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Landslides inventory map as a first step for hazard and risk assessment: Rif mountains, Morocco

La cartographie d'inventaire, première étape de l'évaluation de l'aléa et du risque mouvements de terrain dans le Rif, Maroc

Mohamed Mastere[1, 2*], Bouchta El Fellah[1] & Olivier Maquaire[2]

1. *Scientific Institute, Mohammed V University of Rabat, Ibn Battouta Avenue, B.P 703, Agdal Rabat, Morocco* *(mohamed.mastere@gmail.com)
2. *Normandie University, Unicaen, UMR 6554 - CNRS, LETG-Caen, 14000 Caen, France.*

Abstract. The last two decades have witnessed an important growth in population numbers, and consequently in infrastructures. This has called a better understanding of geomorphological hazards and risks in the Rifean mountains. While the human activities have a direct influence on mass wasting formations via changes of original slopes, heavy-traffic transit, mining, urban development and planning. Geological complexity, steep geomorphology and abundant rainfall also increase landslides hazard. Therefore, the first step of any study on landslide hazard and risk is inevitably the compilation of a landslide inventory using GIS tools. Then a 1/300 000-scale landslides inventory map has been established for the Rifean region (North of Morocco) using extensive geomorphological analysis based on remote sensing imagery and aerial photo-interpretations consolidated with field surveys. 4177landslides were identified, which covered an area of 1065 km², accounting for 3 % of the study area (about 37000 km²). The minimum, the average and the maximum mass wasting areas are respectively 0.0004, 0.1 and 1.47km². This inventory enabled us to recognize three major families of slope failures morphologies: (i) landslides represented by two subtypes: superficial landslides and landslides - undercutting initiated by the erosive action of rivers (64.4%), (ii) rock-falls (25.2%) and (iii) debris flows (10.4%).

Keywords : Landslides, Regional inventory, hazard, risk, Rif, Morocco.

Résumé. Les deux dernières décennies ont connu une croissance importante de la population, et donc en infrastructures. Ce qui implique la nécessité d'une meilleure compréhension des aléas et des risques géomorphologiques dans les montagnes du Rif. L'action anthropique exerce une influence directe sur la formation de mouvements de terrain par la modification des pentes naturelles, un trafic intense, l'exploitation des carrières, l'aménagement et l'urbanisme. La complexité géologique, une géomorphologie abrupte et des précipitations intenses et irrégulières ont aussi un grand effet sur la genèse de ce type de phénomènes. Par conséquent, la première étape de toute étude sur l'aléa et risque mouvements de terrain (MT) consiste inévitablement en la constitution d'un inventaire de MT à l'aide des outils SIG. Un inventaire à l'échelle 1/300 000 de MT a été établi pour la région rifaine (nord du Maroc) à l'aide d'analyses géomorphologiques approfondies basées sur le traitement des images satellitales et des interprétations des photographiques aériennes avec des missions ponctuelles de terrain. 4177 MT ont été identifiés, couvrant une superficie de 1065 km² et représentant 3% de la zone d'étude (environ 37 000 km²). Les superficies minimale, moyenne et maximale sont respectivement de 0,0004, 0,1 et 1,47 km². Cet inventaire a permis de reconnaître trois grandes familles de morphologies de mouvements de versants: (i) les glissements de terrain représentés par des glissements superficiels et des glissements par sapement provoqués par l'action érosive des rivières (64,4%), (ii) des éboulements (25,2%) et (iii) coulées de débris (10,4%).

Mots Clés : Mouvements de terrain, inventaire régional, aléa, risque, Rif, Maroc.

INTRODUCTION

Many regions around the world are facing natural phenomena that are inherently capable of triggering terrible catastrophes. These phenomena have widely varied origins. In fact, earthquakes and volcanic eruptions are geophysical, hurricanes and storms are hydrometeorological, while mass movements are geomorphological. These latter are spread around the globe, especially in highlands and mountainous regions, where they represent a serious geological hazard.

Landslides are among the most devastating natural catastrophes, causing the deaths of an average of 4666 people yearly according to the global fatal landslides from 2004 to 2016 (Froude & Petley 2018). Even though landslides can be punctual, superficial, inscribed in a space and/or time, yet they can be brisk and large in magnitude to affect entire watersheds slopes. Some of these landslides can be a real threat to human life and goods and play an important role in the evolution of landscapes dominated by slope failure processes (Maquaire 2002, El Fellah & Mastere 2015, Mastere 2020).

Despite their high importance, mass movements maps only cover less than 3% of the slopes in the landmasses, and systematic information on the type, abundance, and distribution of mass movements is still lacking (Wood *et al*. 2015, Broeckx *et al*. 2018) . In order to document the expansion of gravitationel movements, their distribution, types, patterns, recurrence (frequence), and statistics of slope failures, preparing landslides maps proves to be an indispensable preliminary step toward landslides susceptibility, hazard, consequences and risk assessment related to human activities, urban planning and territorial management.

Since the first classifications of landslides (Sharp 1938, Varnes 1958 , Nemcok *et al*. 1972, Varnes 1974, Varnes 1978, Hutchinson 1988, Sassa 1988, etc.), a great variety of gravitational movements has been recognized/categorized according to their nature, kinematics or dynamics. These are slides, collapses, mowing, creep, and subsidence ... etc. They often have slow evolution phases, imperceptible to humans, despite the apparent but misleading stability of the slope: at times, they can go from slow evolution phases to sudden accelerations, generally triggered by intense precipitations, seismic solicitations or human activities, which can provoke serious disasters (Maquaire 2002, El Fellah 1996).

Given the diversity of movements encountered in nature, the most appropriate term for bringing together any land movement, soil or rock, on a slope by sliding, pouring, falling or simply crawling is that of “landslides” as it is according to the update of the Varnes classification (Hungr *et al*. 2014).

Consequently, landslides inventories are an important first step for assessing mass movements susceptibility, hazard and risk (Aleotti & Chowdury 1999, Dai & Lee 2002, Van Westen *et al*. 2008). Understanding the spatial and temporal distribution of mass wasting in the Rifean belt is substantial to decision makers and planners due to the damage they generate to life and infrastructure (Mastere *et al.* 2013). Furthermore, they are also indispensable for hazard and risk models that predict landslidesbased on past conditions. Therefore, locating mass wasting occurrences in the past are crucial to predict future ones.Despite the numerous studied inventories that have been established at several limited areas in the Rifean mountains (Lacroix 1968 , Maurer 1968, Chawki 1991, Fares 1994, Margaa 1994, El Khatabi 2001, Azzouz *et al.* 2002, El Kharim 2002, Mansour, 1998, Sossey Alaoui 2005, Mastere 2011…), no previous inventory has been established to include the whole Rif region, enlisting the mechanisms and precursors that lead to mass movements genesis and formation. The aim of this paper is to bring a synthetic insight on landslides inventory and mapping, using bibliographic previous data, medium and high-resolution satellite imagery, 1:17000 scale aerial photographs, Digital Elevation Models (DEMs) at different scales and field surveys. This study enables characterizing the past and present-day active landslides in terms of location, classification and statistically analysis. This regional-scale inventory allows also the interrogation of landslides risk over a wide range of geologies and topographies. Our inventory represents a homogeneous census of mass slope failures processes in the entire region and can be a powerful tool todelineate the distribution and recurrence of landslides processes which is essential for any investigatinglandslides susceptibility and hazard for future studies of the spatiotemporal evolution of landslides phenomena in the study area.

