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Seismicity-structure relationships in the Beni Garfet area (Northern Morocco): A preliminary geomorphological and seismotectonic assessment

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ABSTRACT

The Beni Garfet area, located in the external Rif of northern Morocco, remains poorly documented in terms of its local structural and seismotectonic framework despite its position within an active tectonic setting. This study presents a preliminary local-scale assessment based on the integration of geomorphological observations, geological mapping, field investigations, and spatial analysis of seismicity. The objective is to investigate the relationship between surface structural features and the spatial distribution of seismic events in the vicinity of a mapped anticlinal structure. The results reveal a well-defined anticlinal morphology and a consistent spatial pattern of selected seismic events following an approximate northeast-southwest trend consistent with the orientation of the anticline axis. Geological cross-section analysis and field observations confirm the presence of a folded structural framework, while no clearly expressed surface tectonic structure was identified in the study area. This combination of observations suggests that the spatial distribution of seismicity may be influenced by a concealed or poorly expressed tectonic structure. Although the interpretation remains preliminary and is based on qualitative spatial analysis, the study provides a first integrated geomorphological and seismotectonic framework for the Beni Garfet area. The results further highlight the importance of considering potential subsurface structural controls in land-use planning, particularly in areas characterized by vulnerable building typologies.

Keywords: geomorphology, seismotectonics, anticline, northern Morocco, land-use planning.

INTRODUCTION

The western Mediterranean region is characterized by active tectonic deformation related to the ongoing convergence between the African and Eurasian plates, currently estimated at approximately 4 mm/year (DeMets et al., 1990, 2010). This convergence has led to the development of the Betic–Rif orogenic system, a complex arcuate belt shaped by successive compressional phases, crustal shortening, and the westward motion of the Alboran domain (Andrieux et al., 1971; Chalouan et al., 2001; Platt et al., 2003, 2013). In northern Morocco, the Rif chain represents one of the most tectonically active regions of the country and records a long and complex geodynamic evolution expressed by folding, thrusting, and fault reactivation (Chalouan et al., 2001; Carminati et al., 2012).

Although numerous studies have investigated the regional tectonic and geological framework of the Rif belt, several local sectors remain poorly documented at detailed scale, and their recent tectonic behavior is still insufficiently constrained (Platt et al., 2003; Martín-Martín et al., 2020; Amine et al., 2024). This is particularly the case for the Beni Garfet area, located in the external Rif of northern Morocco, where no local seismotectonic investigation has previously been carried out. Existing geological information is mainly available at regional scale and is therefore insufficient to accurately characterize the local structural framework of the area. In tectonically active regions, the integration of geological observations, seismicity distribution, and geodetic information is essential for improving the understanding of local deformation processes (Bargach et al., 2004; Vernant et al., 2010; Koulali et al., 2011; Chalouan et al., 2014). In this context, the integration of geomorphological observations with the spatial analysis of seismicity represents a relevant approach for investigating possible relationships between surface structures and subsurface deformation. Such an approach is particularly relevant in areas where buried or poorly expressed structures may influence both geomorphology and seismicity. In northern Morocco, the regional distribution of earthquakes indicates that the study area belongs to an actively deforming framework (El Mrabet, 1991; Medina and Cherkaoui, 1992), even though local deformation remains insufficiently documented at detailed scale (Figure 1).

The Beni Garfet area is of particular interest because several observations suggest tectonic significance at the local scale. Geological mapping and structural interpretation indicate the presence of a well-developed anticline expressed in the topography. However, the relationship between this geomorphological structure and the local seismicity distribution remains insufficiently constrained, while regional geodetic data indicate a deformation pattern compatible with the broader compressional setting of the external Rif. Taken together, these elements raise the question of whether the local geomorphological structure may be related to a buried or poorly expressed tectonic feature that remains insufficiently documented.

