Geomorphologic and geologic Analysis of Satellite Data of the Betic and Rif orogenic Belts in the Western Mediterranean Sea

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ABSTRACT

This study is focused on the description of the arcuated geomorphology and the structural pattern of the Betic and Rif Domain surrounding the West-Alboran Sea bordering S-Spain and N-Morocco based on remote sensing data. Sentinel 2, Landsat 8 and ASTER-images and Sentinel 1 radar images help to identify the structural pattern. Digital Elevation Model (DEM) data and the DEM derived morphometric maps support these investigations being integrated into a GeoInformation System (GIS). The evaluations of the various satellite data, especially after digital image processing of the Landsat thermal bands, contribute to the inventory of a large ring structure with more than 130 km in diameter. This distinct expressed ring structure becomes evident even more on slope gradient and drop raster maps.

Keywords: Betic Cordillera, Rif, Remote Sensing, Ring Structure.

I. INTRODUCTION

Although numerous research has been carried out related to the geologic development and structural and tectonic inventory of the Betic-Rif-Orogen in Northern Morocco and Southern Spain, the combined evaluations of different satellite data can still contribute to additional knowledge. The combination of different remote sensing and geodata is used in the scope of this study to derive geomorphologic and geologic information about the area surrounding the West-Alboran Sea.

II. GEOGRAPHIC AND GEOTECTONIC SETTING

The Betic-Rif Orogen surrounding the Alboran Sea is consisting of arcuate mountain belts with a northern branch formed by the Betic cordillera in the Iberian Peninsula and a southern branch formed by the Rif chain in northern Africa (Fig. 1).

These orogenic belts are considered to be the results of the Meso-Cenozoic convergence between Africa and Iberia [1]. The Betic-Rif orogenic belts are formed between two colliding continents between the African and Eurasian plates: Present-day tectonic processes occur within the context of ongoing: NW-SE convergence between Africa and Iberia in the Strait of Gibraltar [2]. It is widely accepted that compressional and extensional structures have deformed the Internal Zones of the Betic Cordillera since the Late Miocene [3] and [4]). The Alboran Sea Basin is considered to be a major extensional basin surrounded by an Alpine orogenic belt, which comprises the Betic and Rif mountain chains and an accretionary wedge in the Gulf of Cadiz. The whole system is described as the Gibraltar Arc System formed during the Neogene by simultaneous outward thrusting in the frontal parts of the surrounding mountain belts and extensional collapse in the inner part of the arc. Extension ceased in Late Miocene and deformation in the internal areas of the Betic-Rif was dominated by the kinematics of African and Eurasian plate convergence. NNW convergence of Africa with Iberia compressed the Alborán basin and reactivated suitably oriented faults in the intramountain basins. The internal areas of the Betic-Rif became a diffuse plate boundary between Africa and Eurasia dominated by wrench tectonics processes that are still active, as shown by recent seismicity of the Carboneras fault and other similar strike-slip faults [5].

The tectonic history of the Alborán Betic-Rif domain is exceptionally complicated, which has in large part contributed to the multitude of contrasting geodynamic models proposed for the Cenozoic evolution of the region [6]. While the location, geometry, and kinematics of the main structures are well established, the processes involved in their
development and the present-day activity of some of these structures are still under debate.

Ideas to explain the striking topographical symmetry of the region, as well as the apparently synchronous extension of the Alboran Sea and shortening of the Betic and Rif belts during the Neogene and Quaternary, are still widely debated [7]. Much of the current debate and controversial hypotheses on the genesis center on the processes that caused the Alboran Sea basin and its link with the tectonic evolution of the Betic-Rif orogen [8]. Current tectonic models for the Alboran area include four broad categories of hypotheses:

1. backarc extension is driven by the westward rollback of an eastward-subducting slab
2. breakoff of a subducting lithospheric slab
3. crustal extrusion due to forces transmitted across the Eurasia-Africa plate boundary and
4. delamination and convective removal of the lithospheric mantle root beneath the collisional orogen [4].