STUDY AREA

The Moroccan Rif situated in the northwest of Africa is a part of an Alpine thrust belt that extends from the Betics in southern Spain and curves through the Straits of Gibraltar into North Africa. They constitute together the westernmost termination of the Peri-Mediterranean Alpine mountain range. The regional thrust sheet transport directions swing through an 180° arc. Thrusting is toward the north in Spain, toward the west around the Straits of Gibraltar and the northwest Rif, and toward the south in the eastern Rif and Tell mountains of Algeria and Tunisia. Many authors attribute the arcuate nature to a collision during the Tertiary period between a micro-plate (Alboran plate), the Iberian plate, and the North African plate (Andrieux *et al*. 1971, Kornprobst 1974, Tapponier 1977, Wildi 1983, Lonergan & White, 1997). The structural units of the Rif mountains are classically grouped into three domains and which are limited by big overlapping accidents with a vergeance toward the NW. From inside to outside and bottom to top, we can find: (i) the Internal Zone, called Alboran Domain; (ii) the Flyschs Domain, and (iii) the External Zone. Each domain consists of tectonic complexes of stacked nappes (Andrieux 1971, Tapponier 1977, Wildi 1983) (**Figure 1**).

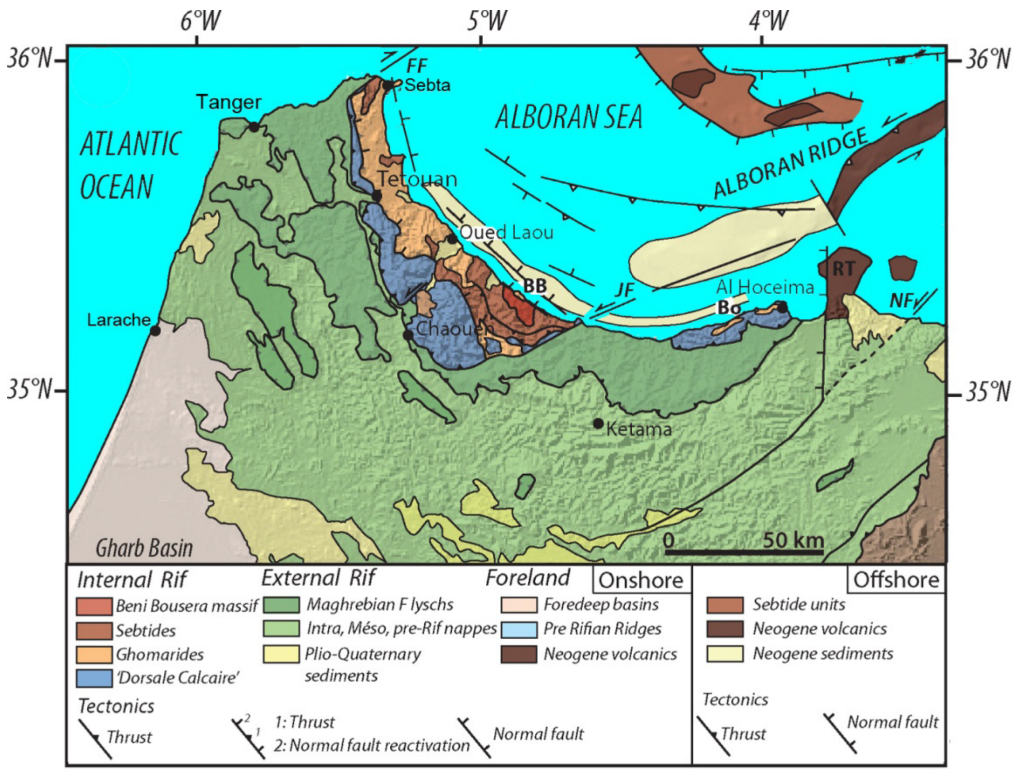

Figure 1. Geological and structural settings of the Rif and south Alboran sea after Chalouan et al., 2008. BB: Beni Bousera massif ; FF: Fahies Fault ; JF: Jebha Fault ; NF : Nekor Fault and RT: Rasel Tarf.

Nonetheless, the Eurasian and African plates convergence is responsible of the present-day continued tectonic activity of the Rifean belt, which is still uplifting and deforming (Tahayt *et al*. 2008, Poujol *et al.* 2014, Gimeno-Vives *et al.* 2020). Very undulating reliefs and very steep slopes reaching maximum values of 80° (Millies-Lacroix, 1974) characterize the resulting morphology. It induces an intense erosive dynamic through the study area associated to the Soft lithological nature of geological formations (Maurer 1964, El Gharbaoui, 1981). The Rif has several peaks over 2000 m, reaching its highest value at Jbel Tidirhine (2456m). They all located in the center of the chain. The calcareous Dorsal forms, from Ceuta (Sebta) to Chefchaouen, the structure of the north-western part of the Rif. Its sharp summits, cliffs and generally clear color are distinct from the rest of the landscape. On both sides of this chain, the topography is much softer, and generally lower. In the part of the Rif that extends between Chefchaouen and Nekor River, the structure/outline of the chain is less sharp but often higher. There are also some rigorously flat plateaus (Ktama - Targuist). The eastern sector is smoother and lower in altitude (rarely more than 1000 m) compared to the Rif chain. The plains or the hilly reliefs are situated by the two ends of the Rifean domain: in the West, the hilly country of Tangier lies along the Atlantic coast to Larache where it is relayed by the low plain of the Loukkos River and the sand-clay plateau of the Rehamna; the latter continues towards the South by the plain of Dradère, which is separated from that of the Rharb only by a border of hills. East to the Rifean territory, the plain of Kerte is relayed by those of Gareb and Bou-Areg which are situated before the plains of Lower Moulouya.The plains are practically non-existent; except for a few coastal alluvial zones, whose surface area does not exceed 2%, ie 700 km² of the approximately 37000 km².

The Rifean domain presents a great diversity, ranging from semi-arid to humid in relation to the altitude of the reliefs and the proximity to the oceans (with equal altitudes, the Atlantic zone receives more rain than the Mediterranean zone). Thus, three main areas can be identified:

• The Rifean chain, from Tetouan to a line joining Guercif to Aknoul, where the rainfall exceeds 1000 mm, or 2000 mm on the summits;

• The Eastern zone where, apart from some more or less extensive spots, the rainfall is less than 500 mm, the passage from this zone to the previous zone being without transition;

• The Northern plains and hills, West and South-West, where the rainfall, very nuanced, goes from 500 to 1000 mm.

Rainfall maxima are generally in December or January, with a secondary maximum in March or April. The driest months are July and August, the latter receiving nevertheless, especially on the reliefs, some thunderstorms which can be violent. Mean annual temperatures vary between 15 and 20 ° C and are inversely related to altitude.

The differences between the annual average maxima and minima are of the order of 12 ° on the coast (Larache, Tangier, Al-Hoceima) and vary from 16 to 19 ° in the inner area, according to altitude and orientation. The dry season lasts four months (June to September) on the reliefs, five months (mid-May to mid-October) on the Atlantic coast and six or seven months, depending on the altitude, in the Eastern Rif. The snowfalls each year on the high peaks of the Rif and can stay there until April (Gaussen 1954, Emberger 1955). The Rifean chain offers a great diversity in the natural stand and in the range of cultures.It is due to its differences in altitude, facies and humidity. Shrub vegetation accounts for about 2/3 of land use, while forest formations, usually discontinuous.