This study is not intended as a methodological development, but rather as a preliminary observational and interpretative analysis based on the integration of geomorphological observations and spatial analysis of seismicity. This study presents the first preliminary seismotectonic investigation of the Beni Garfet area by integrating

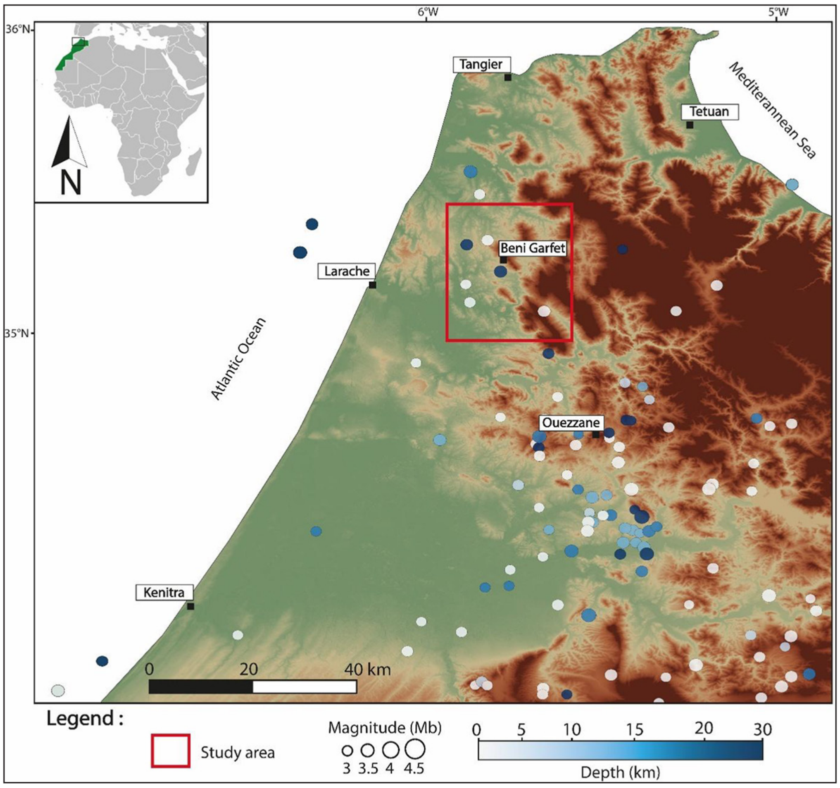

Figure 1. Regional seismicity map of northern Morocco showing the location of the Beni Garfet study area. Seismic data from the Instituto Geográfico Nacional (IGN) earthquake catalog (2000–2024; https://www.ign.es). Coordinate system: WGS84

geological, tectonic, geodetic, and seismological observations. The main objective is to investigate the relationship between surface structural features and the spatial distribution of seismic events at the local scale. Specifically, this work aims to (i) better constrain the structural framework of this poorly documented sector, (ii) examine the relationship between local fold geometry and seismicity distribution, and (iii) assess whether the area may be influenced by a potentially active hidden structure, with particular attention given to the proximity of the rural settlement and its implications for land-use planning and environmental risk awareness

Although the interpretations proposed in this work remain preliminary and require confirmation through further geophysical and geodetic investigations, they are based on qualitative spatial analysis and integrated geomorphological observations, and provide a first structural and seismotectonic framework for the Beni Garfet area. More broadly, this study contributes to the understanding of local deformation in the external Rif and underlines the importance of integrating geological and tectonic information into territorial planning in structurally complex regions.

MATERIALS AND METHODS

Geological, tectonic and geodetic setting

The Beni Garfet area is located in the external Rif domain of northern Morocco, within the western Mediterranean Alpine belt, which developed in response to the convergence between the African and Eurasian plates (Chalouan et al., 2001; Platt et al., 2003, 2013). This regional geodynamic framework resulted in a complex structural organization marked by folding, thrusting, and the reactivation of inherited tectonic structures, especially along the frontal zones of the Rif. The geological framework of the study area is based on the structural map of the Rif by Suter (1980), complemented by field observations.

