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Active tectonics in Quaternary marine formations in the Tangier region (North West Rif, Morocco): Persistent Scatterer (PSInSAR) contribution

Tectónica activa en formaciones marinas cuaternarias en la región de Tánger (Noroeste de Marruecos): Contribución de la técnica PSInSAR

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ABSTRACT

This study investigates recent tectonic activity in Tangier, Morocco, using PSInSAR data and microtectonic field observations. The exploration of marine deposits in the Achakar basin during the Plio-Quaternary period holds significance for tracking the recent geodynamic changes in the study area. Microtectonic analysis revealed a shift from a NE-SW compressive regime in the Late Pliocene to a Quaternary regime dominated by a NE-SW extension regime and a NW-SE compressive regime. PSInSAR detected ground displacement rates ranging from subsidence (-4.9 mm/yr) to uplift (4.9 mm/yr) during the study period (2018-2021).

Key-words: *Atlantic coastline, Neotectonics, Quaternary, Tangier, PSINSAR.*

RESUMEN

Este estudio investiga la actividad tectónica reciente en Tánger, Marruecos, utilizando datos de PSInSAR y observaciones de campo microtectónicas. La exploración de depósitos marinos en la cuenca de Ashokan durante el período Plio-Cuaternario tiene importancia para rastrear los cambios geodinámicos recientes en el área de estudio. El análisis microtectónico reveló un cambio de un régimen de compresión NE-SO en el Plioceno tardío a un régimen cuaternario dominado por un régimen de extensión NE-SO y un régimen de compresión NW-SE. PSInSAR detectó tasas de desplazamiento del suelo que oscilaron entre hundimiento (-4,9 mm/año) y levantamiento (4,9 mm/año) durante el período de estudio (2018-2021).

Palabras clave: *Costa Atlántica, Neotectónica, Cuaternario, Tánger, PSINSAR*

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Introduction

The Rif Mountain range emerges as a highly dynamic geological zone within the broader western Mediterranean. Its neotectonic progression arises from the interaction of the dextral shifts along the Azores-Gibraltar transform fault and the north-south converging motions of Africa in relation to Eurasia (Morel and Meghraoui, 1996). Consequently, the recent Plio-Quaternary tectonics in the Rif region are shaped by the interplay between two geodynamic factors: the convergence of Africa and Europe and the expulsion of the Alboran block to the west-southwest (Morel, 1988).

In the Quaternary, the joint impact of the Africa-Europe convergence and isostatic adjustment phenomena amplified vertical differential movements along key recent fault lines, namely N-S, N40-70E, and N90-120E (Ait Brahim, 1991). Moreover, the examination of elevation differences in ancient Quaternary shorelines (Guillemin et Houzay, 1982, and Cadet et al., 1977) has enabled the characterization of regions undergoing uplift and others experiencing subsidence.

The exploration of marine deposits in the Achakar basin during the Plio-Quaternary period holds significance for tracking the recent geodynamic changes in the study area. This exploration facilitates the delineation and analysis of the distribution and stratification of marine levels, offering insights into variations in the extent and elevations of these units.

Previous research has employed various methodologies to investigate the Achakar basin (Akil et al., 1995; Alouane, 1996; Istiquam, 1999; Aboumaria et al., 2009; Tichli et al., 2023). This study introduces the application of Persistent Scatterer Interferometry (PSInSAR), a technique that allows for precise measurement of both horizontal and vertical ground movements in the study area.

Geological and Tectonic Setting

Our study focuses on Pleistocene and Quaternary marine deposits along the northwest edge of the Rifan belt, namely in the Achakkar area of the Tangier region (Fig. 1C). The Tangier region is separated into three geological units within the Rifan chain that run from northeast to southwest (Fig. 1B): (1) Intrarif, including the Ketama, Loukkos, and Tangier units, all composed of Cenonian marls and clays (Wildi, 1983); (2) Mesorif, which is composed of Paleocene siliciclastic sequences that are characterized by the Triassic (Leblanc, 1979); and (3) Prerif, which is a sequence of nappes thrusting into the foreland and separated from their Mesozoic foundation. Rocks ranging in age from the Triassic to the Neogene (Wildi, 1983) have generated these disordered materials, which are embedded in a marl-clay matrix (Fig. 1B).