LANDSLIDES INVENTORY

Theoretical framework and methodological approach

Any cartography study aimed at landslides hazard and risk or simply the relationship between landslides and the eventual parameters that govern their formation in each sector, must inevitably be preceded by the collection of extensive data as on the position of the inherited (ancient) and current landslides, which amounts to their mapping. Therefore, mass movements inventory should be exhaustively comprehensives and continuous in both space and time (Glade & Croizier 2005, Broeckx *et al.* 2018). It represents the simplest form of their mapping (Hansen 1984) recording their locations and, when possible, the trigger date as well as the type and status of activity if there are perceptible traces still exist (McCalpin 1984, Varnes 1984).

There exist several techniques to carry out an inventory of landslides, depending on the size of the phenomena, the expenditure of the study area, the scales of the base maps, satellite images and photo-aerials, the quality and the accuracy of accessible information, and the resources available to carry out such work (Guzzetti *et al.* 2000).

The current inventory of landslides is based on four fundamental principles:

- First, the gravitational movements do not occur at random, but are the result of the union of (more or less) approximately complex physical conditions and processes that are controlled by mechanical laws that can be determined empirically, statistically or deterministically. Such characters confer on landslides phenomena the possibility of being generalized (Aleotti & Chowdhury 1999).
- Second, the principle of uniformitarianism is often adopted for the characterization of slope movements by assuming that all landslides will be triggered under the same conditions that led, in the past, to instability (Varnes *et al.* 1984, Carrara *et al.* 1991, Aleotti & Chowdhury 1999).
- Third, landslides leave discernible signs, which can be recognized, classified and mapped, in the field and / or by interpretation of airborne or satellite spatial data (Hutchinson 1989). Most of these signs are characteristically morphological, including changes in position, shape, topography appearance, lithology or even land use.
- Fourth, the morphological signature of the slope failures is intimately dependent on their nature. It can therefore be interpreted to delimit the extent (expansion) and type of movement. From its surface morphology, it is also possible to suggest a qualitative assessment of the age, the degree of activity and the depth of landslides (Varnes 1978, Cruden & Varnes 1996, Dikau *et al*. 1996).

Consequently, the current inventory map was performed by a combined analysis of several data sources (Figure 2, 3 & 5): geomorphological maps, geological maps, topographic maps, aerial photos, medium and high-resolution spatial remote sensing data, historical archives. Thereupon, and considering the extent of the study area (37000 Km²) as well as the frequency of gravitational movements, the inventory and the characterization of these last ones were mainly based on visual interpretations of the high and very high-resolution satellite images, completed (aggregated) by GIS digital processing and field verification.

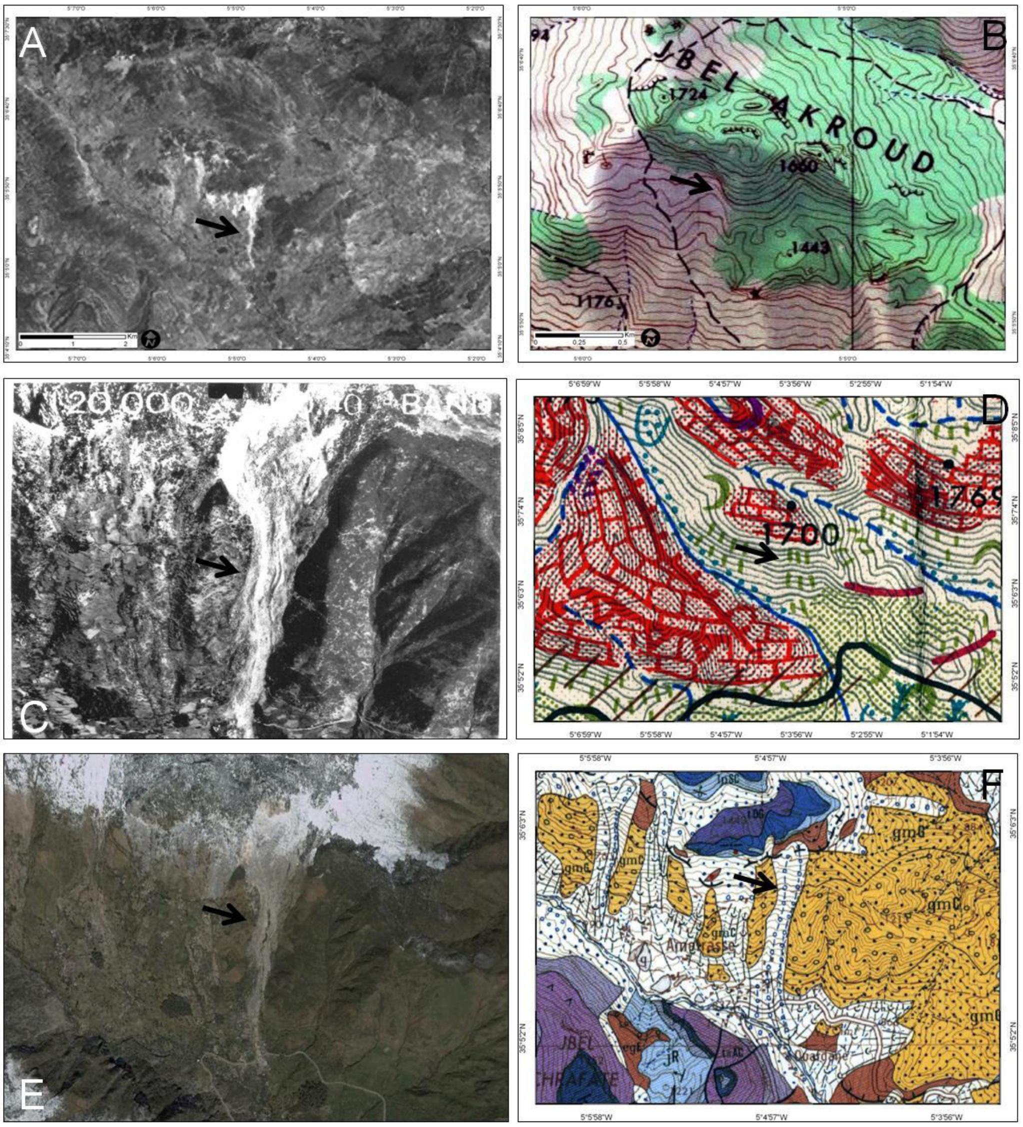

Figure 2. Example of Amtrass debris flow spotted in many thematic data sources. A: Landsat image with 15m resolution; B: topographic map; C: Aerial photo; D: Geomorphological map from Maurer, 1968; E: Spot image with 2.5m resolution and F: Geological map from Wildi 1976.