The external Rif is mainly composed of Mesozoic to Cenozoic sedimentary formations, including marls, limestones, and flysch units, affected by compressional tectonics during the Neogene and Quaternary (Ben Yaïch and Chabli, 1991; Tejera de León, 1993; Martín-Martín et al., 2020). In the study area, the regional geological framework is characterized by a structural arrangement involving nappes and folded sedimentary units

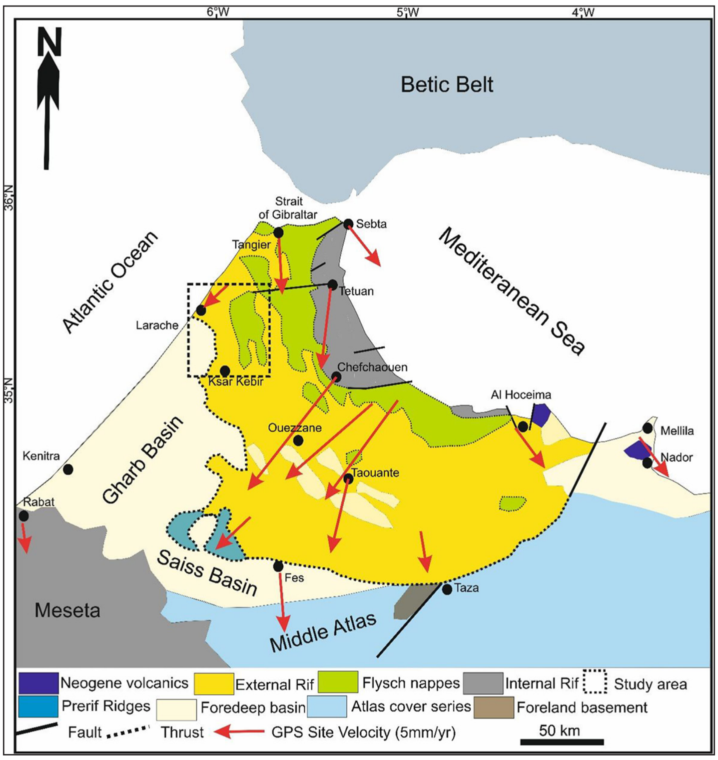

Figure 2. Geological, tectonic and geodetic setting of the Beni Garfet area within the external Rif (northern Morocco). Geological framework adapted from Suter (1980, structural map of the Rif, 1:500 000). Geodetic vectors adapted from Koulali et al. (2011) and Chalouan et al. (2014), with lengths scaled according to horizontal velocities (mm/year), with the reference arrow indicating 5 mm/year

consistent with the broader tectonic style of the external Rif. The geological and tectonic context of the Beni Garfet area, together with the regional geodetic framework, is illustrated in Figure 2.

Previous works in the Rif have shown that regional shortening was accommodated through folds, thrusts, and the reactivation of inherited tectonic structures, producing a complex deformational framework throughout northern Morocco (Chalouan et al., 2001, 2006; Bargach et al., 2004). This tectonic inheritance is reflected in the external Rif by the development of structurally controlled reliefs and fold-related geomorphological features. In the Beni Garfet area, this framework is expressed by folded sedimentary formations and a prominent anticlinal morphology, highlighting the strong relationship between tectonic deformation and present-day topography.

The geodetic context also supports the interpretation of an actively deforming regional setting. GPS measurements in northern Morocco indicate ongoing crustal shortening and deformation trends compatible with the tectonic evolution of the Rif front (Bargach et al., 2004; Carminati et al., 2012; Chalouan et al., 2014). These geodetic vectors, illustrated in Figure 2, are scaled according to horizontal velocities (mm/year), with a reference value of 5 mm/year. Although these data are regional in scale, they provide a kinematic framework for interpreting the local structural configuration of the Beni Garfet area.

Field observations further support the geological interpretation of the study area. The outcrops documented in Figure 3 show clear structural and lithological relationships, including deformed flysch formations and major tectonic contacts, which are consistent with the regional compressional setting of the Rif. These field observations confirm the presence of a folded structural framework and contribute to the identification of geomorphologically expressed structures in the study area. No clearly expressed surface tectonic structure was identified during the field survey in the vicinity of the mapped anticline.

This section provides the geological, tectonic, and geodetic context used as a basis for the subsequent seismotectonic interpretation, rather than constituting an independent analytical dataset. Overall, the Beni Garfet area appears to be located within a geologically and tectonically coherent sector of the external Rif, where regional shortening, inherited structures, and local deformation interact. This geological, tectonic, and geodetic framework provides the basis for the seismotectonic interpretation developed in the following section.

