Operational Procedures of Agencies Contributing to the ISC

From Analogue to Digital: Evolution of Morocco's Seismic Network and Its Implications for Seismotectonic Studies

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Excerpt from the Summary of the Bulletin of the International Seismological Centre:

Timoulali, Y., M. Kasmi and N. Jabour (2026), From Analogue to Digital: Evolution of Morocco's Seismic Network and Its Implications for Seismotectonic Studies, *Summm. Bull. Internatl. Seismol. Cent.*, January – June 2022, *59*(I), pp. 31–39, `https://doi.org/10.31905/JCIX0KKS`.

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Operational Procedures of Contributing Agencies

5.1 From Analogue to Digital: Evolution of Morocco's Seismic Network and Its Implications for Seismotectonic Studies

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Morocco lies at the northwestern margin of the African Plate, where oblique convergence with the Eurasian Plate defines a complex zone of distributed deformation extending from the Azores–Gibraltar region to the western Mediterranean. The country exhibits moderate to significant seismic activity governed by both interplate and intraplate processes. Seismicity is mainly concentrated in the Rif belt, the Middle and High Atlas ranges, and the Atlantic and Mediterranean margins, reflecting the interaction between active plate boundary dynamics and reactivation of inherited crustal structures. This study, presents an overview of the historical development of seismic monitoring in Morocco. It traces the transition from the first analogue instruments to the modern digital broadband network, highlighting key milestones in instrumentation, data processing, and network expansion. The modernisation of the Moroccan seismic network has significantly improved earthquake detection capabilities, location accuracy, and data reliability, thereby enhancing our understanding of regional seismicity and active tectonic processes. The results contribute to refining the seismotectonic framework of Morocco and support ongoing efforts in seismic hazard assessment and risk mitigation.

5.1.1 Introduction

Moroccan seismicity reflects the interplay between Africa–Eurasia convergence and intraplate deformation within the North African margin. The rate of plate convergence, estimated at 4–5 mm/yr (*DeMets et al.*, 2010; *Nocquet*, 2012), is accommodated across several tectonic domains exhibiting distinct stress