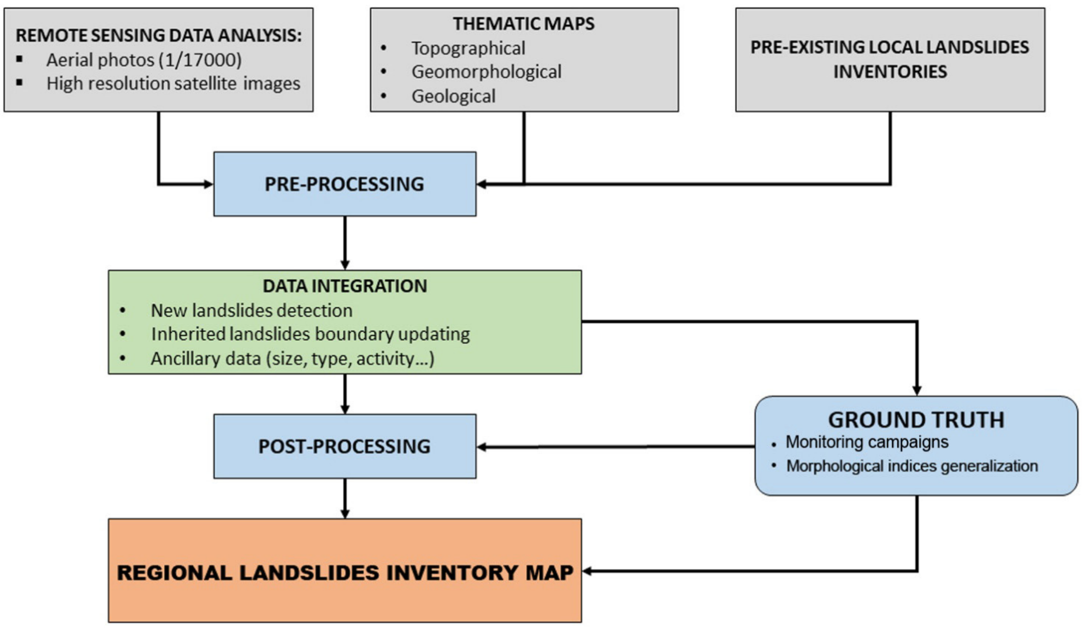

Figure 3. Methodological flowchart of landslides inventory mapping.

This demarche was motivated by the fact that the majority of traces left by a landslide are morphological in nature and may result from changes in shape, position or appearance of the topographic surface, thus allowing their (cartographic) mapping and their classification from the interpretation and analysis of spatial data (Varnes 1978, Hansen 1984, Hutchinson 1988). This was conditioned by one-off observations and verifications of several cases of field landslides (Figure 4 & 5) as shown in the methodological flowchart (Figure 3). Then, we have generalized, as much as possible, the same criteria on the rest of the phenomena. Since, on the one hand, the morphological signature of a ground motion depends on the dynamics of the slipped mass and the displaced volume, and on the other hand, the same type of motion implies similar morphological responses (Varnes 1978, Hansen 1984, Hutchinson 1988, Cruden & Varnes 1996).

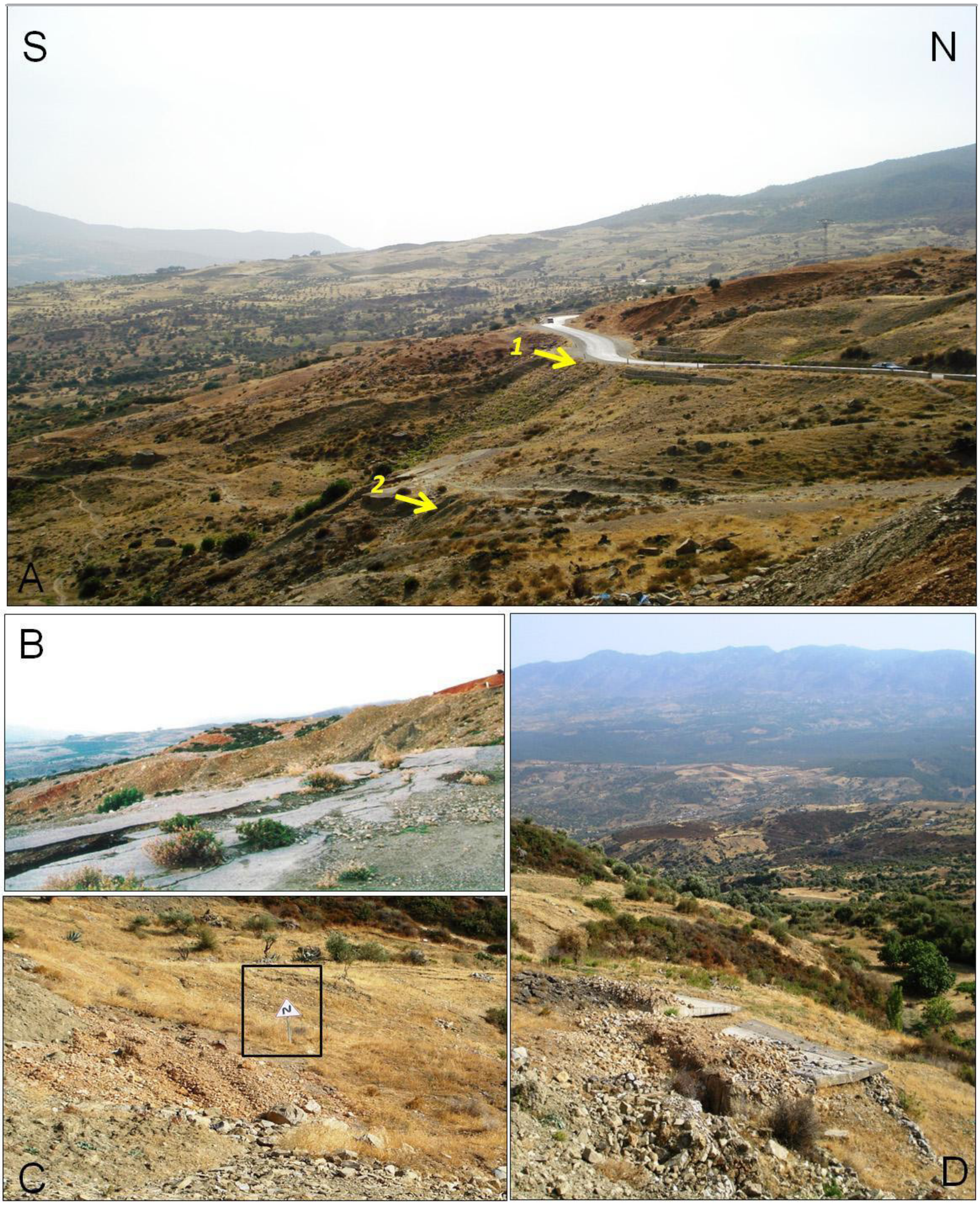

Figure 4. Example of an inventoried landslide A: General view of the national road N°2 passing through the BouHalla landslide; 1: Current road; 2: Ancient road destroyed by the 1984 Bou Halla landslide activity; B: Detail of the road destroyed by the BouHalla landslide activity. C: Road sign taken by the BouHalla landslide, with 20m displacement; D: Retaining wall recently destroyed by the Bou Halla landslide.