Seismotectonic framework

The seismotectonic framework of the Beni Garfet area was investigated through the combined analysis of geological structures, field observations, and the spatial distribution of seismic events. Seismic data were obtained from the publicly available Instituto Geográfico Nacional (IGN) earthquake catalog (https://www.ign.es), covering the period 2000–2024. Earthquake parameters, including epicentral coordinates, focal depths, and body-wave magnitudes (mb), were directly extracted from the IGN database without recalculation of hypocentral parameters.

For the purpose of this study, seismic events located within an approximately 5 km buffer from the mapped anticline axis were selected in order to focus the analysis on earthquakes potentially related to the local structural framework. This

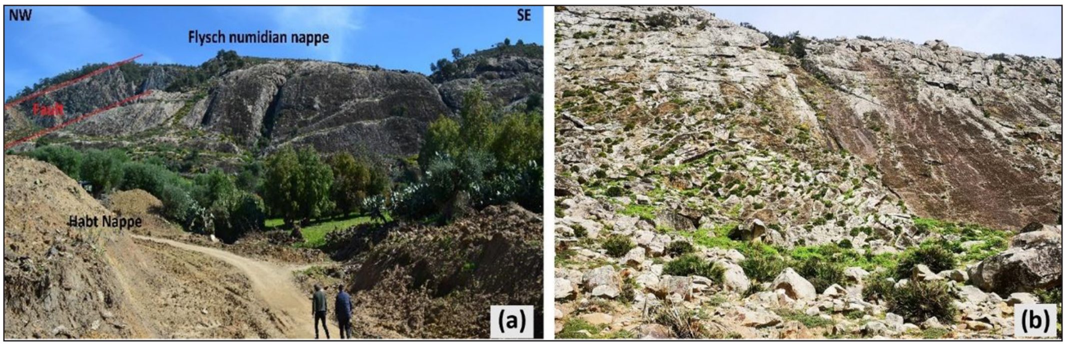

Figure 3. Field photographs illustrating the geological and structural characteristics of the Beni Garfet area: (a) outcrop showing a major tectonic contact affecting the Numidian Flysch nappe, (b) general view of the deformed flysch formations and structurally controlled relief

threshold was chosen because the closest seismic events are located within approximately 3–5 km of the mapped fold structure, while also accounting for possible epicentral location uncertainties associated with low- to moderate-magnitude earthquakes. The selection was therefore intended to include earthquakes spatially associated with the anticline while excluding more regional seismicity unrelated to the local geomorphological framework.

The selected seismic events correspond to earthquakes recorded between 2002 and 2018. No depth filtering was applied because the objective of the study was to examine the overall spatial relationship between local seismicity and geological structures. Likewise, no magnitude completeness analysis (Mc) or declustering procedure was performed, as the analysis remains qualitative and exploratory in nature.

The spatial distribution of seismic events was analyzed using QGIS software (version 3.34). Earthquake epicenters were projected using the WGS84 geographic coordinate system. The analysis consisted of visual spatial comparison between earthquake distribution and mapped geological structures. No statistical clustering analysis, relocation procedure, or probabilistic spatial modeling was applied.

The geological cross-section presented in Figure 5 was constructed through manual structural interpretation based on surface geological mapping, field observations, topographic expression, and the regional geological framework derived from the structural map of the Rif by Georges Suter (1980). The cross-section was generated by projecting geological contacts along the section line without vertical exaggeration. The interpretation integrates observed fold geometry and regional structural continuity. Structural dip measurements observed in the field were qualitatively considered in the interpretation of fold geometry, although no balanced cross-section restoration or subsurface structural modeling was performed.

Field investigations were conducted during multiple campaigns between 2023 and 2025 in the Beni Garfet area. Geological and geomorphological observations were collected from approximately 15 observation points distributed across the study area, with particular attention given to fold geometry, tectonic contacts, lithological organization, and geomorphological expression. Geographic coordinates were acquired using handheld GPS devices with an estimated positional accuracy of approximately ±5 m under normal field conditions.

Structural observations included the description of bedding geometry, fold orientation, tectonic contacts, and deformation affecting the flysch formations. Geomorphological observations focused on the relationship between topography and structural organization. These field observations were integrated with geological mapping and seismicity distribution analysis to establish the preliminary seismotectonic interpretation proposed in this study.

