Deep-seated slope deformation in the headwaters of the Audour River (Central Rif Mountains): morphology, kinematics and present day activity

Deformação profunda de vertente na cabeceira da bacia do rio Audour (Montanhas do Rif Central): morfologia, cinemática e actividade actual.

A. Fonseca[1], J. L. Zêzere[1], J. Madeira[2], A. Faleh[3], A. Sadiki[4]

[1]RISKam – Research group on Environmental Hazard and Risk Assessment and Management, Geographical Research Centre, University of Lisbon, Edifício da Faculdade de Letras, Alameda da Universidade, 1600-214 , Lisbon, Portugal. E-mail: afonseca.geo@gmail.com; zezere@campus.ul.pt.
[2]LATTEX-IDL (LA), Department of Geology, Faculty of Sciences, University of Lisbon, Edif. C2, 5° piso, Campo Grande, 1749-016 Lisbon, Portugal. E-mail: jmadeira@fc.ul.pt
[3]University Sidi Mohammed Ben Abdallah, Faculty of Letters, Department of Geography, B.P. 59 Saïss, Fès, Morocco. E-mail : falehali2001@yahoo.fr
[4]University Sidi Mohammed Ben Abdallah, Faculty of Sciences Dhar el Mahraz, Department of Geology, B.P 1796 Atlas- Fès, Morocco. email: sadiki_a@yahoo.fr

Abstract

The Rif Mountains extend along the northern coast of Africa forming the south western-end of the Betic-Rif-Tell orogen. Convergent mountain belts reaching thousands of meters are the result of the balance between tectonic, climatic and surface processes (Willet *et al.* 2006). Deep-seated mass movements are among the most efficient processes to erode mountainous terrains (Korup *et al.* 2007). As deep-seated landslides tend to evolve over larger time frames (thousands to hundreds of years) they constitute geomorphic markers to slope deformation passing through different periods of tectonic and climatic forcing. Our research project is divided into two primary objectives: 1) to understand the feedbacks between mountain uplift, drainage network incision and deep-seated slope deformation; 2) to analyze present day evolution and kinematics of deep-seated slope deformation. In this work we present preliminary results from the first field campaign, focusing our discussion on the morphology, kinematics and present day activity of a deep-seated landslide located 50km east of Chefchauen in the headwaters of the Audour River.

Keywords:
Deep-seated landslides, Central Rif, Morocco, geomorphological mapping

Resumo

As Montanhas do Rif prolongam-se ao longo da costa noroeste do continente Africano formando o sector ocidental do orógeno Bético-Rif-Tell. Cadeias montanhosas formadas em regime de convergência expressam o equilíbrio entre processos tectónicos, climáticos e erosivos (Willet *et al.* 2006). Os movimentos de massa profundos estão entre os processos mais eficazes na erosão de cadeias montanhosas activas (Korup *et al.* 2007), tendendo a evoluir ao longo de escalas temporais alargadas (milhares a centenas de anos). Por esse motivo, estes constituem marcadores geomorfológicos de deformação de vertente, passando por diferentes fazes de actividade tectónica e por periodos climáticos distintos. O presente projecto de investigação assenta em dois objectivos principais: 1) compreender as relações de *feedback* entre o levantamento da cadeia montanhosa, a incisão da rede hidrográfica e a deformação profunda de vertente; 2) analisar a evolução actual, o comportamento cinemático e os factores desencadeantes de deformação. No presente trabalho apresentamos os resultados preliminares da primeira campanha de campo, focando a nossa discussão nos aspectos morfológicos, cinemática e actividade actual de um movimento de vertente profundo localizado a 50Km a Este de Chefchauen, na cabeceira do rio Audour.

Palavras chave:
Deformação profunda de vertente, Rif Central, Marrocos, cartografia geomorfológica

1. Research project presentation

Convergent mountain belts reaching thousands of meters are the result of the balance between tectonic, climatic and surface processes functioning within a *Coupled Dynamic System* (Willet *et al.* 2006). Feedback mechanisms between tectonic, climatic and surface processes exert strong control over the shape, maximum height and time necessary to build, or destroy, a mountain range (Pinter & Brandon, 1997). Increased elevation over thousands of years through faulting, isostatic compensation and crustal thickening, increases river channel gradients and erosion rates through fluvial incision and sediment transport (Willet *et al.* 2006). As mountain systems uplift, topography tends to enhance orographic precipitation increasing river discharge and incision through direct flow or snow melt (Willet *et al.* 2006). As rivers set local base level for hillslope processes, base level fall and channel incision lead to increased slope failure and sediment supply to channels. At shorter timescales earthquake triggering of landslides and seismic weakening of rock masses can exert influence erosion rate (Hovius *et al.* 2004; Willet *et al.* 2006; Korup, 2009).