Arc curvature, arc magmatism, and back-arc extension were formed during Miocene time by the westward rollback of a narrow eastward-subducting slab fragmented from the African plate. Westward retreat of the subducted slab was accompanied by thinning of the continental crust, formation of oceanic crust and extension, leading to the formation of Neogene intramountain basins in the internal areas of the Betic–Rif.

Some first-order questions remain pending, such as the emplacement mechanism of subcontinental peridotite massifs, the timing of development and exhumation of metamorphic complexes during syn- and post-orogenic extension or the formation of intramountain basins in a rather short period in the Oligocene and Miocene. Large longitudinal displacements, strong paleomagnetic rotations, coeval thrusting in the External Zones and extension in the Internal Zones are considered to be ingredients of a complex 3-D evolution of the piece of lithosphere deforming between converging Africa and Eurasian plates in the western Mediterranean [9].

The central part of the structures is covered by the Alboran Sea, however, many geophysical and bathymetric research was carried out [10] and [7]. Seismic refraction data and two-dimensional gravity modeling show that the crust thins from ~35 km beneath the internal zones of the Betic and Rif Chains to ~15-20 km beneath the central Alboran Sea [11].

III. METHODS

The interdisciplinary approach used in the scope of this study comprises remote sensing data, geological, geophysical and topographic data and GIS methods. Earthquake data were provided by the European-Mediterranean Seismological Centre (EMSC) [12], International Seismological Centre (ISC) [13], US Geological Survey (USGS) [14].

A. Digital Image Processing of Different Optical and Radar Satellite Data

Satellite imageries and Digital Elevation Model (DEM) data were used for generating a GIS database and combined with different geoata and other thematic maps. Satellite data such as Sentinel 1 – C-Band, Synthetic Aperture Radar (SAR) and optical Sentinel 2 images, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat optical data (Landsat TM and Landsat 8 and 9, the Operational Land Image-OLI). ENVI software from Harris Geospatial Solutions and the Sentinel Application Platform (SNAP) provided by ESA were used for the digital image processing of the optical Landsat 5 and 8, Sentinel 2, and ASTER data. SNAP provided the tools as well for the processing of radar data. The evaluation of Sentinel 1 A and B radar images requires geometric correction and calibration. Digital image processing of LANDSAT 5 Thematic Mapper and Landsat 8 – The Operational Land Imager (OLI) data was carried out by merging different Red Green Blue (RGB) band combinations with the panchromatic Band 8 to pan-sharpen the images.

Based on the different satellite data a lineament and structural analysis was carried out. Especially Sentinel 1 radar images reveal larger fault zones.

Special attention was directed at distinct expressed linear features (tonal linear anomalies, geomorphologic linear features, drainage segments, etc.). In the scope of this study, several types of linear and curvilinear features were mapped: lineaments (as a neutral term for linear features without precisely knowing their origin (probable fault zones), and structural features. Lineaments are often expressed as scars, linear valleys, narrow depressions, linear zones of abundant watering, drainage network, linear vegetation occurrence, and geologic anomalies. Tonal linear anomalies such as a linear arrangement of pixels depicting the same color / gray tone were visually mapped as linear features or lineaments as well. Lineaments represent in many cases the surface expression of faults, fractures or lithologic discontinuities [15].

Lineament analysis can contribute to the detection of structural features that in the field are sometimes not visible or can be mapped only based on time and cost-intensive field investigations. Traces of structural features such as synclines or anticlines, bedding structures or traces of foliation in metamorphic rocks were digitized based on the different satellite images. Structural features appear on satellite images often as dense, arc-shaped, parallel lines.

B. Processing of Digital Elevation Data

Digital Elevation Model (DEM) data gained from the Shuttle Radar Topography Mission (SRTM) and ASTER DEM data, were downloaded from open sources such as USGS / Earth Explorer, Sentinel Hub / ESA.

Special focus was directed towards bathymetric data provided by GEBCO [16]. The bathymetric DEM data provided by General Bathymetric Chart of the Oceans (GEBCO), International Hydrographic Organization and the Intergovernmental Oceanographic Commission of UNESCO were integrated into the research in order to derive slope and hillshade maps from the sea bottom and drainage basins from the surrounding areas.

