the state of the snowpack. The absence or the low presence of snow is indeed generally synonymous to less intense backcountry ski activities, and therefore to less accidental triggering. All factors are therefore thoroughly interconnected.

6. Conclusion and outlooks

This study shows that it is possible to reconstruct *a posteriori* a geo-chronology of avalanches, even for a relatively benign, medium-high mountain area that one would barely think of as prone to avalanches risk. To do this, the combination of questions, methods and tools of the historian and the geographer as well as diachronic and multiscale approaches applied to conventional and less common sources has undeniable strongpoints, both for building the geo-chronology (by looking for facts, cross-checking them, analyzing and retrieving their meaning in the social space) and for its understanding. Indeed, the combination of approaches allows us to explain the singular periodicities and evolution shown by the geo-chronology as resulting from the interactions between the temporality of social actors and nature. The importance of the work done (variety and volume of the relevant sources browsed, extensive field visits conducted, etc.) as well as the consistency of the chosen spatial scale, a whole massif, gives confidence in the robustness of our conclusions. Such an approach is very innovative in the field of natural hazards, particularly avalanches, where existing historical studies remain relatively rare, and often based on information less widely collected and / or considered at a spatial scale less relevant for the phenomenon.

In order to question the way the society relates to the avalanche phenomenon and, more generally, how the at-risk system is generated, the analysis exploits, very diverse kinds of data, but with a generic approach, information contextualization, without which the results are uninterpretable. This is a classic but relevant demonstration of the fundamental role of the

[19] However, it should be noted that the abandonment of pastoral practices in avalanche starting zones also affects avalanche activity, but in a way which is difficult to assess because opposite effects may be observed. The presence of non-mown and ungrazed, long and flexible grass is a remarkable slab plane while the presence of cut or grazed grass allows greater anchorage of snow (Loup and Lovie, 1967). The current colonization by tree species such as alder or mountain ash also plays a role. These flexible shrubs lie under the weight of snow and also form a sliding plane for the coming snow layer. On the contrary, as soon as the trees are big enough, they are anchors prevailing the triggering of the avalanche. Finally, pastoral activity that is still very strong on the high submit pastures hinders forest recolonization and promotes sweeping snow on flat ridges and thus the formation of wind slabs and of imposing cornices on the eastern slope, that are the more active in terms of avalanche activity (Figure 1).

historian in the study of risks over a long time period. Thus, although the obtained results are highly dependent on the geographical and institutional contexts, on the local socio-environmental relations (land use, memory, risk representations, relation to the risk, etc.) and on their interactions, the overall reflection and the methodology used could be profitably transposed to other risks or to other mountain areas, particularly medium high ones where knowledge is still very partial, if not absent.

The results show, in fact, that avalanche activity and risk is significant in the Vosges range, both in terms of frequency and intensity, especially in terms of human casualties (a dozen deaths since 1970, so one of the deadliest natural hazards in the Alsace region). It thus seems reasonable to think that the low 'advertising' of avalanche risk in the Vosges range is more due to a lack of consideration as a 'public problem', which is explained historically and socially by the local relations to the avalanche phenomenon we have detailed, than linked to an actual absence of avalanche activity. With few exceptions, the risk does not constitute a structural constraint, neither for the past and present everyday life, nor for the practice of the massif. The risk has been and remains essentially of individual nature. In this context, it is not surprising that it does not appear as a component of the local 'mountain culture', and that little evidence of collective heritage could be identified, except the existence of some memorial objects – such as crosses, a postcard and local stories.

In view of the continuous existence of the risk during the study period, the geo-chronology reflects only part of the avalanches that actually occurred. The 'low' number of avalanches recorded until the mid-twentieth century corresponds essentially to damaging avalanches, especially large ones. Inhomogeneity of the timeline could not be explained solely through the prism of the corpus of sources because of the importance of geographical and biophysical contexts. Thus, the increasing human pressure and deforestation accompanying the eighteenth century, in a context probably aggravated by large snow amounts during the Little Ice Age, may have favored the formation of large-scale avalanches but also allowed activity in low altitude paths located close to valley bottoms. On the contrary, man-made reforestation accompanied by a natural forest afforestation, had likely an impact on avalanche activity, at least in some sectors, in the sense of a reduction of frequency and intensity, or even of disappearance in certain valley sites. This is attested to by instructions nowadays given to scientists and managers to remove trees that grow in certain areas, no longer hampered by avalanche activity, in order to preserve the 'natural' plant and animal heritage typical of the Vosges landscape (Conservatoire des sites lorrains and Service d'appui technique Office national des forêts de Colmar, 1999)! Hence, the analysis shows that the temporal dynamics of the hazard is not only influenced by natural factors but depends heavily on interactions between society and its environment, both through human impacts on the environment and through the presence of stakes that may play a role in the triggering mechanism.

More generally, because knowledge of its occurrence is partially conditioned by the (re)sources available, the avalanche exists only as an object perceived and constructed by societies. The event is a social construction, related to the relations maintained by the societies with the avalanche phenomenon and the space in which it happens. Thus, the shape of the geo-chronology reflects the complex interrelationships between various interrelated factors: the sources, the social practices of the territory and the natural phenomenon. Reproduction this type of study in other contexts should, in the future, lead to better understand this rich but complex mechanics.

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