Inventory map: results and analysis

Figure 6D represents a cartographic zoom of the landslides inventory map and detailing their geometry as well as their typology and other information as reported in table 1. It materializes an intermediate landslides inventory of Chaouen area and which is the result of the combination of several sources of information (Figure 6A, B and C) where the number of the recorded mass movements is proportional to the accuracy of the used source data and the working scale as shown in table 2. For example, in Maurer (1968) geomorphological mapping at 1: 300,000 scale, only 49 movements were inventoried. These become 122 on geological and geomorphological cartography carried out by Wildi et *al.* 1976 at 1 / 50 000 scale, and 247 movements from high resolution satellite (2,5 m) and aerial photographies data (1 / 20 000 scale). More details about the three-intermediate-inventory maps characteristics are shown in table 2. In addition to the scale and resolution of the baseline data used for the inventory, manyr factors can influence the last result of such a procedure, the study purpose (global recognition, geomorphological study, spatio-temporal evolution, etc.); the available resources (financial and human), the spent time and the implemented experience.

A mass movement, once recognized on aerial photo or in the field, must be drawn on the inventory map, in a form that will reflect its characteristics (scale, size, geometry,etc.) and its position at a given time. This passage, which is purely interpretative, is most often accompanied by a number of errors, especially since the geomorphologist is based on sufficiently old topographic maps (IGN) (50 years in our case).

The old data sources, like geological, geomorphological and topographic maps contain already many errors related the absolute values of the geographical coordinates, which makes difficult positioning the inventoried slope failures. To overcome this, the use of remote sensing data which reflect the current position, morphology with reasonable accuracy, the uncertainty related to the landslides inventory positioning has been minimized.

With a goal of simplification and within the framework of this first exploratory study of landslides inventory mapping of in the Rifean zone. An abstraction of creeping, solifluxion and other superficial debris affecting the whole of the Rifean slopes, the inventory only concerns especially events authenticated by filed observations and verifications from thematic documents and measurable data. The inventoried landslides include 4177 events (Figure 7) and covers an area of 1 065 km² or approximately 3% of the overall surface area within the region (37 000 km²). This inventory enabled us to recognise three major families of slope failures morphologies, namely: 1) landslides represented by superficial landslides and landslides - undercutting initiated by the erosive action of rivers, 2) rock-falls, and 3) debris flows. The maximum size of the recorded movements of 147 0000 m² for a minimum of 400 m² and an average of 100 000 m². The small size of land movement (<100 000 m²) number 3209 or 76.8% of all movements and cover an area 467.7Km² or 43.9% of the entire area affected by the landslides. Those of average size between 100 000 and 300 000 m² account for 759 movements corresponding to 18.19% of the total number, and an area of 249.1 Km² corresponding to 23.4% of the totality of the zones of movements. As for those of large size, they do not exceed 59 for an area of 348.2 Km². It respectively represents 4.98% and 32.6% of the total number of phenomena on the overall study area (Tables 3 & 4). It should be noted, however, that the change in the size of landslides is a gradual process between the small and large areas, which justifies that in the same region, it is possible to meet all types of landslides and of variable magnitudes and that there is no preferential geographical distribution of phenomena according to their size (area).

Figure 5. View of Wad Feddal watershed shows Douar Wahran basin (C) and Boujibar landslide moving toward the opposite bank.

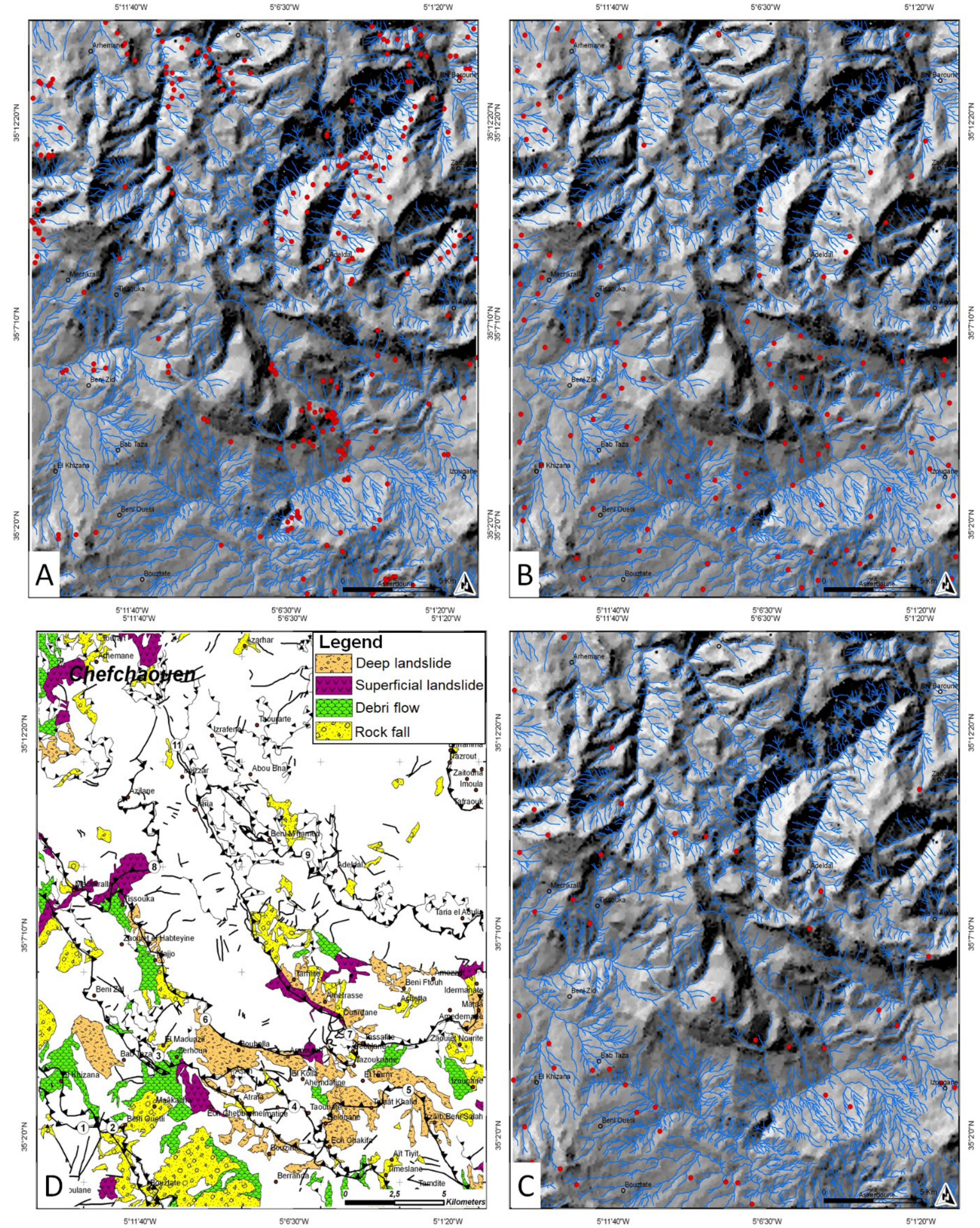

Figure 6. Zoom of three intermediate landslides inventory maps of Chaouen area achieved from. A: high resolution satellite images (Spot5 2,5m) and aerial photographies 1/20 000 scale (1962, mission number 245) ; B: geological and geomorphological maps from Wildi *et al*. 1976 at 1 / 50 000 scale; C: geomorphological map from Maurer 1968 at 1 / 300 000 scale and D: synthetic landslides inventory map (A+B+C) of Chefchaouen area showing theirs geometry and typology.