The data were processed using geoinformation systems ArcGIS from ESRI and QGIS. Shapefiles from Morocco and Spain were downloaded from the Geofabrik's download server [17].

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IV. RESULTS

The different satellite data allow correspondent evaluation feasibilities and results:

A. Evaluations of Landsat Data

Landsat 5 image data taken between 1972-1975 were combined into a mosaic. These images were chosen because 5 decades before with less settlement and infrastructure density geologic information can be derived from areas that nowadays are sealed by cities and roads. Nevertheless, the improved quality of Landsat 8 data with higher spatial and radiometric resolution offers additional evaluation possibilities. Merging the Landsat 8 data with SRTM digital elevation data allows 3D perspective views in ArcScene/ESRI-software (Fig. 2 and 3 a/b). A large circular structure becomes visible on the Landsat mosaics.

Fig. 2. Landsat 5 mosaic merged with GEBCO DEM hillshade data.

Fig. 3a. Landsat 8 Mosaic of RGB images, Bands 2,7 and 10 acquired in 2021.

Fig. 3 b. 3D perspective views of the Landsat 8 RGB, Bands 2,7,10 mosaic.

Fig. 4 a. Landsat 8 Band 10 (Colour-coded).

Fig. 4 b. Landsat 8 colour-coded Band 10 scene and structural evaluation

Thermal images based on Landsat 8 thermal bands contribute as well to the detection of structural features as demonstrated in the next figures from the southern part of the ring structure in N-Morocco (Fig. 4 a and b). These structural features were digitized (Fig. 5).

Fig. 5 is summarizing the structural evaluation results showing the circular arrangement of the curvi-linear structural features. The distinct circular arrangement of the curvi-linear features is striking.

Fig. 5. Structural evaluation based on Landsat and Sentinel 2 data.
Such distinct visible circular structures in this dimension are rare on earth. The question arises whether an additional hypothesis about the origin of this circular structure might be added.

Looking at this clearly visible ring structure the similarity to large cosmic complex impact craters becomes evident such as the Vredefort Dome in South-Africa [18] and [19] or the Domo de Araguainha ring structure in Central-Brazil [20] and [21]. The hypothesis of a large cosmic impact by an asteroid causing and influencing the development of the geologic structure of the Alboran basin should be not excluded from the discussions before proved otherwise.

There are some discussion points that could support this theory such as the occurrence of concentric faults. Concentric faults are documented on the geologic maps (such as provided by the British and Spanish Geological Survey in the OneGeology portal) that could be interpreted as part of marginal, down- and inward faulted collapse zones. It could be assumed that the arc-shaped fault systems surrounding the West Alboran Sea are related to deformation processes of impact crater development. Broadly radial and concentric oriented symmetric and asymmetric folds ranging to kilometers and conjugate radial to oblique faults with strike-slip displacements of tens to hundreds of meters can be observed on the geologic maps [9]. The occurrence of nappes [22] and [23] might be partly related to the overturning of strata during the crater deformation process?

The thinning and considerable uplift of the basement at the center of the West-Alboran Basin could be interpreted as being part of a central uplift (Fig.6 a and b). The Alboran range, Tofino Bank or the Xauen Bank within the West-Alboran basin might be relict parts and remnants of a crater formation, that were later compressed and modified by plate tectonic movements and processes as well as by submarine erosion.

The influence of plate tectonic movements and deformation on the tectonic pattern is obvious as most of the lineaments are oriented in WSW-ENE direction, perpendicular to the main moving direction towards NW [24] and [25].

Further traces of compression can be detected in the bending, faulting and folding of outcropping rocks, especially in the western part of the Alboran ring structure around Gibraltar. Fig.7 shows the results of a lineament analysis.

B. Evaluations of Digital Elevation Model (DEM) Data

The prominent circular structure covering the Betif and Rif orogenic belt becomes clearly visible on GEBCO bathymetric data and SRTM DEM data covering the Alboran Sea area. The following figures demonstrate the outline of this ring structure on morphometric maps derived from GEBCO and SRTM DEM data such as the height level, slope, aspect and drop raster map.