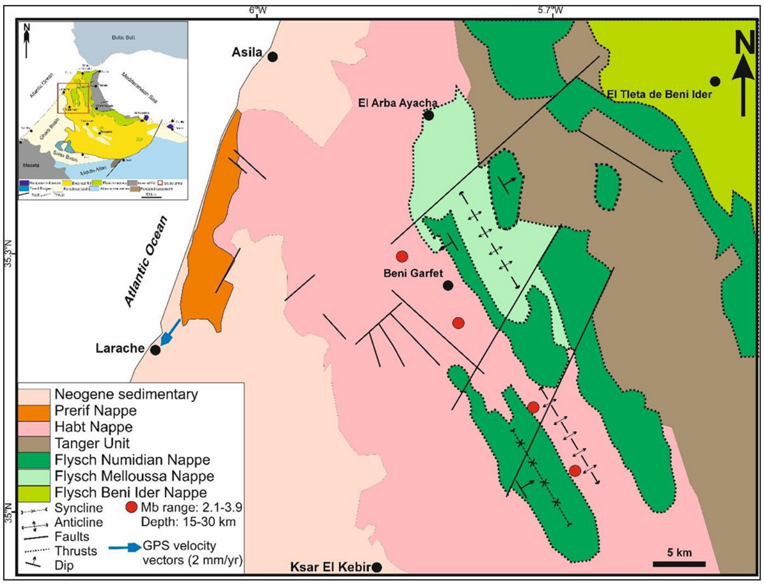

Figure 4. Local seismotectonic framework of the Beni Garfet area showing the spatial distribution of selected seismic events derived from the IGN database

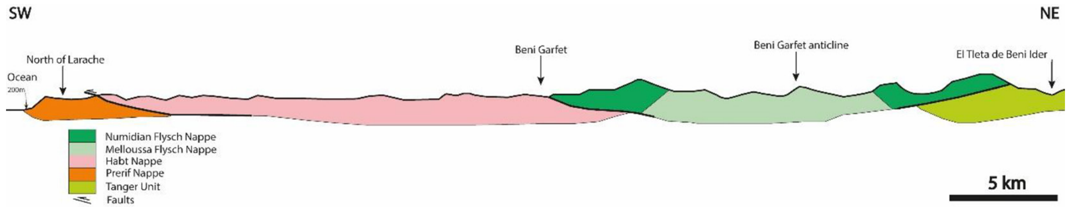

Figure 5. Geological cross-section across the Beni Garfet area highlighting the anticlinal structure

RESULTS

Geological and structural observations

Geological mapping and field observations reveal the presence of a well-defined anticlinal structure affecting the sedimentary units of the Beni Garfet area. The fold is expressed both in the lithological arrangement and in the morphology of the landscape, as illustrated by the geological map and geological cross-section (Figures 4 and 5). The structure trends approximately NE-SW and affects Mesozoic-Cenozoic sedimentary formations, including flysch deposits.

Field observations confirm the presence of deformed flysch formations and major tectonic contacts consistent with a compressional structural framework (Figure 3). The observed geomorphology is characterized by structurally controlled relief associated with folded sedimentary units. No clearly expressed active fault trace was identified at the surface in the immediate vicinity of the mapped anticline during the field survey.

The geological cross-section highlights the folded geometry of the sedimentary units and confirms the presence of a prominent anticline affecting the local structural organization (Figure 5). The fold geometry appears coherent with the compressional tectonic framework of the external Rif described in previous regional studies (Chalouan et al., 2001; Martín-Martín et al., 2020).

Seismicity distribution

A subset of seismic events extracted from the Instituto Geográfico Nacional (IGN) earthquake catalog covering the period 2000-2024 was analyzed in the vicinity of the Beni Garfet area. The selected seismic events correspond to occurrences recorded between 2002 and 2018 and located within the sector surrounding the mapped anticlinal structure (Figure 4).

Moderate-magnitude earthquakes (mb $\geq$ 3.0) define an elongated spatial pattern broadly following the orientation of the anticline axis, whereas lower-magnitude events (mb $<$ 3.0) display a more dispersed distribution but remain concentrated within the same sector. Earthquake depths range approximately between 0 and 30 km according to the IGN catalog.