The microtectonic examinations of the formations at Cap Achakkar suggest that the extension, driven by two primary normal fault systems oriented N10 to N40 and N90 to N120, led to gradual stretching and the formation of a subsidence area towards the South and West (Istiquam.,

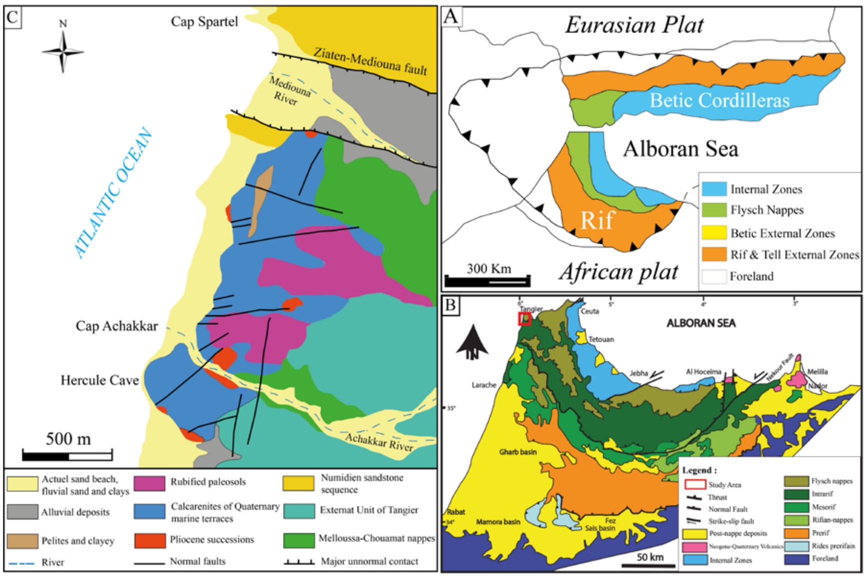

Fig. 1.- A- Geological map of the middle Western Mediterranean region showing the Alpine range. B- Simplified geological map of the Rif chain. C- The Structural map of Achakkar region (Tangier, Morocco). (modified from Boccaletti and Conedera, 1985 and Suter, 1980).

Fig. 1.- A - Mapa geológico de la región del Mediterráneo occidental central que muestra la cadena alpina. B - Mapa geológico simplificado de la cadena del Rif. C - Mapa estructural de la región de Achakkar (Tánger, Marruecos). (modificado de Boccaletti y Conedera, 1985 and Suter, 1980).

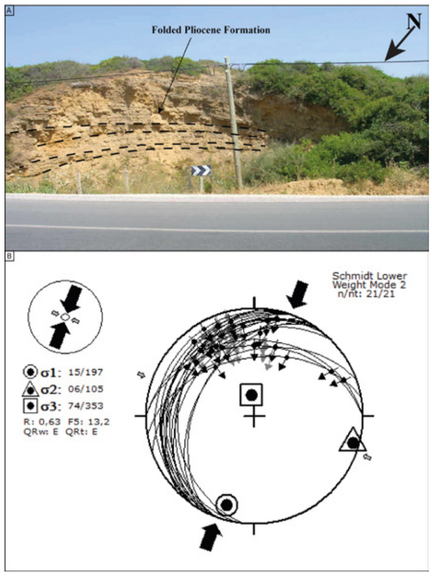

Fig. 2.- Outcrop of Upper Pliocene Sandy Marls at Oued Zitoun Exhibiting a NW-SE Trending Anticline (A). The Anticline Likely Formed Due to NE-SW Compressive Stress (B).