According to Montgomery & Brandon (2002) high-relief landscapes tend to respond to changes in rock uplift rate through adjustments in the frequency of slope failure. Deep-seated mass movements, which strongly correlate with high relief landscapes (Hovius *et al.* 2004), are among the most efficient processes to erode mountainous terrains (Korup *et al.* 2007). These processes tend to evolve over very long time intervals, affecting entire slopes and displacing rock volumes up to hundreds of millions of cubic meters (Soldati, 2006). Evolution is controlled by the variation in the post glacial piezometric level, high-relief slopes, fault orientation and tectonic stress, seismicity and fluvial lateral erosion (Agliardi *et al*., 2009). Nevertheless, problems such as inaccessibility, size of slope failures, high depth of rupture plane and presence of multiple rupture surfaces make the study of deep-seated slope deformation a difficult and still poorly understood topic (Agliardi *et al*., 2009).

Studies on deep-seated slope deformation in the Central Rif Mountains are poorly developed. The first descriptions of deep-seated landslides are owed to Maurer (1968), focusing mostly on active processes such as active deep rotational slides. Azzouz (2002) and El Khattabi & Carlier (2003) analyzed examples of deep-seated slope deformation in the Rif Mountains focusing their work on morphology, structure, tectonic and hydrodynamic control on mass movement triggering. Although other examples of deep-seated slope deformation have already been identified in the Rif (e.g. Saadi *et al*. 1980), the the tectonic and climatic conditions driving slope failures are not studied. Present-day activity is poorly understood and attention is only given when infrastructures are destroyed through reactivation of deep-seated mass movements.

Our work is developed in the headwaters of the river Audour (Central Rif Mountains) where several examples of deep-seated slope deformation were identified. As deep-seated landslides tend to evolve over larger time frames (thousands to hundreds of years) they constitute geomorphic marker to slope deformation passing through different periods of tectonic and climatic forcing. Our project is divided into two primary objectives: 1) to understand the feedbacks between mountain uplift, drainage network incision and deep-seated slope deformation; and 2) to analyze present day evolution and kinematics of deep-seated slope deformation, identifying the main triggering mechanisms controlling its reactivation. In this work we present preliminary results from the first field campaign, focusing our discussion on the morphology, kinematics and triggering mechanisms of a deep-seated landslide located 50km east of Chefchauen.

In order to facilitate data management and analysis we created a digital database of the study area containing the following cartographic information: 1) Digital Elevation Model (pixel size=20m) created from the 1:50.000 topographic maps of the study area (Carte Topographique 1:50.000 de la region de Bab Taza, Service Géographique du Maroc); 2) Geological map of the Rif Mountains, scale 1:500.000 (Saadi *et al*. 1980); 3) Mosaic of images extracted from GoogleEarth database; 4) Landsat 7 images. Lineament mapping was performed using shadow-relief and Landsat 7 images. These where validated using published geological maps and during field survey. During field work we performed detailed geomorphological mapping at the scale of 1:10.000, supported by digital photo-interpretation using the image database from GoogleEarth.

2. Case study presentation

The Rif Mountains extend along the northern coast of Africa forming the south western-end of the Betic-Rif-Tell orogen. This mountain system has been uplifting over the last 70 million years due to the convergence between the African and Eurasian plates. The structure of the Rif is characterized by southward dipping thrust faults and folds forming tectonic *nappe* complexes. From inside to outside and bottom to top, it is possible to identify three complexes, each one subdivided in two tectonic *nappes* with similar lithology (Chalouan *et. al.*, 2008): 1) the *Internal Zones*, or *Alboran Domain*; 2) the *Maghrebian Flyschs*; 3) and the *External Zones*.

The study area is located within the contact between the *Maghrebian Flyschs* (J. Tisiren and Beni Ider *nappes*) and the *External Zones* (Intrarif - Tanger Unit). The *Maghrebian Flyschs* complex is characterized by a *nappe* stack consisting of turbiditic sediments topped by the Internal Zones and overlaying the *External Zones*. The more internal and higher units are known as the *Mauritanian nappes* composed by the J. Tisiren and Beni Ider *nappes*. From bottom to top the J. Tisiren *nappe* is composed by marly limestone followed by turbiditic levels consisting of graded siliciclastic sandstone with argillaceous-pelitic horizons of Berriasian – middle Albian age. The Beni Ider *nappe* consists of black shales (*pre-flysch unit*), pelites, schists and sandstone of upper Albian – Eocene - Oligocene age (Saadi *et al*. 1980; Chalouan *et. al.*, 2008).