Table 1. An extract from the attribute table of the global inventory of land movements at the scale of the Rif chain and summarizing the characteristics of these movements.

ID	Type	Area (km²)	Lithology	Longitude (m)	Latitude (m)	Locality	Slope class	Perimeter (km)	Fault
28	Landslide	0,69	sandstone-pelite	514010	503680	Mechkralla	0 to 10°	4,89	Bni amar-Bni zid
40	Rock fall	0,75	sandstone-pelite	514210	501980	Maôkacha	0 to 10°	4,97	Bni amar-Bni zid
16	Landslide	1,43	sand-conglomerate	514910	503220	Mechkralla	0 to 10°	11,31	Bni amar-Bni zid
19	Landslide	3,85	sand-conglomerate	515090	495120	El Khizana	10 to 20°	18,44	Jbel khizana
39	Rock fall	1,16	sandstone-pelite	515280	500680	Beni Zid	0 to 10°	4,61	Bni amar-Bni zid
6	Debri flow	3,51	sand-conglomerate	516590	496500	Bab Taza	10 to 20°	9,40	Bni amar-Bni zid
11	Landslide	0,77	sand-conglomerate	517230	489730	Bouztate	10 to 20°	4,50	Jbel khizana
24	Landslide	1,26	sand-conglomerate	517680	502960	El Khizana	10 to 20°	6,92	Bni amar-Bni zid
18	Landslide	0,40	sand-conglomerate	517720	494360	El Khizana	10 to 20°	5,06	Jbel khizana
20	Landslide	0,23	sandstone-pelite	517720	493030	Beni Outoli	0 to 10°	3,34	Jbel khizana
25	Landslide	0,30	sand-conglomerate	517740	497270	Bab Taza	0 to 10°	3,34	Bni amar-Bni zid
15	Landslide	3,18	sand-conglomerate	518120	504520	Tissouka	10 to 20°	13,25	Bni amar-Bni zid
27	Landslide	0,08	sandstone-pelite	518290	498380	Beni Zid	10 to 20°	1,39	Bni amar-Bni zid
42	Rock fall	0,20	sandstone-pelite	519200	498740	Majjo	10 to 20°	2,40	Bni amar-Bni zid
29	Landslide	1,44	sand-conglomerate	519340	499850	Majjo	10 to 20°	7,50	Bni amar-Bni zid
26	Landslide	4,10	sand-conglomerate	520100	494680	Zerhoun	0 to 10°	18,83	Bni amar-Bni zid
41	Rock fall	1,34	sandstone-pelite	520300	499200	Majjo	10 to 20°	6,73	Bni amar-Bni zid
21	Landslide	0,93	sand-conglomerate	520510	492050	Maôkacha	0 to 10°	6,03	Jbel khizana
17	Landslide	2,16	sand-conglomerate	521660	494310	Ech Chebbarine	0 to 10°	12,55	Bni amar-Bni zid
34	Rock fall	3,66	Limestone	523350	489200	Bouztate	0 to 10°	10,11	Jbel khizana
8	Debri flow	6,77	sand-conglomerate	523720	496150	Bouhalla	0 to 10°	21,58	Bni amar-Bni zid
7	Debri flow	0,25	sand-conglomerate	525190	494090	Ech Chebbarine	0 to 10°	2,83	Bni amar-Bni zid
43	Rock fall	0,33	sandstone-pelite	525550	494710	El Kolla	0 to 10°	3,75	Bni amar-Bni zid
36	Rock fall	3,16	Limestone	525620	501910	Tarhlite	10 to 20°	21,57	Jbel bousliman
4	Debri flow	0,84	sand-conglomerate	526740	499890	Tarhlite	10 to 20°	7,26	Jbel bousliman
14	Landslide	1,81	sand-conglomerate	526830	498950	Amtrasse	30 to 80°	13,35	Jbel bousliman
22	Landslide	0,20	sandstone-pelite	526980	500880	Tarhlite	10 to 20°	2,12	Jbel bousliman

The occurrence of the inventoried landslides depends upon the conjunction of several parameters, called causative variables (El Fellah & Mastere 2015). In the study area, lithology, rainfall, fracturing and land use are considered as the most important factors of landslides formation. In addition, seismicity, slope degree, stream network and slope aspect also have a significant impact on landslides forming. From a lithological point of view, nearly 40% of the inventoried landslides were triggered at the level of the schistosed and diaclastic marl formations of the Tangier-Ketama unit, the unit of the internal mesorif, the unit of Tisirene and that of Loukkos.

Table 2. Comparison of landslides inventory characteristics.

	Inventory A	Inventory B	Inventory C
Total landslides number	247	122	49
Total landslides area (km²)	135	123,13	27,05
Ratio (area) landslides – study area	21,42	19,52	4,29
Area of the smallest landslide (km²)	0,04	0,05	0,1
Area of the biggest landslide (km²)	7,4	14,42	8,7
Average landslide area (km²)	0,1	1	0,5

As for debris flows, their distribution proves to be intimately related to the lands that constitute the outermost part of the internal domain materialized by the limestone ridge (Dorsale calcaire). Rock-falls, are preferentially localized at massive dolomites with calcareous intercalations, limestone with flint, sandstones and quartzites.

These forms are also mainly related to the limestone ridge and Tizirene formations, including the Numidian sandstones widely present on the central Rif massifs and the western Rif south of Tangier.

The Rif region is subject to temporal as well as spatial variation in rainfall. On average, it rains 78 days per annum. These days of rain can be continuous with torrential rain for several days. Landslides formation are not due to the amount of annual rainfall, but rather the conjunction of several pluvial periods during the same year, with unusually heavy intensity and pace. Furthermore, the study area is characterized by significant flood events caused by heavy rainfall. The hydro-climatic hazards are the main cause of the erosion processes that not only carve the watersheds, but also shape the river landscapes by giving rise to bank undercutting, modifying of the dynamics of the rivers, and by reactivating or initiating certain landslides.

Table 3. Landslides inventory.

Study Area (km²)	000 37
Number of Inventoried landslides	177 4
Covered Area (km²)	065 1
Minimum Size of landslides (m²)	400
Average Size of landslides (m²)	000 100
Maximum Size of landslides (m²)	147 000

Land use in the study area is characterized by a strong human footprint/activity that is manifested in the degradation of vegetation cover aggravating the effects of water erosion, the undercutting of river banks in coastal Mediterranean area but also in the whole Ouergha and Loukkos wadi. The development of badlands is carried out in particular in the marly formations of the southern Rif margins. These last two account for about 20% of the total land area used for agriculture and grazing (Mastere *et al.* 2020). Deforestation for land-grabbing purposes for farming makes the hillsides subject to intense constraints undermining their equilibrium.

Table 4. Landslides detailed Inventory.