Fig. 2.- Afloramiento de margas arenosas del Plioceno Superior en Oued Zitoun que exhibe un anticlinal con tendencia NO-SE (A). El anticlinal probablemente se formó debido a un esfuerzo compresivo NE-SO (B).

1999). In this region, the Quaternary marine formations are overlaid, as reported by Akil et al. (1995) and Alouane (1996).

Methodology

To gain insights into the geological history of the study area and the current stress regime acting on the rocks, we employed microtectonic analysis. This involved field data collection and processing using Win-Tensor software (Delvaux, 2012) (https://damiendelvaux.be/Tensor/WinTensor/win-tensor.html). We measured the orientation (strike and dip) and sense of slip (movement direction) of 164 fault planes and diaclases, which are natural fractures in the rock. By analyzing these measurements with Win-Tensor, we could reconstruct past tectonic events and infer the present-day stress field in the region.

To investigate ongoing ground surface displacement and its relation to current tectonic activity, we utilized the Persistent Scatterers Interferometry (PSInSAR) technique. PSInSAR analyzes a series of radar images acquired by satellites over time to detect minute changes in the ground's reflection properties (Ferretti et al., 2001). In this study, we employed 20 Sentinel-1A Synthetic Aperture Radar (SAR) images acquired in the C-band between January 16, 2018, and December 26, 2021. These images were obtained from NASA's Alaska Satellite Facility (ASF) (https://search.asf.alaska.edu/). The extensive dataset allowed us to capture subtle ground movements and analyze trends in surface displacement over this four-year period. The PSInSAR data processing involved a two-stage workflow: snap2stamps package for pre-processing (Delgado Blasco, 2018; Foumelis et al., 2018) using SNAP ESA open-source software and the StaMPS software (Hooper et al., 2010) (https://github.com/dbekaert/StaMPS/blob/master/Manual/StaMPS_Manual.pdf) for PSI processing to generate high-resolution displacement maps. This approach provided valuable insights into recent ground movements and ongoing tectonic processes in the study area.

Results and discussion

Upper Pliocene

The exposure of the Upper Pliocene is limited in the area. The one noticeable exception is the area around Hercule Cave, where they modestly emerge beneath the old Quaternary marine calcarenites. Moreover, the stratified sandy marls of the Upper Pliocene can be observed at Oued Zitoun, unveiling an anticline, located upstream from the S701 road bridge (X = 451,479; Y = 573,429, N: 35.76, W: -5.93) (Fig. 2A).

The analysis of bedding planes in the Oued Zitoun anticline (Fig. 2A) indicates a NE-SW compressive stress direction (Fig. 2B). This suggests a NW-SE fold trend for this particular fold, likely reflecting the regional stress regime.

The Quaternary coastal formations

1. At the Hercules Cave

In this region, fractures are classified into two sets: sub-parallel and sub-perpendicular oriented fractures to the coast between Cap Achakkar and Cap Spartel (fig. 3A). Microfolds indicate evidence of recent compressive stress, responsible for the folding of lumachellite calcarenites (fig. 3B). It should be noted that this microfold has been discovered for the first time in the study area.

2. Between Cap Achakkar and Cap Spartel

The microtectonic study conducted along this coast highlights structures related to extensional and compressive tectonic activity. Figure 4 summarizes extensional structures represented by normal faults (fig. 4A, 4B), synsedimentary normal faults (fig. 4E, 4F), and occasionally horst and graben structures fig.4C, 4D).

Therefore, Quaternary extensional activity has affected marine formations in the studied area. Furthermore, stratifications in Quaternary sediments show abrupt tilt from 10 to 20°, in agreement with the subsidence caused by normal faults (fig. 5A). This recent tectonic instability is also expressed by the interpreted seismite features (Aboumaria, 2009, and Istiquam, 1999) (Fig. 5A).