The *External Zones* of the Rif are subdivided into three structural zones from north to south and top to bottom: the *Intrarif, Mesorif* and *Prerif*. The northernmost sector of the *Intrarif* is subdivided into the Ketama, Tanger and Loukkous Units. Within the study area the Internal Tanger Unit is overthrust by the Tisiren and Beni Ider *nappes* and is characterized by marly-pelitic and marly-limestone of Cenomanian-Maastrichtian age (Saadi *et al*. 1980).

The contact between *nappes* within the study area is established by N135 trending, north dipping thrust faults. Secondary fault systems are oriented N40 and N90 (Saadi *et al*. 1980). Lineament mapping and field validation resulted in the identification of a conjugated set oriented to N45 and N135 controlling drainage network orientation, summit offsets and wind gap alignments.

The key morphological features of the study area are three N65 trending elongated summits from which the valley of Beni Derkoul develops: the Koudiet es Sbaa (1768m), the Jebel Beni Salah (1504m) and the Jemaat Ben Troun (1287m). Valley carving throughout upper Pliocene and most of the Quaternary was performed at the expenses of the lithological differences between the Tanger Unit (softer) and the Tisiren and Beni Ider *nappes* (harder rocks). Evidences from this last period of evolution are poorly represented due to intense erosion; it is only possible to find 4 strath terraces along the Maâmala River, dated from middle to upper Quaternary (Maurer, 1968) and a thick slope deposit (over 40 meters in thickness) composed by angular and sub-angular sandstone blocks (0.3 to 20m^3) within a poorly consolidated yellow-orange colored sand-clay matrix.

The valley of Beni Derkoul flows from Koudiet es Sbaa into the Maâmala River, a tributary of the Audour River. Drainage patterns analysis along the upper sections of the valley shows a dissymmetric catchment extending towards N135 and tilted towards the east, incising the lower stratigraphic sections of the Tiziren *nappe* and the Tanger unit.

From the village of Beni Derkoul to the top of Koudiet es Sbaa, several morphological anomalies point out to the presence of slope deformation and allow the subdivision of the study area in three different sectors (Fig.1):