At the local scale, the seismic events do not appear randomly distributed across the study area. Instead, most events are concentrated within a relatively restricted zone surrounding the anticlinal structure. The spatial distribution highlights an apparent organization of seismicity broadly consistent with the structural orientation observed in the geological framework.

Spatial relationship between structure and seismicity

The projection of seismic events onto the geological framework indicates that the majority of earthquakes are located within or near the zone defined by the mapped anticline (Figure 4). Several seismic events show an alignment broadly consistent with the NE-SW orientation of the fold axis, although variability in both epicentral position and focal depth is observed. The spatial correspondence between fold geometry and seismicity distribution is particularly evident for the moderate-magnitude events, which define the principal alignment observed in the study area. Lower-magnitude earthquakes remain spatially associated with the same structural sector despite their more scattered distribution. The observed relationship between the mapped anticline and seismicity distribution indicates a coherent spatial association between surface structural features and local earthquake occurrence. However, this observation remains descriptive and does not by itself demonstrate the existence of an active tectonic fault.

Settlement distribution

The rural settlement identified in the study area is located in close proximity to the mapped anticlinal structure (Figure 6). The village includes both reinforced concrete buildings (RC3 typology) and masonry constructions (M1.2 typology).

No clear spatial segregation between building typologies and the structural axis was identified. Masonry constructions and reinforced concrete buildings are both distributed within the structurally controlled sector surrounding the anticline.

Figure 6 illustrates the main building typologies observed within the settlement area, including masonry and reinforced concrete constructions. The spatial relationship between the settlement and the structural framework highlights the presence of human occupation within an area characterized by complex geological and geomorphological conditions.

DISCUSSION

Structural control on seismicity

The spatial association between the mapped anticline and the distribution of seismic events suggests that local deformation may be influenced by an underlying tectonic structure. In fold-and-thrust belts, such as the external Rif, anticlines are commonly associated with blind thrusts or inherited compressional structures that may remain seismically active without clear surface expression.

The regional tectonic context of the Rif is characterized by active compressional deformation and stress partitioning associated with the convergence between the African and Eurasian plates. Previous studies conducted in northern