The arc-shaped outline of the Betic and Rif Domain have been discussed in previous works, however, not the distinct expressed circular arrangement of hill ranges with heights above 1600 m and valleys in the area surrounding the West-Alboran Sea forming this large ring structure of more than 130 km in diameter. Explanations and discussions related to this clearly visible and distinct expressed ring structure on the DEM derived morphometric maps should be carried out.

Fig.8 a shows the height level map, Fig. 8 b a 3D perspective view of the height level map.
Especially the slope gradient map enhances the visibility of the ring structure (Fig. 9). Although the eastern part of the ring structures is only partly visible on the bathymetric data of the West-Alboran Sea the circular outline is evident.

When comparing the slope gradient map of the large impact crater Vredefort Dome in South Africa with the Alboran ring structure in North Morocco and South Spain the geomorphologic and geologic similarities are obvious (Fig. 9 and 10).

The Vredefort Dome reveals like the Alboran structure a highly heterogeneous internal structure involving folds, faults and fractures. In the case of the Vredefort Dome these are interpreted as the product of shock deformation and central uplift formation during the 2.02 Ga Vredefort impact event. Broadly radially oriented symmetric and asymmetric folds with wavelengths ranging from tens of meters to kilometers and conjugate radial to oblique faults with strike-slip displacements of, typically, tens to hundreds of meters [19].

The aspect map reveals the circular arrangement of the morphology as well (Fig. 11) by showing the concentric orientation of the slopes.

By using the Hydrology-tools in ArcGIS the dropraster, flow accumulation, and drainage basin (Fig. 12 and 13) were calculated. The drainage pattern was included into these maps to show the concentric and radial arrangement of the waterways.

The dropraster and drainage basin calculation based on GEBCO and SRTM DEM data visualizes that the circular structure influences surface run-off and, thus, the hydromorphologic processes.

All the presented morphometric maps indicate the distinct visible circular character of the Betic-Rif area, untypical for a plate tectonic origin alone.
C. Evaluations of Sentinel 1 Radar Image

Due to the subtle surface reflection of radar signals structural features become visible revealing the ring structure, of course overprinted by plate tectonic processes, especially compression.

The dark-grey areas (Fig. 14) correspond to flat areas and valleys filled with Plio-Pleistocene sediments causing a mirror-like radar backscatter. The arc-shaped outline is clearly visible forming the northern part of the Alboran ring structure, see red arrows. Ring depressions are visible in darker gray tones.

Fig. 15 presents the radar scene from the southern part of the circular structure.

V. CONCLUSIONS

Satellite images and morphometric map derived from Digital Elevation Model (DEM) data reveal a distinct expressed ring structure with a diameter of more than 130 km surrounding the West-Alboran Basin. Such a distinct ring structure like this situated within tectonic plate boundaries could not be observed anywhere else.

Different hypotheses have been invoked to explain the tectonic development of the study area such as the convective removal mantle delamination, and subduction models [26]. The formation of the Gibraltar Arc System began in the Late Oligocene. The Miocene westward migration of the subduction system led to the collision of the allochthonous Alboran terrane with the Tethyan South-Iberian and African margins [26]. This terrane was stacked over the Iberia and Africa passive margins, forming the inner zones of the Betics and the Rif ranges. At the same time, extensional processes took place within the Alboran Basin. However, the question arises whether there might be other causes involved in the origin of the complex ring structure surrounding the West-Alboran Sea besides plate tectonic processes.

An additional hypothesis to explain this ring structure could include its origin caused by a large cosmic impact as structural and geomorphologic features of the West-Alboran area are similar to those of large cosmic impact craters such as the Vredefort Dome in South Africa.

The hypothesis of a cosmic impact origin could be supported for example by the investigation of the nappes in the Betic Domain. Complex impact craters often exhibit raised rims built of deformed and overturned rock units overlaid with ejecta [27].

The further analysis of geophysical data (magnetic
anomalies, gravity, 3D analysis of earthquakes) could support this hypothesis as well, although volcanism and plate tectonic dynamics meanwhile might have overprinted the effects of a cosmic impact.