Landslides size (m²)	Number	Area (km²)	Percentage to size (%)	Percentage to study area (%)
Inferior to 100 000	3209	476.7	76.8	43.9
Between 1000 and 300 000	759	249.1	18.3	23.5
Superior to 300 000	59	348.2	4.9	32.6

Slopes destabilization caused by earthquakes can occur in different ways due to soil thixotropy. They can immediately trigger landslides, mudslides, rock-fall and significant damage to habitations, infrastructures and plantations. However, they may have longer-term effects, increasing the control of rock fracturing, reducing the slope strength. In addition, enlarged cracks tend to increase the infiltration of water in the longer term, to encourage the freeze-thaw of the material and thus to lead to a movement. For the same material whose weight and mechanical characteristics are invariable, the increase in the slope angle results in an increase in the shear tangential stress; and therefore, a decrease in the safety factor. The average slope of the study area is about 16° with a standard deviation of 9°. The slopes of 20 to 30°, occupy more than half of the area and have a sporadic distribution with a particular localization downstream of the limestone chain and the north-western half of the Ghomarides lands on the one hand. On the other hand, their distribution goes in parallel with the extension of the slopes occupied by the flysch plies. These slopes shelter the majority of the inventoried landslides.

The hydrographic network is one of the parameters that control the occurrence of landslides. It acts both at the surface and at depth. In the study area, slopes are clearly disturbed by the water flow, which is considered an important factor to slope instability. The drainage network by its mobility and its erosive power is responsible for significant disruption and generates instabilities. Surface runoff generates extensive zones of gullies (badlands) and piping in friable geological formations. Additionally, the hydrographic network has a destabilising effect by the undermining of shoreline riverbanks. This is what initiates a new landslide or reactivates a stabilised one.

The slope aspect, which expresses the relative slopes orientation to the north. Variation in the slope aspect is associated with a large variability in the obliquity of solar rays, the duration of sunshine in the hillside, and energy inputs like wind and temperature. This factor affects the predisposition of the hillside to landslides even if it is very difficult to prove statistically.

The present day tectonic of the Rifean belt is characterized by active deformation which is dominated by the ongoing Eurasian-African plate convergence since the Upper Cretaceous as shown by a regular seismic activity andseveral destructive historical earthquakes (Meghraoui *et al.* 1996, Tahayt *et al.* 2008, Vernant *et al.* 2010, Pérouse *et al.* 2010, Koulali *et al.* 2011, Poujol *et al.* 2014). This kinematics intervene on landslide in already weakened zones of the earth/soil, either by pre-conditioning the material or as a trigger during an intense seismic crisis. It is obvious that the fracture network favours the water infiltration, thus increasing the pore pressure and reducing the shear resistance of the soil. It is also clear that their abundance is proportional to the increase of the density of fracturing or networks of faults.

To quantify the geographical (spatial component of hazard) abundance of mass movements, a landslides density map has been prepared (Figure 7). Many techniques of spatial analysis exist in literature. In this article we used the kernel method density estimation which allowed us to measure the spatial distribution (frequency) of slope failures. This map provide insight on the expected occurrence of slope failures overall the study area without leaving unclassified areas. The inventoried landslides were plotted on a global map and then were entered into a Geographical Information System (GIS), where each event, represented by a dot, has an associated information sheet. Then, the landslide density map produced using this tool helps explain hazard and risk assessment to land developers, planners and decision makers. It provides also a synoptic view of the spatial distribution of mass movements at a regional scale, and offers first-order insight of hazard, helping to define the “hot spots” that require more detailed study.

CONCLUSION

The current study covered the inventory of landslides on a total area of 37 500 km² in the Rifean belt region situated north of Morocco. The study area’s geomorphological context is under the influence of Mediterranean and oceanic climates and is part of the active tectonic domain of the Rif. The resulting morphology is therefore characterised by very rugged land marked by the narrow valleys, strong slopes, ramps and powerful impact in such massive rock walls at the limestone ridges and at major overlapping contacts.Under those circumstances, the present inventory helped identify 4 177 landslides, grouped under three main types, which resulted as much from the combination of natural as anthropic factors, namely: 1) landslides represented by superficial landslides and landslides - undercutting initiated by the erosive action of rivers, 2) rock-falls, and 3) debris flows.

The mapping of the study area landslides has been directly processed within and with a GIS program, in order to build parts of the database, and to complete the metadata containing the characteristics (coordinates, area, perimeter, type ... etc.) of the landslides in the study area supplemented by field surveys as well.In fact, a reliable landslides inventory describing the type and spatial distribution is essential for landslides susceptibility, hazard and risk assessment, since it is the fundamental component of the assessments. Like the various hazards, the management of the landslides is an essential step that must precede any development project within the framework of sustainable development.

It is obvious, from the analysis of this mass movements density mapping that most phenomena are related to the lithological contrast, the geomorphological settings with abrupt slopes, deep streamlines and several fault scarps characterizing the whole region. The unconsolidated geological formations are also marked by deep gullies developed on thick sequences, some of them very altered have also an important number of landslides.

The superimposition of the main cities, villages and basic infrastructures of S. Miguel on the Landslides Density Map emphasizes the high risk that exists in certain areas of the island (Fig. 8). Emergency and land use planning are needed in order to minimize the impact of future complex/multiple events. Authorities should be aware of the importance of hazard and vulnerability assessment to ensure the normal socio-economic development of the region.

Evaluating landslides susceptibility/hazard is an indispensable component in the process of proactive management centred on the prevention of landslide risk, through the creation of susceptibility/hazard maps. These maps will assess the risk by integrating the vulnerability and its different dimensions. This can be done after (1) analysing the conditions under which landslides happened in the past and (2) identifying relevant combinations that has led to such formations in order to predict future landslides occurrences and frequency by crossing the inventoried phenomena, the various causative parameters and temporal information. For that matter, and in view of the scale of the study area, a mapping of the susceptibility / hazard by the index map combination method is among the most adapted to apply. It is an indirect and qualitative heuristic method. It enables the evaluation of susceptibility/hazard based on the hierarchization of the different significant terrain parameters, by assigning different weights to each class of parameters in accordance to their importance in the formation of landslides. The application of this methodology will constitute the continuity of this work in a second/coming article.

An inventory map can have several limitations, mainly regarding their intrinsic subjectivity and the difficulty of assessing their exhaustiveness (Van Westen 1993, Van Westen *et al.* 2006, Guzzetti *et al.* 2000, Malamud *et al.* 2004). A map is in itself an interpretative document. It is therefore essential to always ask the question about its quality, reliability and resolution, before making and when consulting a landslides inventory map, because of the interpretive nature which impact greatly the final landslides hazard map zonation . However, it is admitted that an established mass movements inventory maps from high and very high resolution images (satellite and aerial), coupled with even limited field observations, are of a wide reliable quality when using GIS processing. This quality depends also on several parameters such as the age or freshness of the landslide, the persistence of its morphological signature in relation to the regional morphobioclimatic context, the type and resolution of satellite images and aerial photos as well as the base maps used for the inventory, the morpho-geological framework of the study area; and land use. But the most important parameter is the degree of experience of the analyst carrying out the inventory.