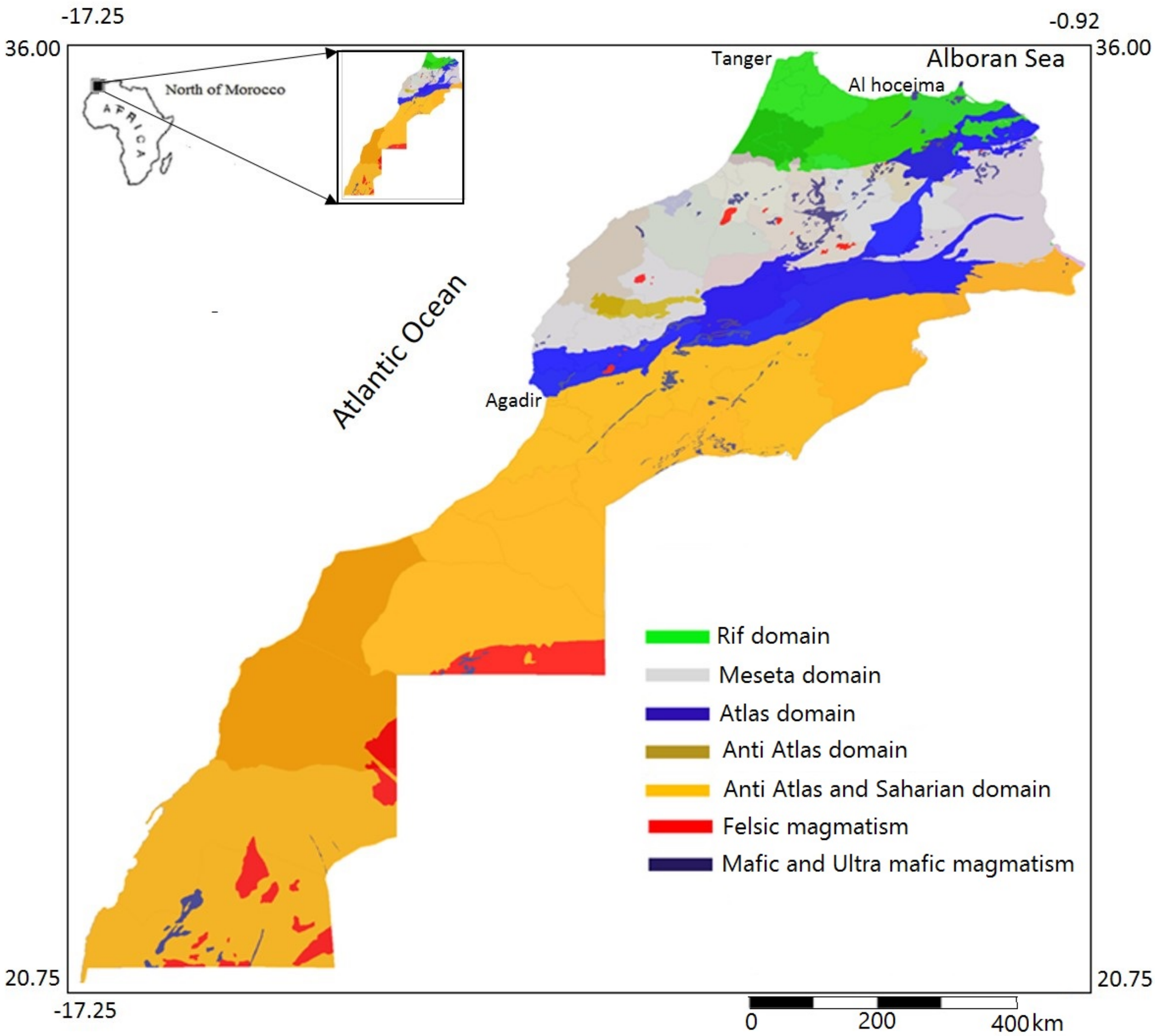

Figure 5.1: *The regional location of Morocco in North Africa (top left) and the major tectonic domains (modified after* Service Géologique du Maroc *(1985)).*

regimes and fault kinematics. Although seismic activity is moderate compared to other Mediterranean regions, Morocco has experienced several damaging earthquakes, demonstrating the persistence of active crustal deformation and the potential for significant seismic hazards.

5.1.2 Regional Tectonic Setting

The seismicity of Morocco is primarily distributed across three major tectonic domains: the Rif system, the Atlas system and the Atlantic–Mediterranean margins (Figure 5.1).

- **The Rif Domain:** These northern orogenic belts form part of the Gibraltar Arc system, resulting from the convergence of the African and Alboran domains. Deformation is dominantly compressional to transpressional, expressed through thrust and strike-slip faulting. Major active structures include the Jebha–Al Hoceima–Nador corridor, the Bokkoya Fault System, and the Trans-Alboran

Fault Zone, which have generated destructive events such as the Al Hoceima earthquakes of 1994 and 2004 (M_W 6.0–6.3) (*Akoglu et al.*, 2006).

- **The Atlas Mountains:** The High, Middle, and Anti-Atlas ranges represent an intraplate orogenic system formed by the Cenozoic inversion of Mesozoic extensional basins under the Africa–Eurasia compressional regime. Seismicity within the Atlas is generally moderate (M_W 4–6), but the Al Haouz earthquake of 8 September 2023 (M_W 6.8) revealed the capacity of this belt to produce large crustal earthquakes through the reactivation of deep-seated thrusts within the High Atlas structural block.
- **The Atlantic and Mediterranean Margins:** These margins host offshore fault systems such as the Azores–Gibraltar Transform Zone (AGFZ) and the Southwest Iberian Margin Faults, capable of generating major interplate earthquakes (e.g. the Lisbon event of 1755, M_W 8.5). Although the Moroccan Atlantic margin exhibits lower seismicity, occasional moderate events suggest reactivation of inherited Hercynian structures.

5.1.3 Seismotectonic Characteristics

Moroccan earthquakes are predominantly crustal, with focal depths ranging between 5 and 25 km, and are associated with reverse, strike-slip, or normal faulting mechanisms (Figure 5.2). Focal mechanism solutions indicate a prevailing NW–SE compressional stress orientation, consistent with the Africa–Eurasia convergence direction (*Medina*, 1995; *Stich et al.*, 2010).