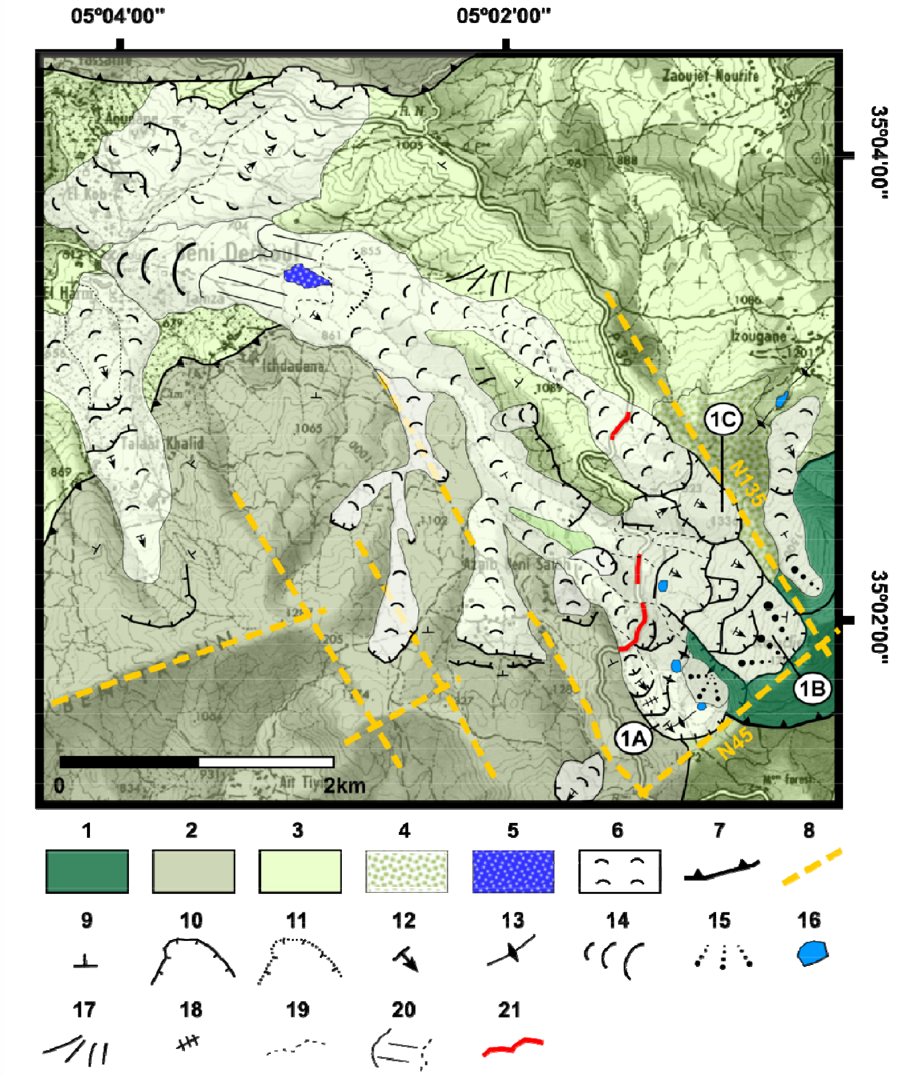

Figure 1. Simplified geomorphological map of the study area: 1) Tiziren nappe; 2) Beni Ider nappe; 3) Tanger Unit; 4) Slope deposit; 5) Fine alluvial sediments; 6) Landslide mass; 7) Thrust fault; 8) Lineament; 9) Strike and dip of stratification; 10) Landslide scarp; 11) Probable landslide scarp; 12) Reverse slope; 13) Extension; 14) landslide frontal lobe; 15) Rockfall deposit; 16) Lake; 17) Glacis; 18) Tension fractures; 19) Limit to landslide units showing different kinematical behavior; 20) Semi-flat surface; 21) Signs of deformation along the road.

Sector 1. The area affected by deep-seated slope deformation is limited by two lineaments oriented to N45 and N135, separated by a 300m offset along a N135 scarp with down-throw of the southwestern block. This morphological step allows the definition of three sub-sector of deformation (Fig.1). Deformation along Sector 1A is characterized by two morphological steps affecting the lower stratigraphic sections of the Tiziren *nappe*, creating an offset of over 40m between the first and the second step. These are apparently connected to deep-seated rupture plane, for which depth is unknown. The area is poorly drained creating lakes within the landslide mass. Some information regarding mass movement kinematic can be inferred. The presence of active tension fracturing and slope deformation on the western side of Sector 1A, testifies for differences in rates and speed of deformation within the landslide body, being higher for this sector.

Slope deformation along Sector 1B is defined by a triangular scarp facing NW and by a complex hummocky topography extending from 1700 to approximately 1300 meters. From the top of Koudiet es Sbaa, three morphological steps (forming reverse-slopes) gradually lower topography towards northwest, affecting a slope deposit at least 40 meters thick. Deformation along slope progressively changes from planar-deep-seated failure to rotational sliding around 1450m, point at which the propagation azimuth changes from N315 to N290. Deformation on Sector 1C begins at 1420 meters on the northeastern edge of the drainage water divide, affecting the Tanger Unit and the slope deposit previously described. It shows characteristic of a typical deep-seated rotational slide propagating towards N330, presenting two circular scarps offset by over 60 meters.

Sector 2 - Below 1300 to 1400m, all of the sub-sectors described above seem to change mechanics and rate of deformation, changing from deep-seated slope deformation to complex rotational sliding, limiting deformation to surface deposits. The transition between sectors 1 and 2 is still poorly constrained, but the sudden change in slope processes might signify that deep-seated deformation is no longer present. Nevertheless, the presence of bedrock outcrops within the landslide mass (i.e. north of sub-sector 1A) prevents placing a rigid limit between the two sectors. Fractured houses and road deformation testifies for present day activity along this transition zone. Down slope from this point, the landslide mass enters the valleys around Azaib Beni Salah, filling valley bottoms and coalescing as it reaches the main valley. The landslide mass is incised along its flanks by temporary torrential gullies and presents successive slope breaks on which small lakes and poorly drained areas can be found.

Sector 3 - The lower section of the valley is 1km wide and presents a semi-flat hummocky surface which contrasts with the 30 to 65 degree bedrock carved valley slopes. Valley morphology results from the coalescence of the landslide masses descending from Koudiet es Sbaa. Fluvial incision is processed along the margins and central sections of the valley through seasonal torrential gullies. Along these gullies, exposures reveal the two following sequences: 1) bedrock (Beni Ider *nappe*), landslide debris; 2) bedrock (Beni Ider *nappe*), landslide debris, terrace.

Approximately 2.5Km east of Beni Derkoul valley orientation shifts from S - N to E – W. At this point, a tenuous morphological step (probable landslide scar) leading to a semi-flat surface (2 - 3° slopes) between 800 and 740 meters, creates an area of fine sediment accumulation. This morphology is consistent with landslide morphology. Further evidence of deformation is found along the central section of the valley, testified by poorly drained areas, temporary lakes and reverse slope morphology.