As for structures related to N-S compression, they are rare and appear modestly in the study area. They are limited to microfolds affecting calcarenitic formations (Fig. 5B). This N-S compression phase is the result of the convergence between the African and Eurasian plates during the Quaternary period.

The analysis of orientation of fault planes and joints affecting these Qua-

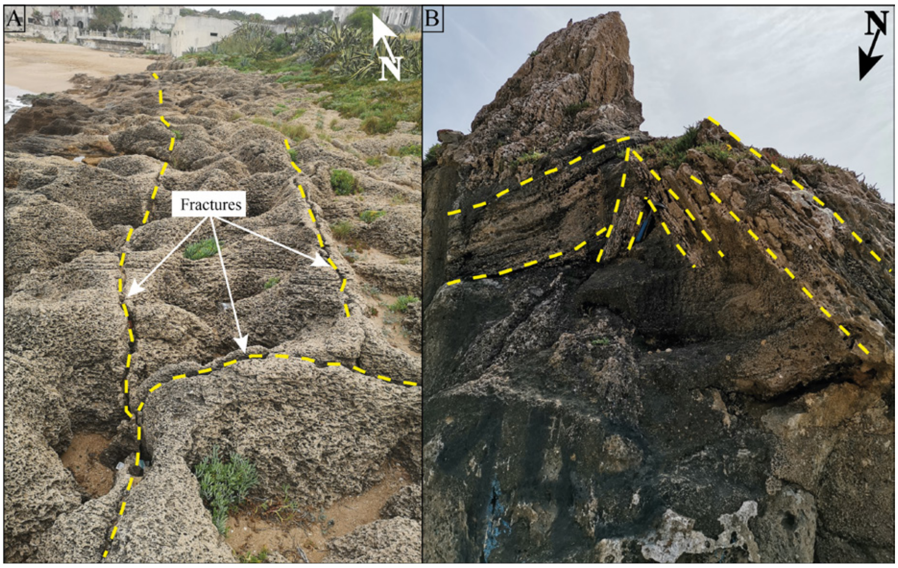

Fig. 3.- A- The figure shows the various fractures observed at the Cave of Hercules. B- Mesofold at the Cave of Hercules.

Fig. 3.- A- La figura muestra las diversas fracturas observadas en la Cueva de Hércules. B- Pliegue de pequeña en la Cueva de Hércules.

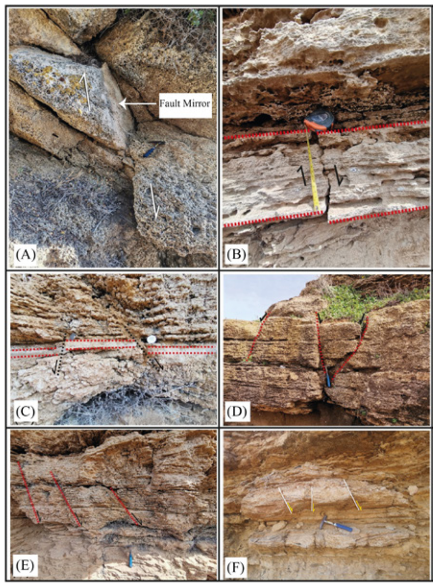

Fig. 4.- Photographs of the extensional deformation affecting Quaternary marine formations between Cap Achkar and Cap Spartel. (A) and (B): normal faults; (C): horst; (D): graben; (E) and (F): synsedimentary normal faults.

Fig. 4.- Fotografías de la deformación extensional que afecta a las formaciones marinas cuaternarias entre Cap Achkar y Cap Spartel. (A) y (B): fallas normales; (C): horst; (D): graben; (E) y (F): fallas normales sinsedimentarias.

ternary marine formations provided a WNW-ESE to NW-SE oriented compression associated with an extension in NE-SW direction (fig. 5C).