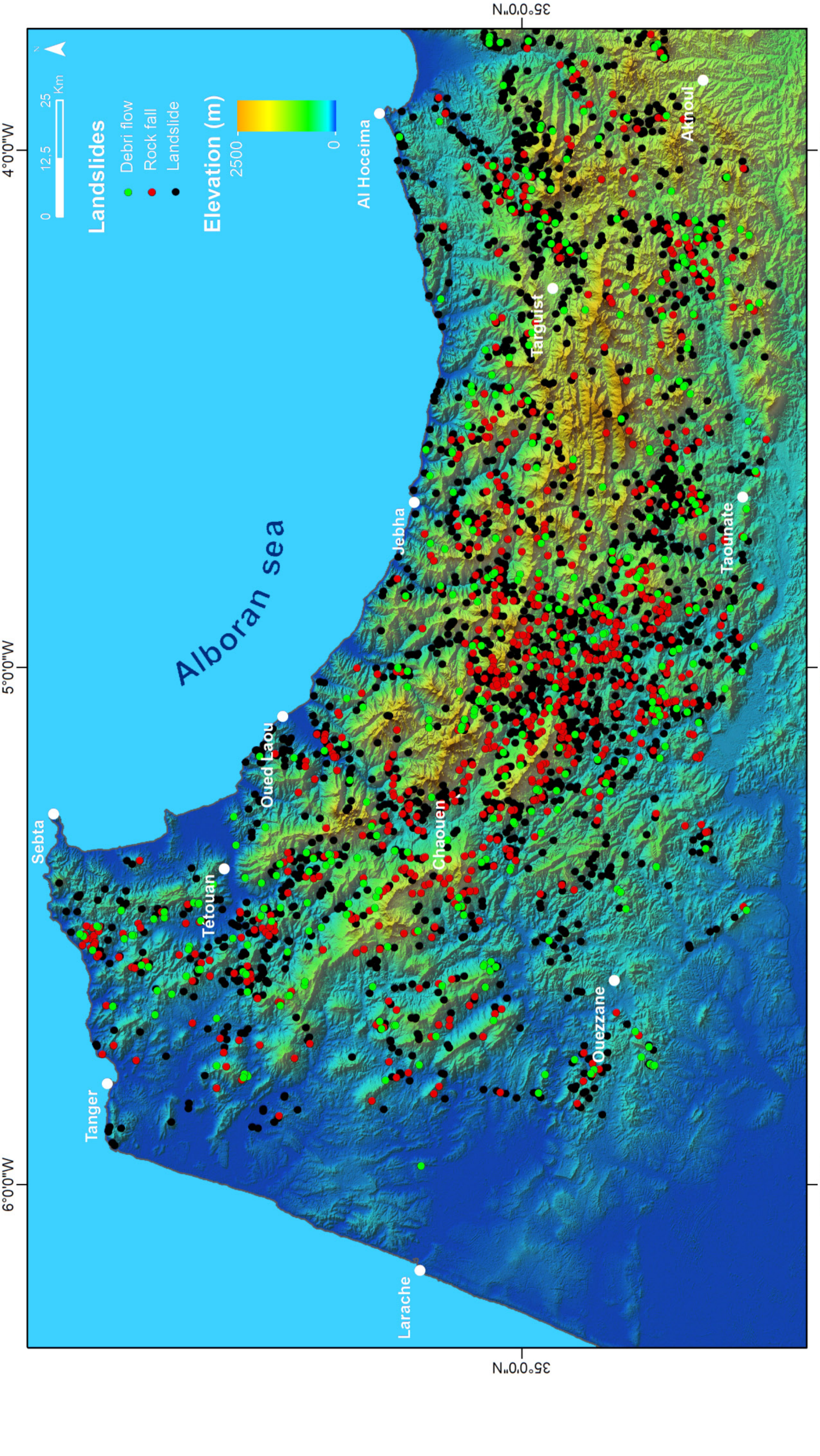

Figure 7. Mass movements regional inventory map of the Rifean belt.

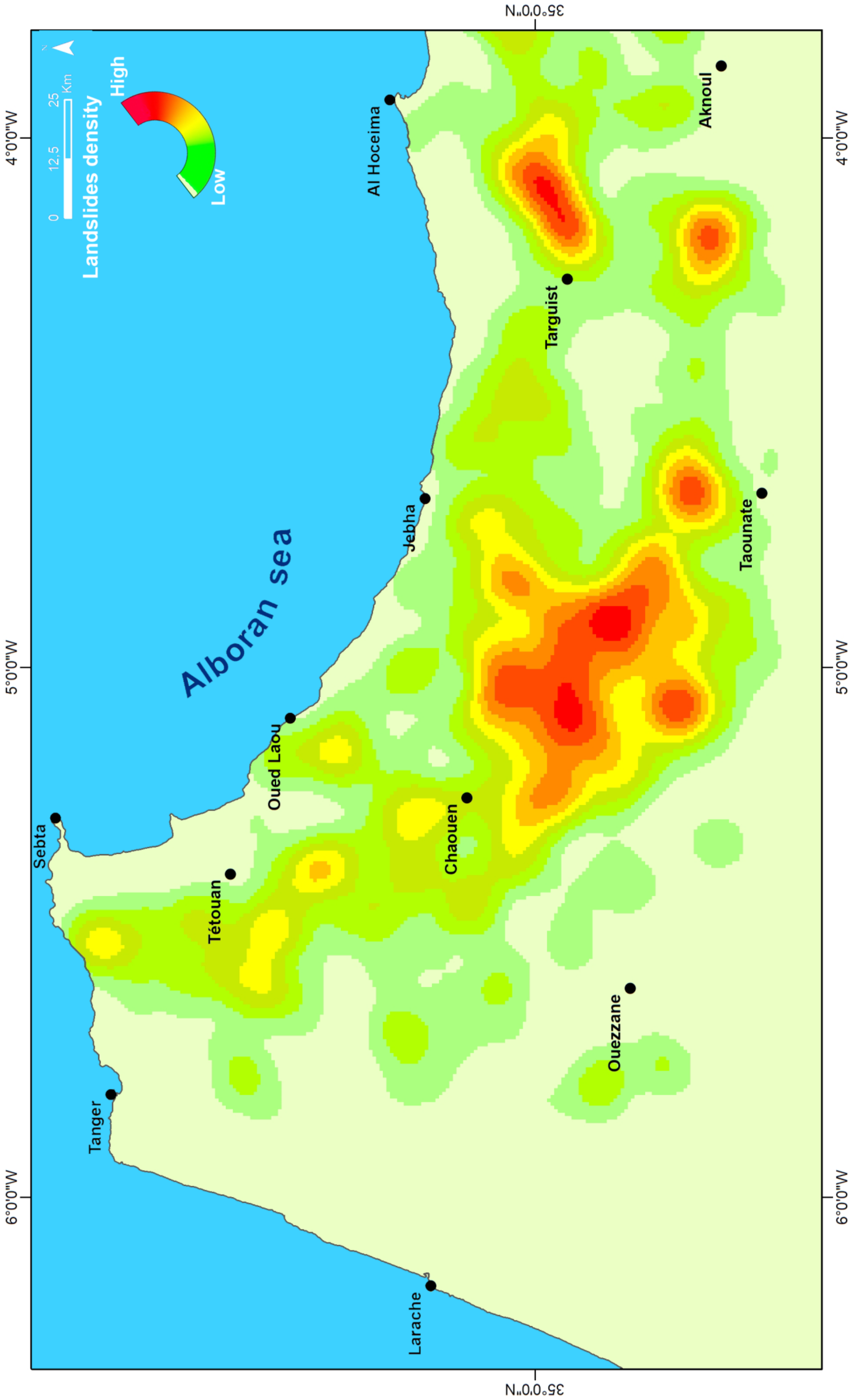

Figure 8. Mass movements regional density map of the Rifean belt.

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