Spatially, seismicity clusters along the northern Rif, the Middle Atlas corridor, and the central High Atlas, while the southern and Saharan domains remain relatively aseismic. Active fault mapping and geodetic investigations have identified key structures such as the Tizi n'Test Fault, Imilchil–Tadighoust Fault, and the South Atlas Front, suggesting the potential for moderate to strong intraplate events (*El Mrabet*, 1991).

Historically, Morocco has been affected by several destructive earthquakes, including the earthquakes in Fez (1624), Agadir (1960, M_W 5.7) -which caused over 12,000 fatalities- and Al Hoceima (1994, 2004, 2023, M_W 6.3–6.8). These events highlight the recurrence of damaging earthquakes in both plate boundary and intraplate settings, reinforcing the need for continuous seismic monitoring and hazard reassessment.

5.1.4 Seismic Monitoring

The history of seismic monitoring in Morocco dates back to the early twentieth century. In 1906, Montessus de Ballore, one of the pioneering French seismologists, identified the potential seismic hazard affecting North African countries and Spain (*Montessus de Ballore*, 1906). The first seismic instrument in Morocco was installed in 1937 at the Averroès Observatory, marking the beginning of instrumental seismology in the country. However, the establishment of a structured national seismic monitoring system only gained real momentum following the Agadir earthquake of 29 February 1960 (M_W 5.7), which revealed the need for continuous seismic surveillance and rapid response capabilities.