PSINSAR Time Series

Deformation mean velocity (LOS)

Results from PSInSAR analysis reveal that the coastline displacement varied between 4.9 mm/yr and -4.9 mm/yr throughout the observation period, January 16, 2018, and December 26, 2021 (Fig. 6). This indicates a range of movement rates, with some areas experiencing subsidence (movement towards the satellite) and others exhibiting uplift (movement away from the satellite). Generally, there is a trend of increasing subsidence rates, reaching a maximum of -4.9 mm/yr at the Mediouna Beach. Conversely, values decrease progressively in the south of Mediouna Beach (Cap Achakar) and also north of it (Cap Spartel).

Displacement time series

PSInSAR time series analysis reveals contrasting displacement patterns across the study area (Fig. 7). Point (A) exhibits minimal displacement, with data points clustered around zero on the LOS (line-of-sight) displacement axis. This indicates relatively stable ground motion at this location throughout the observation period (January 16, 2018–December 26, 2021). Conversely, point (B) shows a wider range of displacement values, ranging from approximately +2 mm to -2 mm on the LOS axis. The red line suggests a possible trend of either ongoing subsidence (movement towards the satellite) at an increasing rate or a cyclical pattern of movement at point B.

The GNSS velocity field from Lakhouidsi et al. 2024 indicates subtle geodynamic movements at the Tangier (TANG) GPS station across three components: north, east, and vertical. The northward component displays a velocity of approximately -1.24 mm/year, suggesting a slight southward movement. The eastward component shows a minimal westward movement at about -0.06 mm/year. Vertically, the station experiences a subsidence rate of approximately -0.82 mm/year, reflecting a slow downward movement of the surface. These measurements are crucial for assessing the deformation patterns and tectonic dynamics of the region, significantly influenced by the ongoing interactions at the Africa-Eurasia plate boundary.

Conclusion

After the NE latest Pliocene compressive phase, the study area experienced a recent NE oriented extension, contemporary with a general NNW-SSE to N-S oriented. compression in agreement with the Africa-Iberia convergence.

The early effects of this extension timidly appear along the coast between Cap Spartel and Cap Achakar; they are characterized by the development of normal faults, microfolds, and slumps, which are interpreted as seismites. This Quaternary tectonic instability is the result of the 'Ziaten-Mediouna' normal fault reactivation (Fig. 1C).

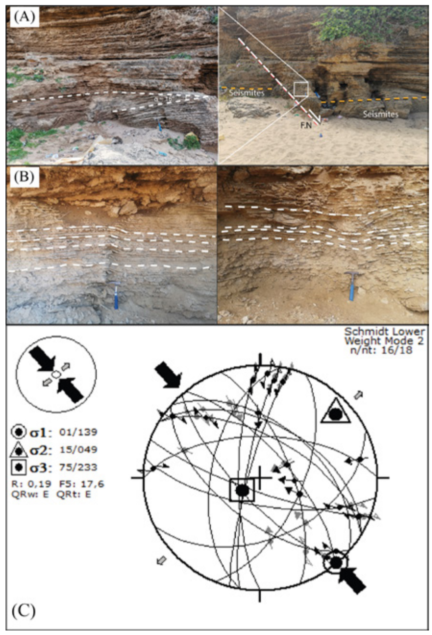

Fig. 5.- A- Normal fault affecting the Quaternary formations in the study area. B- Folding affects the calcarenitic formations in the study area. C- Cumulative stereo plot showing WNW-ESE to NW-SE - oriented compression and NE-SW oriented extension.

Fig. 5.- A- Falla normal que afecta las formaciones cuaternarias en el área de estudio. B- El plegamiento afecta las formaciones calcareníticas en el área de estudio. C- Gráfico estéreo acumulativo que muestra la compresión orientada a WNW-ESE a NW-SE y la extensión orientada a NE-SW.

References

Aboumaria, K., Zaghloul, M.N., Battaglia, M., Loiacono, F., Puglisi, D., Aberkan, M. (2009). Journal of African Earth Sciences 55, 10–35. https://doi.org/b62sm5

Ait Brahim, L., (1991). Brittle tectonics and recent stress states in Northern Morocco. Results from the kinematics of the Africa - Europe plates and the Alboran block. State Thesis, Mohamed V University, Rabat, 244p.