Mineralogic investigations would clarify whether there are traces of shock metamorphism and the typical minerals such as stishovite crystallized and coesite, found in impact craters and in ultra-high pressure rocks [28].

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REFERENCES

[1] Janowski M, Loget N, Gautheron C, Barbarand J, Bellahsen N, van den Driesche J, Babault J, Meyer B. Neogene exhumation and relief evolution in the eastern Betics (SE-Spain): insights from the Sierra de Gador. *Terra Nova*, 2017; 29(2):91-97. Available from: https://hal.archives-ouvertes.fr/hal-01447798.

[2] Martínez-García P, Comas M, Loneran L, Watts AB. From Extension to Shortening: Tectonic Inversion Distributed in Time and Space in the Alboran Sea, Western Mediterranean. *Tectonics*, 2017; 36: 2777–2805. Available from: https://doi.org/10.1002/2017TC004489.

[3] Pedreira A, Galindo-Zaldívar J, Marín-Lechado C, García-Tortosa FJ, Ruano P, López Garrido AC, Azahón JM, Peláez JA, Giudiccia F. Recent and active faults and folds in the central-eastern Internal Zones of the Betic Cordillera. *Journal of Iberian Geology*, 2012; 38 (1): 191-208. Available from: http://dx.doi.org/10.5299/jrneg_2012;v38.n1.39213.

[4] Fadil A, Vernant P, McClusky S, Reilinger R, Gomez F, Ben Sari D, Mourabit T, Feigl K, Barazangi M. Active tectonics of the western Mediterranean: Geotectonic evidence for rollback of a delaminated subcontinental lithospheric slab beneath the Rif Mountains, Morocco. *Geology*, 2006; 34 (7): 529. doi:10.1130/G22291.1.

[5] Soriano C, Cas RA, Riggio NR, Giordano G. Submarine Volcanism of the Cabo de Gata Magmatic Arc in the Betic–Rif Orogen, SE Spain: Processes and Products. In: Nemeth K (ed.), Updates in Volcanology - From Volcanic Modelling to Volcano Geology, *IntechOpen*. 2016 London. D M C, doi: 10.5772/63579. Available from: https://www.intechopen.com/chapters/51456.

[6] Williams JR, PL. A new structural and kinematic framework for the Alborán Domain (Betic–Rif arc, western Mediterranean orogenic system). *Journal of the Geological Society*, 2018; 175:465-496. Available from: https://doi.org/10.1144/jgs2017-086.

[7] Stich D, Martin R, Morales J, López-Comino JA, de Lis Mancilla F. Site Partitioning in the 2016 Alboran Sea Earthquake Sequence (Western Mediterranean). *From: Earth Sci.*, 29 September 2020. Available from: https://doi.org/10.3389/feart.2020.587356.

[8] Comas MC, Platt JP, Soto JI, Watts AB. The Origin and Tectonic History of the Alboran Basin: Insights from LÉG 161 Results. *Proceedings of the Ocean Drilling Program, Scientific Results*. 1999; 161, Chapter in: Integrated Ocean Drilling Program: Preliminary Reports. *From: Earth Sci.*, 29 December 1999. doi:10.2973/odp.proc.sc.161.262.1999.

[9] Bessière E, Jolivet L, Augier R, Scallet S, Pécigout J, Azahón JM, Crespo-Blanc A, Masina E, Do Couto D. Lateral variations of pressure-temperature evolution in non-cylindrical orogens and 3-D subduction dynamics: the Betic-Rif Cordillera example. *BSG – Earth Sciences Bulletin*. 2021; 192: 8. Available from: https://doi.org/10.1051/bsg/2021007.

[10] Galindo-Zaldívar J, Gonzalez-Lodeiro F, Jabaloy A, Maldonado A, Schreider AA. Models of magnetic and Bouguer gravity anomalies for the deep structure of the central Alboran Sea basin. *Geo-Marine Letters*, 1998; 18: 10-18.