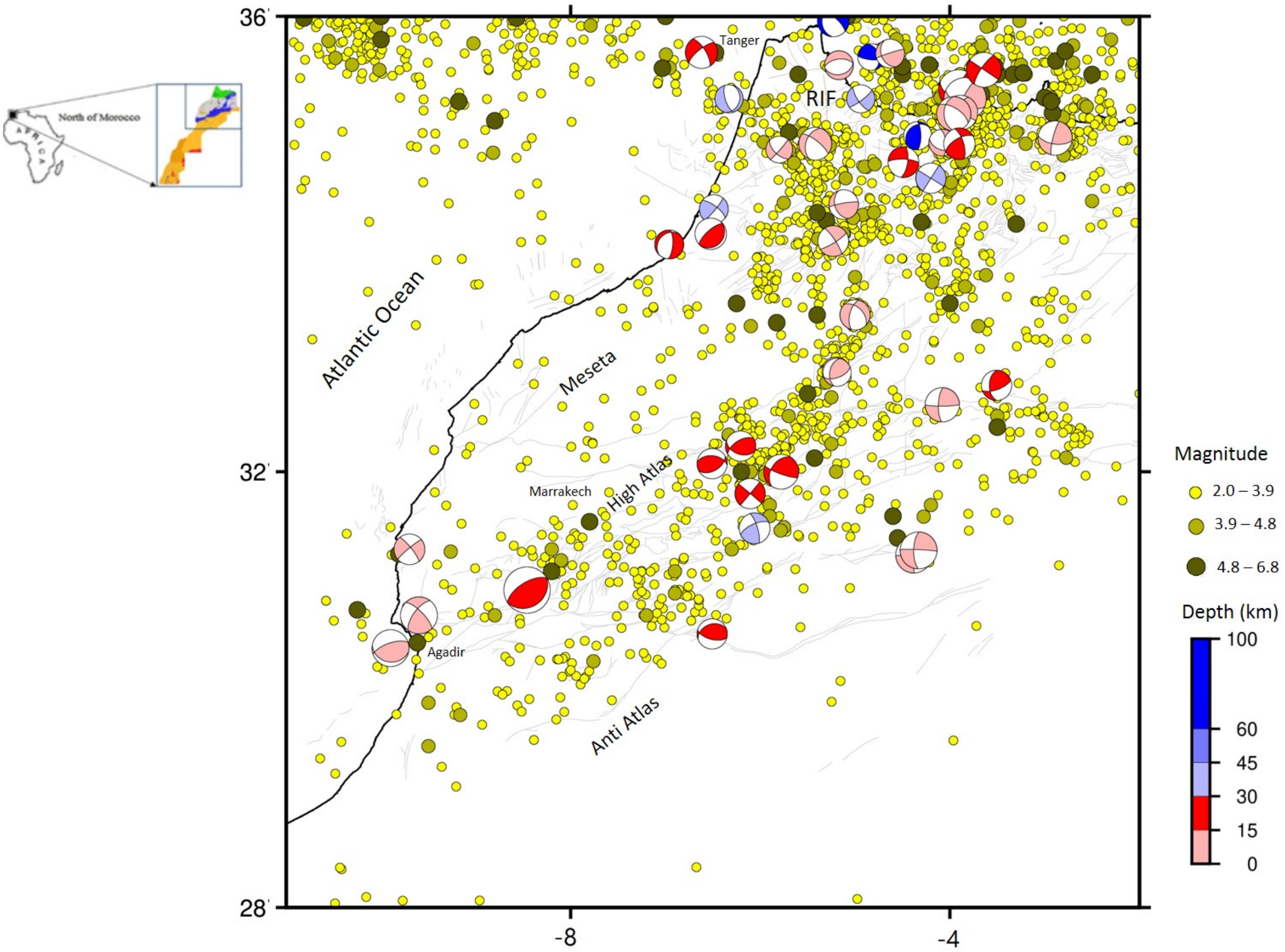

Figure 5.2: *Instrumental seismicity from catalogue of CNRST-Morocco and focal mechanisms from Global CMT (Ekström et al., 2012). The compressional quadrants of the focal mechanisms are coloured coded by depth.*

During the 1980s, significant progress was achieved with the installation of 15 seismic stations, substantially improving the country's capacity to detect and locate earthquakes. In 1982, the Council of Arab Ministers of Housing and Urban Development initiated the Program for the Assessment and Mitigation of Earthquake Risk in the Arab Region (PAMERAR), which enabled Morocco to acquire telemetric seismic networks and upgrade its monitoring infrastructure.

Since then, the National Institute of Geophysics (ING), under the National Centre for Scientific and Technical Research (CNRST), has developed three successive generations of observation networks, each incorporating progressively more advanced technologies. These networks have significantly enhanced the precision, reliability, and real-time capabilities of seismic data acquisition, improving both the detection threshold and the rapid determination of earthquake parameters at the national scale.

History of National Seismological Network (1970 – 2012)

The first national seismological network, established during the 1970s by the Geophysics Department of the Scientific Institute of Mohammed V University, consisted of a combination of short- and long-period analogue instruments (*Ben Sari*, 2004): 14 short-period stations with analogue visible recording;