Akil, M., Chalouan, A., Istiquam, H., El Fahssi, A., Mamad, A. (1995). Les formations quaternaires de la Rive Sud du Detroit de Gibraltar: Stratigraphie et déformation. El Enlace Fijo del Estrecho de Gibraltar 2. 71-79.

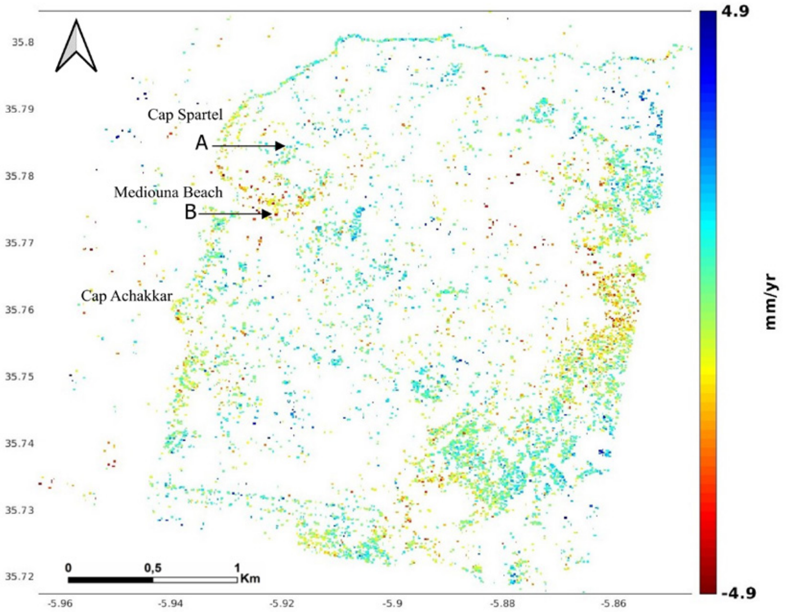

Fig. 6. Map of Ground Rate Motion in the Tangier, Morocco Area (mm/year). See color figure in the web.

Fig. 6. Mapa de Movimiento de Velocidad del Suelo en el Área de Tánger, Marruecos (mm / año). Ver figura en color en la web.