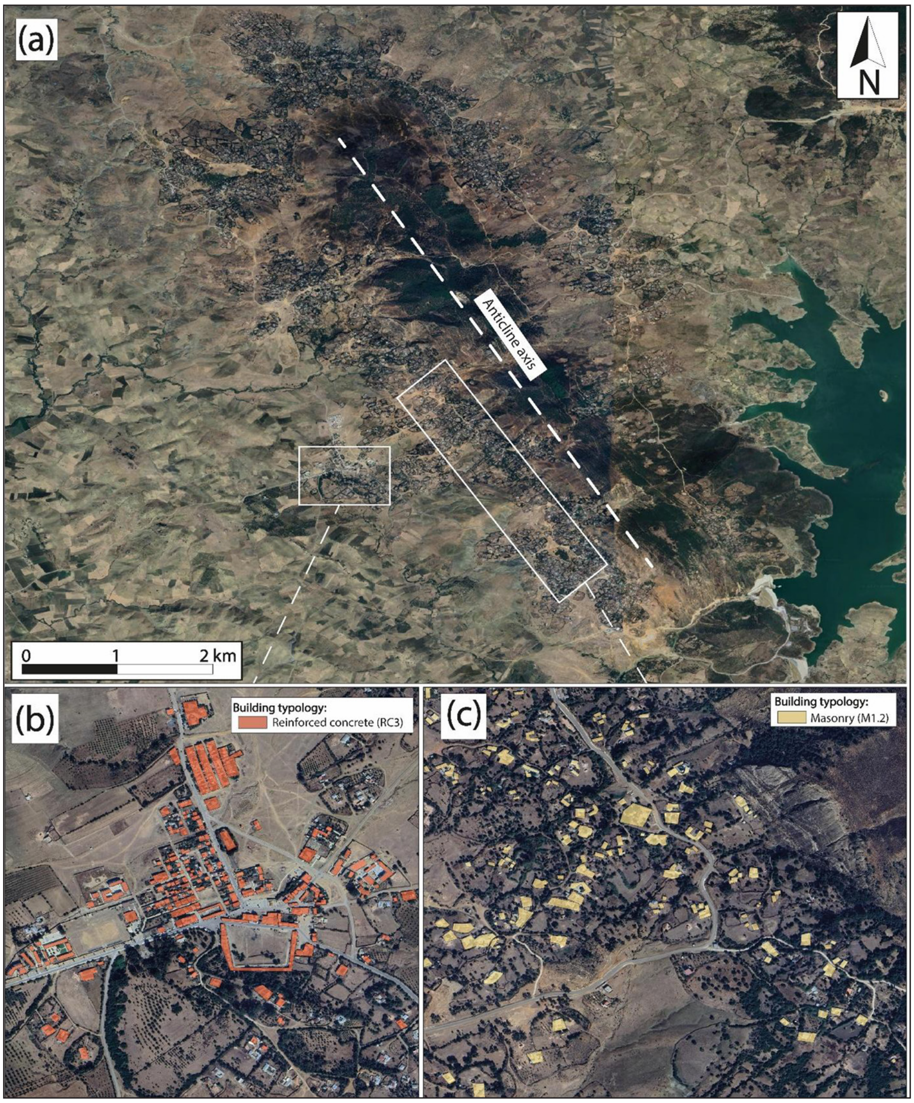

Figure 6. Spatial distribution of building typologies in relation to the Beni Garfet anticline: (a) general view of the study area showing the anticline and the nearby village, (b) reinforced concrete buildings (RC3), (c) masonry constructions (M1.2)

Morocco and adjacent regions highlighted the role of active tectonic deformation and stress reorganization along the frontal domains of the Rif Cordillera (Bargach et al., 2004).

In this context, the observed pattern is consistent with a scenario in which the mapped anticline reflects deformation above a deeper structure, possibly a blind thrust or a reactivated inherited discontinuity. This interpretation is supported by: (i) the compressional regional setting, (ii) the clear fold geometry, and (iii) the non-random spatial association of seismic events with the structural trend.

Comparable relationships between folding, concealed compressive structures, and seismic activity have been documented in other tectonically active fold-and-thrust systems. Stein and King (1984), for example, demonstrated that seismic deformation may occur along concealed reverse faults beneath active folds, even in the absence of clear surface rupture.

The conceptual interpretation proposed for the Beni Garfet area is summarized in Figure 7, which illustrates the possible relationship between the anticline geometry, an inferred blind tectonic structure, and local seismicity. However, this interpretation remains indirect and subject to several limitations.

Alternative explanations

The observed spatial pattern may also result from non-tectonic or methodological factors. These include:

- location uncertainties in earthquake hypocenters, particularly for low-magnitude events;
- incomplete detection of small earthquakes in the catalog;
- clustering effects related to aftershock sequences;
- apparent alignments produced by limited sample size.

Given that no magnitude completeness analysis or declustering procedure was applied, the possibility that the pattern reflects catalog artefacts cannot be excluded.

Implications for tectonic interpretation

Despite these limitations, the convergence of geological and seismological observations supports the interpretation of a tectonically organized sector. Rather than demonstrating the presence of an active fault, the results indicate that the Beni Garfet area is consistent with deformation localized along a pre-existing structural framework.

Such behaviour is characteristic of fold-and-thrust systems, where deformation may be partitioned between folding, distributed strain, and slip along blind or poorly expressed faults.

Implications for settlement and land-use

The proximity of the rural settlement to the inferred structural zone highlights the potential relevance of geological constraints for land-use planning. Although no quantitative seismic hazard assessment was performed, the coexistence of structurally controlled relief, local seismicity, and vulnerable building typologies (e.g., masonry constructions) suggests a non-negligible exposure to deformation-related processes.