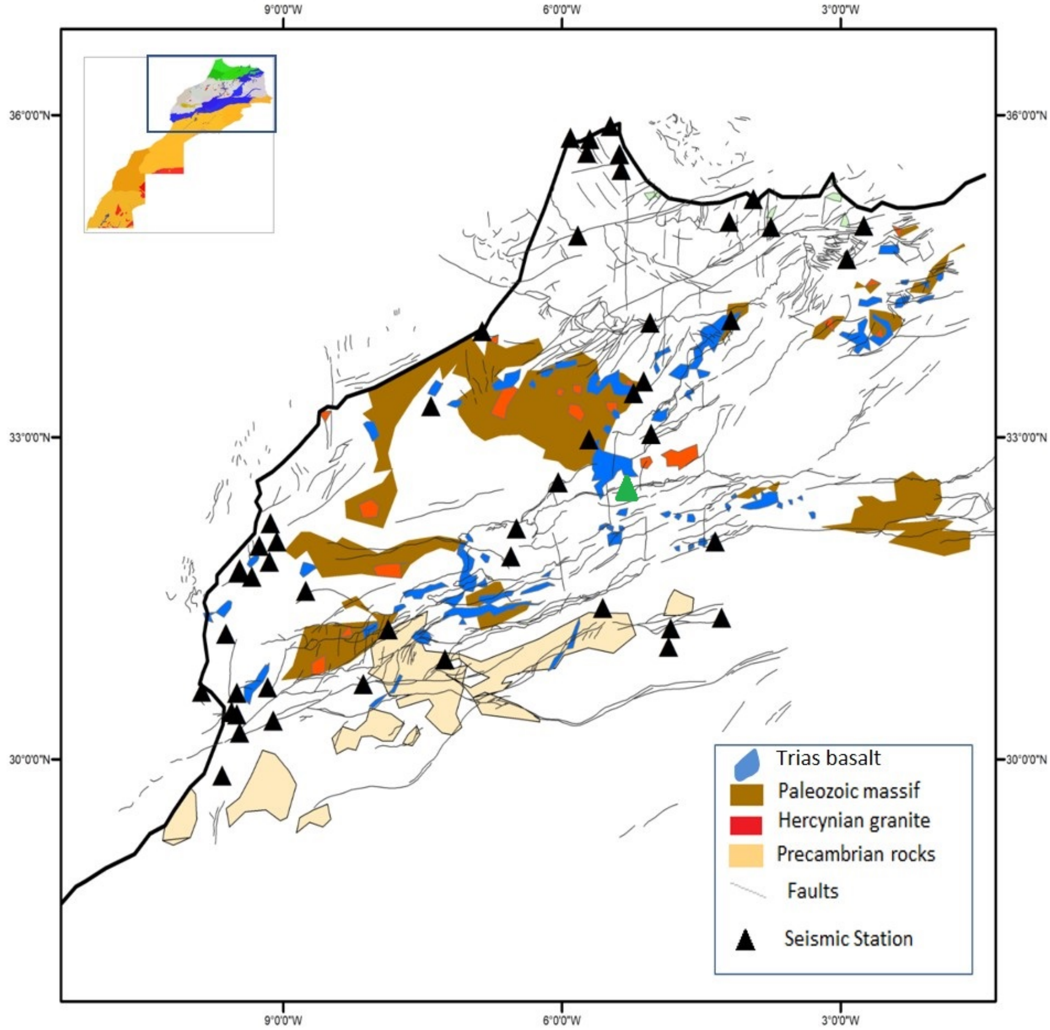

Figure 5.3: *The Moroccan analogue seismic network, operated between 1988 and 2012, was deployed across northern Morocco. The green triangle represents the (VBB) observatory located in the Midelt region.*

2 short-period stations with analogue magnetic tape recording, offering improved bandwidth; 5 long-period stations with analogue visible recording; 2 accelerographs, one recording on photographic paper and the other on magnetic tape.

Most of these instruments were installed at dam sites, complemented by three observatories located in Averroès (Berrechid region), Ifrane and Tiouine (Ouarzazate region). This early network represented the foundation for modern seismic monitoring in Morocco.

The National Seismic Monitoring and Early Warning Network, established in 1988 by the Laboratory of Geophysics (LAG) under the CNRST, constituted a real-time data acquisition system covering the national territory and adjacent regions. Over 70 seismic instruments were deployed across Morocco, approximately half of which were telemetric stations connected to the central processing facility in Rabat via UHF/VHF radio transmission links (31 in total) and dedicated telephone lines (6 lines) (Figure 5.3).

The telemetric component comprised of 30 short-period stations, each equipped with a vertical component seismograph. In addition, 23 accelerographs and 9 relay stations formed part of the national network.

Data were recorded in both analogue and digital formats for the telemetered network, digitally for accelerographs and portable stations, and analogically for other mobile instruments. Timing synchronisation was ensured by GPS satellite clocks for telemetered stations and accelerographs, and by DCF77 radio time signals for portable systems.

The short-period network (1 Hz) operated on analogue frequency modulation. Data acquisition was conducted at the central observatory in Rabat, which included 31 analogue drum recorders and one digital acquisition unit equipped with two threshold-detection tape readers for data storage.

In regions where telemetered stations could not be installed, a portable seismic network was deployed, consisting of six portable seismographs using thermal-paper recording. For microseismicity investigations and aftershock monitoring, six analogue seismographs and two three-component digital stations were utilized.

Furthermore, 23 accelerographs equipped with three-component sensors had been installed to monitor strong ground motions and hydraulic structures, in collaboration with the Directorate of Hydraulic Infrastructure.

As part of bilateral cooperation between the CNRST and the Istituto Nazionale di Geofisica (INGV), Italy, a Very Broad-Band (VBB) observatory was installed in the Midelt region (Figure 5.3). This observatory represented the latest generation of seismic instrumentation in Morocco at the time, equipped with Streckeisen STS-1 sensors and a 24-bit digitizer. This station was relocated to Rabat and is now operating under the code RTC.

Current National Seismic Network and Future Perspectives

Over the past two decades, Morocco has undertaken significant modernisation efforts to enhance its national seismic monitoring and early warning capabilities. These initiatives aim to improve the spatial coverage, data quality, and real-time transmission of seismic information, thereby supporting both scientific research and disaster risk reduction policies.