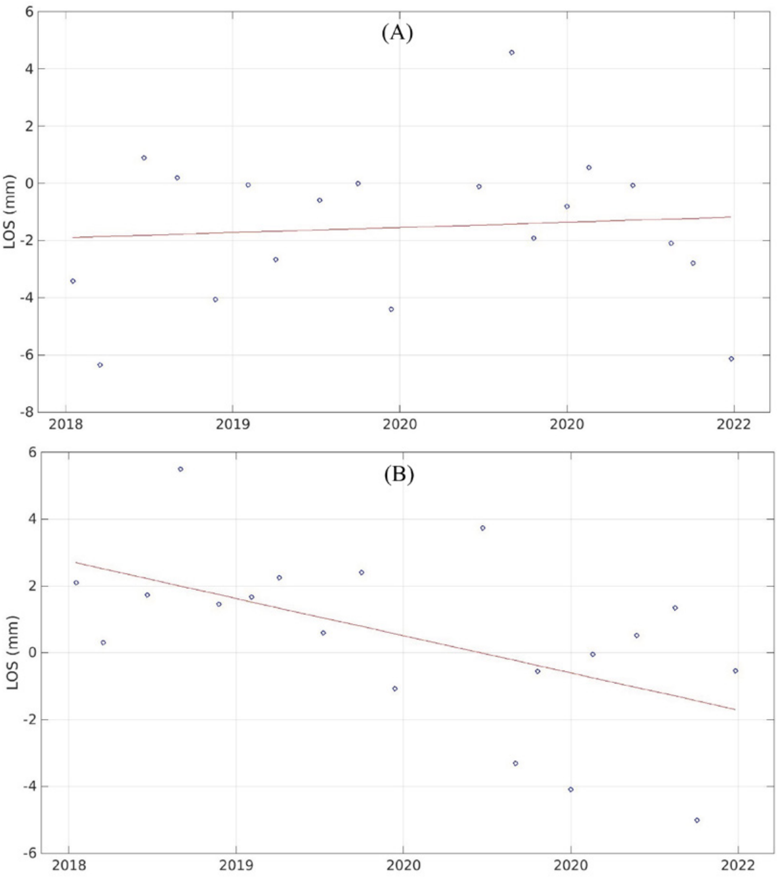

Fig. 7.- Line-of-Sight (LOS) deformation velocity maps (mm/year) of the study area

Fig. 7.- Mapas de velocidades de deformación de la línea de visión (LOS) (mm/año) del área de estudio.

Alouane, M., (1996). Géologie Méditerranéenne 23, n34, 187-199.

Boccaletti, M., Conedera, C., Dainelli, P. (1985). Tectonic map of the Western Mediterranean area. Scale 1:2.500.000.

Cadet, J.P., Fourniguet, J., Gigout, M., Guillemin, M. and Pierre, G., (1977). Bulletin of the Geological Society of France, (7), 19, n3, 600 - 605.

Crosetto, M., Monserrat, O., Devanthéry, N., Cuevas-González, M., Barra, A., Crippa, B. (2016). Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLI-B7, 835-839. https://doi.org/gcc8cp

Delvaux, Damien (2012). Geophysical research abstracts. Vol 14. No. 2. EGU General Assembly Vienna

Díaz García, F. (1993). Revista de la Sociedad Geológica de España 6, 105-114.

Foumelis, M., Delgado Blasco, J.M., Desnos, Y.-L., Engdahl, M., Fernandez, D., Veci, L., Lu, J., Wong, C. (2018). *IEEE International Geoscience and Remote Sensing Symposium,* Valencia, 1364-1367. https://doi.org/gfwvdq

Guillemin, M., Houzay, J.P., (1982). Notes Mémoires du Service Géologique du Maroc, 314, 7 pp

Hooper, Andy, et al. (2010). "StaMPS/MTI manual". Delft University of Technology, The Netherlands, 26 p.

Istiquam, H., (1999). Alpine tectonics, neotectonics, and study of Quaternary marine formations on the southern shore of the Strait of Gibraltar (Tangier - Charf-Al-Akab sector). D.E.S. (Diplôme d'Études Supérieures) Thesis, Mohammed V University, Rabat, 253 p.

J. M. Delgado Blasco, M. F. (2018). Automated snap sentinel-1 dinsar processing for stamps psi with open-source tools. 2.4.2, 3.2

Khalid Lakhouidsi, Abdelali Fadil, Abdelilah Tahayt, and Abderrahmane Soulaimani (2024). Canadian Journal of Earth Sciences, 61, 586-596. https://doi.org/mvpg

Leblanc, D. (1979). Etude géologique dans Le Rif Externe Oriental au Nord de Taza (Maroc).

Morel, J.L., Meghraoui, M. (1996). Geology 24, 755-758. https://doi.org/dfqd94

Morel, J.L., (1988). Recent evolution of the Rif orogeny and its foreland since the end of nappe emplacement. Mémoires de Géodiffusion, Paris, 4, 584 p.

Suter, G. (1980). Carte géologique de la chaîne rifaine 1/500 000. Notes et mém, serv. Géol. Maroc, 245a.

Tichli, S., Outiskt, M., Bernoussi, A.S., Aboumaria, K. (2024). Journal of African Earth Sciences 209, 105120. https://doi.org/mvph

Wildi, W. (1983). Revue de géographie physique et de géologie dynamique, 24(3) 201-297.