Slope deformation also occurs along the eastern and western sides of the valley. These landslides tend to coalesce with the main landslide body contributing with mass and energy for further deformation down slope. From approximately 700 to 620 meters the landslide mass enters the Maâmala River with a frontal lobe reaching 80m in height and 800 meters of circular length.

3. Future work

The example of slope deformation here presented testifies for the complexity deep-seated mass movements can attain. These processes impose several geomorphological problems for which resolution can only be achieved by adopting an integrated approach, combining information from different fields of research.

Several question remain to be answered: what was the tectonic and climatic context on which slope failure began?; what is the link between present-day tectonic activity, climate and slope deformation?; are deformation rates similar along the landslide body?; what is the depth of the failure surface and how is the transition between sectors 1 and 2?; what is the chronology of deformation?; are partial reactivations the result of local conditions or derive from deep-seated deformation in the upper sectors of the slope?; what is present-day kinematics and how does it correlate with past activity?

In order to accomplish our objectives we need to improve the understanding of the structure and stratigraphy of the area as well as on the age of the Quaternary formations. Chronology of deformation might be achieved by applying carbon dating to lacustrine sediments within lakes and by dendrochronology on over 100 year old oaks grown within the landslide mass. By using INSAR technology we hope to get answers regarding present-day activity and kinematics.

References

Agliardi F., Zanchi, A., Crosta, G.B. (2009). Tectonic vs. gravitational morphostructures in the central Eastern Alps (Italy): Constraints on the recent evolution of the mountain range. *Tectonophysics*, doi:10.1016/j.tecto.2009.02.019.

Azzouz, O., El Fellah, B., Chalouan, A. (2002). Processus de glissement dans le Massif de Bokoya (Rif interne, Maroc) : exemple de Cala Bonita, Bulletin de l'Institut scientifique, Rabat, section Sciences de la Terre, n° 24, 33-40.

Chalouan, A., Michard, A., El Kadiri, K., Negro, F., Frizon de Lamotte, D., Soto, J.I; Saddiqi, O. (2008). The Rif. *In* Continental Evolution: The Geology of Morocco - Structure, Stratigraphy, and Tectonics of the Africa-Atlantic-Mediterranean Triple Junction. Michard, A.; Saddiqi, O.; Chalouan, A.; Frizon de Lamotte, D. (Ed.) Springer, 424p.

El Khattabi, J. & Carlier, E. (2003). Tectonic and hydrodynamic control of landslides in the northern area of the Central Rif, Morocco. Engineering Geology, Volume 71, 3-4, 255-264.

Hovius, N., Lague, D., & Dadson, S. (2004). Processes, rates and patterns of mountain-belt erosion. *In* P. N. Owens, & O. Slaymaker (ed). Mountain Geomorphology. London: Arnold, 109-131.

Korup, O., Clague, J.J., Hermanns, R.L., Hewitt, K., Strom, A.L., Weidinger, J.T. (2007). Giant landslides, topography, and erosion**.** Earth and Planetary Science Letters; 261; 578 – 589.

Maurer, G., (1968). Les Montagnes du Rif Central. Etude Géomorphologique (Vol. Nº14). (I. S. Cherifien, Ed.) Rabat: Serie Geologie et Geographie Physique, 499p.

Montgomery, D. R., Brandon, M. T., (2002). Topographic control on erosion in tectonically active mountain ranges. Earth and Planetary Science Letters; 201 481 – 489.

Pinter, N. & Brandon, M. (1997). How Erosion Builds Mountains - An understanding of how tectonic, erosional and climatic forces interact to shape mountains permits clearer insights into the earth's history. Scientific American 74, 74-79.

Saadi, M., Hilali, E.A., Boudda, A. (1980). Carte Géologique de la chaîne Rifaine – echelle 1:500.000. Ministere de l'Energie et des Mines, Direction de Geologie, Service de Géologie du Maroc, Notes et Mémoires, Nº 245ª.

Soldati, M. (2006). Deep-seated gravitational slope deformation. In Goudie, A.S. (edi.), Encyclopedia of Geomorphology, Vol.1, 226-228.

Willett, S.D., Hovius, N., Brandon, M.T., and Fisher, D.M. (2006). Introduction, *in* Willett, S.D., Hovius, N., Brandon, M.T., and Fisher, D.M., (eds.), Tectonics, Climate, and Landscape Evolution: Geological Society of America Special Paper 398, Penrose Conference Series, p. vii–xi.