The major modernisation phase took place over the period 2012–2025, involving the progressive adoption of satellite-based data transmission. In addition to hardware modernisation, substantial progress has been made in the development of automated data processing and early warning systems. The implementation of real-time algorithms for event detection, location, and magnitude estimation enables rapid generation of preliminary bulletins, supporting emergency response coordination. Data management and analysis capabilities have also been enhanced through the establishment of dedicated computing infrastructure and national databases accessible to researchers and public institutions.

The National Institute of Geophysics (ING), under the National Center for Scientific and Technical Research (CNRST), has progressively upgraded its seismic infrastructure through the integration of digital broadband technology, satellite telemetry (figure 4), and automated data processing systems. A total of 36 seismic stations are presently operational within the network. These include 12 Streckeisen STS-2, 2 Streckeisen STS-2.5, 8 Nanometrics Trillium-240, 4 Kinemetrics MBB-2, and 10 short-period Lennartz 3Dlite instruments, ensuring broad frequency coverage and high-quality waveform acquisition across the monitored region.

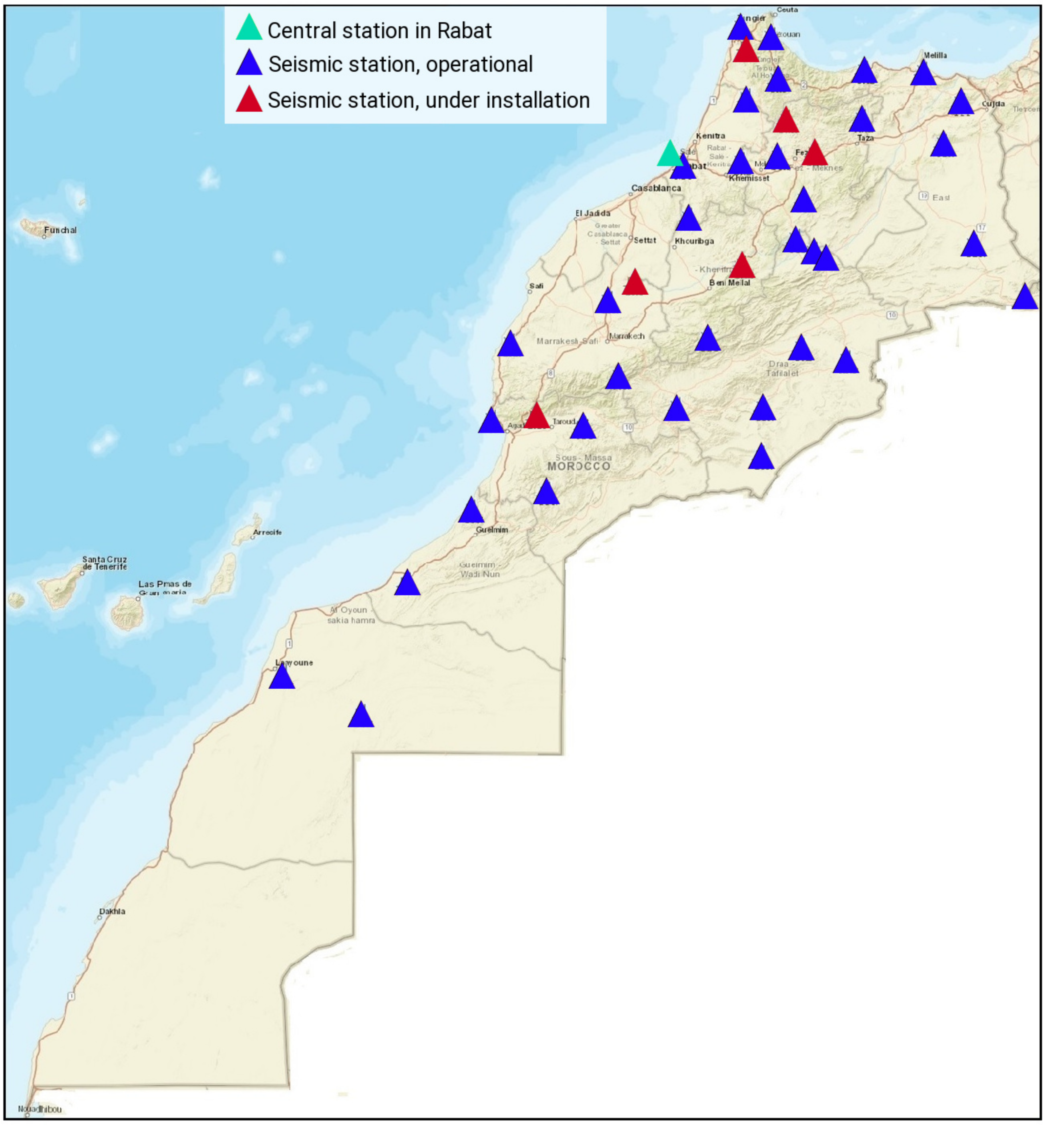

Figure 5.4: *The Moroccan digital seismic network has been deployed across the entire national territory, providing comprehensive coverage for seismic monitoring.*

5.1.5 Data Processing

A central aspect of the network modernisation is the implementation of the Antelope real-time seismic monitoring system (Boulder Real Time Technologies), which offers comprehensive tools for data acquisition, processing, analysis, archiving, and rapid dissemination of seismic alerts. This system enables the seamless integration of telemetry streams with real-time event detection, hypocentre determination, magnitude estimation, and automatic alert generation, significantly enhancing the operational performance of Morocco's seismic monitoring system.

Seismic event processing and location are conducted using the IASP91 velocity model as the reference Earth structure, with depth discretisations tailored to the scale of seismicity. For local earthquakes, the model is sampled at depths of 0–30 km at 2 km intervals to achieve higher resolution within the crust. For regional events, a simplified configuration with depth levels at 15 km and 30 km is applied to optimise computation while maintaining adequate accuracy. Magnitude estimation is performed within the Antelope framework: local magnitudes (ML) are derived from the maximum amplitude recorded by short-period and broadband stations, whereas body-wave (mb) and surface-wave (MS) magnitudes are determined for regional and teleseismic events using standard amplitude–period correction functions.