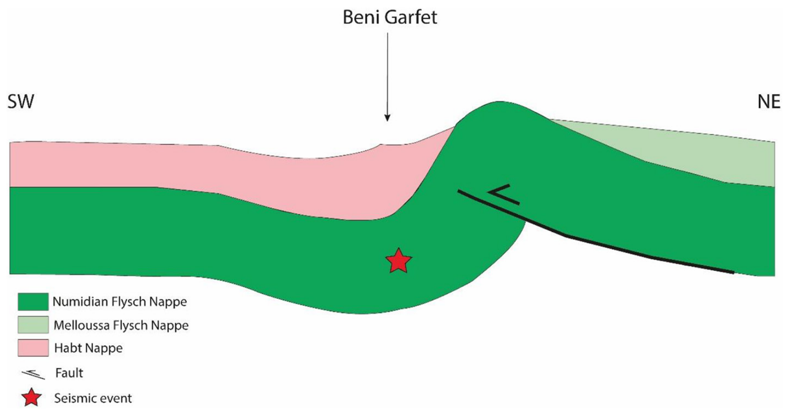

Figure 7. Conceptual seismotectonic model illustrating the possible relationship between the Beni Garfet anticline, a concealed tectonic structure, and local seismicity. The proposed interpretation is consistent with the compressional tectonic model of the Rif Cordillera described by Bargach et al. (2004)

The observed building typologies, particularly masonry constructions illustrated in Figure 6, may increase the local vulnerability to deformation-related processes. These observations do not allow quantitative risk evaluation but underline the importance of integrating geological and seismotectonic information into territorial planning, particularly in regions where active deformation is not clearly expressed at the surface.

Limitations and future work

The present study is based on qualitative spatial analysis and indirect evidence. No geophysical imaging, paleoseismological investigation, or high-resolution geodetic monitoring was conducted to constrain the geometry or activity of the inferred structure. Future work should include:
- quantitative spatial analysis of seismicity;
- assessment of catalog completeness and location uncertainties;
- geophysical surveys (e.g., seismic reflection, electrical methods);
- detailed structural mapping and morphotectonic analysis;
- geodetic or remote sensing approaches (e.g., InSAR).

Such data would allow testing whether the observed spatial pattern reflects an active tectonic structure or results from catalog and sampling limitations.

Overall, the results indicate that the Beni Garfet area is consistent with a structurally controlled sector within the external Rif, where fold geometry and seismicity distribution exhibit a coherent structural relationship. This association does not constitute proof of an active structure but provides a coherent framework for further investigation.The conceptual model proposed in Figure 7 supports this preliminary interpretation by illustrating the possible relationship between folding, a buried tectonic structure, and local seismicity.

CONCLUSIONS

The Beni Garfet area represents a previously undocumented case where fold geometry and micro-to-moderate seismicity exhibit a spatial association within the external Rif of northern Morocco. The main result of this study is the identification of a consistent spatial correspondence between an anticlinal structure and the distribution of seismic events in a sector where no mapped active fault has been previously defined at comparable local scale. This finding contributes to improving the understanding of deformation patterns along the Rif front, where seismicity is commonly interpreted at regional scale but rarely examined in direct relation to specific fold structures. The results suggest that, in compressional domains of the western Mediterranean, anticlines may not only represent surface expressions of shortening but may also reflect deformation linked to deeper tectonic structures capable of influencing local seismicity despite the absence of obvious surface faulting.

The observed relationship does not constitute direct evidence of an active fault or rupture surface. However, it defines a constrained structural domain in which seismicity is non-randomly distributed with respect to mapped geological features. Such relationships may remain insufficiently recognized in fold-dominated tectonic settings where deformation is partitioned between folding, blind faulting, and inherited structural reactivation.

From a broader perspective, the study provides a transferable example of how integrated geological mapping, geomorphological observations, field investigations, and seismicity analysis can reveal hidden deformation patterns in regions where geophysical imaging or dense monitoring networks are not available. This is particularly relevant for structurally complex sectors of the external Rif, where deformation is distributed between folding and faulting and where active structures may lack clear surface expression.

The results do not provide a definitive characterization of seismic hazard in the area, nor do they demonstrate the existence of an active tectonic fault. However, they establish a preliminary geological and seismotectonic framework that highlights the tectonic significance of the Beni Garfet area and provides a scientific basis for future investigations. The conceptual model proposed in this study further supports the interpretation of a possible relationship between folding, concealed tectonic structures, and local seismicity. In this sense, the main contribution of this work lies in identifying a previously unrecognized spatial link between folding and seismicity that warrants further quantitative, geophysical, and geodetic investigation.

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