[11] Tomé M, Fernandez M, Comas MC, Soto JL. Lithospheric Structure Beneath the Alboran Basin: Results from 3D Gravity Modeling and Tectonic Relevance. *Journal of Geophysical Research, February 10:2000, 105 (B2): 3209-3228.

[12] European-Mediterranean Seismological Centre (EMSC). Available: https://www.emsc-csem.org/Earthquake?filter=yes.

[13] International Seismological Centre (ISC), Available: http://www.issc.ac.uk/isbcallback/search/catalogue/interactive/.

[14] US Geological Survey (USGS). Available: https://earthquake.usgs.gov/earthquakes/search/.

[15] Theilen-Willige B. Morphometric and structural Evaluations of Satellite Data from the Bosumtwi Impact Structure and adjacent Areas in Ashanti, Ghana. *European Journal of Environment and Earth Sciences*, May 2021; 2 (3). doi:10.24018/ejgeo.2021.2.3.137. Available from: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1945-5100.2003.tb00300.x.

[16] General Bathymetric Chart of the Oceans (GEBCO). Available: https://www.gebco.net/data_and_products/graded_bathymetry_data/.

[17] GEOFABRIK downloads. Available: http://download.geofabrik.de/.

[18] Lana C, Gibson RL, Reimold WU. Impact tectonics in the core of the Vredefort dome, South Africa: Implications for central uplift formation in very large impact structures. *Meteoritics & Planetary Science*, 2003; 58 (7): 1093–1107. Available from: https://www.researchgate.net/publication/333236864_7?GeowissLate namerika_Kolloquium.

[19] Theilen-Willige B. The Araguainha Impact Structure / Central Brazil, *Revista Bras. Geociencias*, 1981;11:91-97, Sao Paulo, Brazil. Available from: https://www.researchgate.net/publication/259576248_The_Araguainha_a_Impact_Structure_Central_Brazil.

[20] Mazziotti S, Martin-Algarra A, Reddy SM, López-Sánchez-Vizacino V, Fedele L, Noviello A. Deformation partitioning during transpressional emplacement of a ‘mature’ extrusion wedge. The Bona Pedroites, Western Betic Cordillera, Spain. *Journal of the Geological Society*, February 2011, doi: 10.1144/0016-76492010-126.

[21] Guerrera F, Manchone MA, Martin-Martin M, Raffaelli G, Rodriguez-Estrella T, Serrano F. Paleogene evolution of the External Betic Zone and geodynamic implications. *Geologica Acta*, 2014; 12 (3): 171-192; doi:10.1344/GeologicaActa2014.12.3.1.

[22] Serpelloni E, Vannucci G, Pondrelli S, Argnani A, Casula G, Anzidei M, Baldi P, Gasperini P. Kinematics of the Western Africa-Eurasia plate boundary from focal mechanisms and GPS data. *Geophys. J. Int.*, 2007; 169: 1180-1200. doi:10.1111/j.1365-246X.2007.03567.x.

[23] Ruiz-Constáñ A, Pedreira A, Galindo-Zaldivar J, Stich D, Morales J. (2) Recent and active tectonics in the western part of the Betic Cordillera. *Journal of Iberian Geology*, 2012; 38 (1): 161-174. Available from: http://dx.doi.org/10.5299/jrneg_2012;v38.n1.39211.

[24] Giménez de la Peña L, Greweiemeyer I, Kopp H, Diaz J, Gallart J, Booth-Rea G, et al. The lithospheric structure of the Gibraltar Arc System from wide-angle seismic data. *Journal of Geophysical Research: Solid Earth*, 2020; 125, e2020JB019854. doi:10.1029/2020JB019854. Available from: https://doi.org/10.1029/2020JB019854.

[25] Osinski G, Spray G. Tectonics of complex crater formation as revealed by the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science*, 2005; 40(12): 1813–1834.

[26] Spékont K, Nylen J, Mathew R, Edén M, Stoyanov E, Navrotsky A, Lavenexweber C, Häussermann U. Formation of hydrous stishovite from coesite in high-pressure hydrothermal environments. *American Mineralogist*, 2016; 101: 2514-2524. Available from: https://doi.org/10.2138/am-2016-5609.

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