The transition from analogue to digital acquisition systems has markedly improved the precision and reliability of earthquake detection and localisation, while also facilitating rapid dissemination of seismic alerts to national authorities and civil protection agencies. Recent developments include the installation of Very Broad-Band (VBB) stations and Global Positioning System (GPS) time-synchronized sensors, allowing continuous recording of ground motion across a broad frequency range.

The implementation of satellite-based data transmission, currently underway, represents a major advancement toward a fully digital, real-time monitoring network. Out of 50 planned satellite-linked stations, 36 have already been completed, significantly extending national coverage, particularly in remote and seismically active regions such as the High Atlas and Rif domains.

Parallel efforts have focused on the integration of seismic and accelerometric data to improve the characterisation of strong ground motion and site effects. The expansion of the accelerograph network, notably in urban centres and critical infrastructure sites (e.g., dams, bridges, and industrial facilities), provides essential input for seismic microzonation, structural safety assessment, and the calibration of ground-motion prediction models.

In addition to hardware modernisation, substantial progress has been made in automated data processing and early warning systems using Antelope's capabilities. Real-time algorithms for event detection, location, and magnitude estimation now allow the generation of rapid bulletins to support emergency response. Data management has also been enhanced through the creation of centralized databases, accessible to researchers and relevant public institutions.

5.1.6 Data Availability

The CNRST provides access to seismic data, including a comprehensive seismic catalogue and bulletins in collaboration with the International Seismological Centre (ISC) and Euro-Mediterranean Seismological Centre (EMSC). Several stations are jointly operated within the Western Mediterranean network, in partnership with the Instituto Geográfico Nacional (IGN) of Spain, Instituto Português do Mar e da Atmosfera (IPMA) of Portugal and Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy, through the Mediterranean Very Broadband Seismographic Network (MedNet), in addition one station operates as an auxiliary station of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

5.1.7 Conclusions

Moroccan seismicity results from the complex interaction between active plate boundary dynamics and intraplate reactivation of inherited faults. The Rif belt and Atlas Mountains remain the most active zones, while offshore structures along the Azores–Gibraltar–Iberian system are capable of producing large-magnitude events. The occurrence of the 2023 Al Haouz earthquake underscores the seismic potential of the Atlas domain and the importance of continued instrumental observation, seismotectonic research, and hazard reassessment for effective seismic risk management.

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