Chapter 10
Conclusion: Continental Evolution in Western Maghreb

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In this conclusive chapter, our aim is to summarize the lessons which can be drawn from the preceding chapters with regard to continental evolution. Obviously, only part of the vast geophysical/geochemical/historical problem of continental evolution can be enlightened through the Moroccan case study, as Morocco extends only on a very restricted, marginal part of Africa. Moreover, Morocco is located in a particular area of the continent, at its northwest "corner" (Fig. 10.1). This restricted region of the large African continent is bounded by the Atlantic passive margin to the west, as old as Early Jurassic, and by the Oligocene-Neogene West Mediterranean Sea to the north, a young thinned continental crust/oceanic basin born within the Alpine collisional domain. The geological evolution of the Moroccan lithosphere is deeply marked by this situation.

Second, this chapter aims at evoking the most important avenues of research, which are currently opened or should be traced in the near future in order to get a best and fruitful knowledge of the Moroccan subsurface geology and deep lithosphere structure. In this field, the interpretation of topography still occupies a significant place.

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A. Michard et al., *Continental Evolution: The Geology of Morocco*. Lecture Notes in Earth Sciences 116,

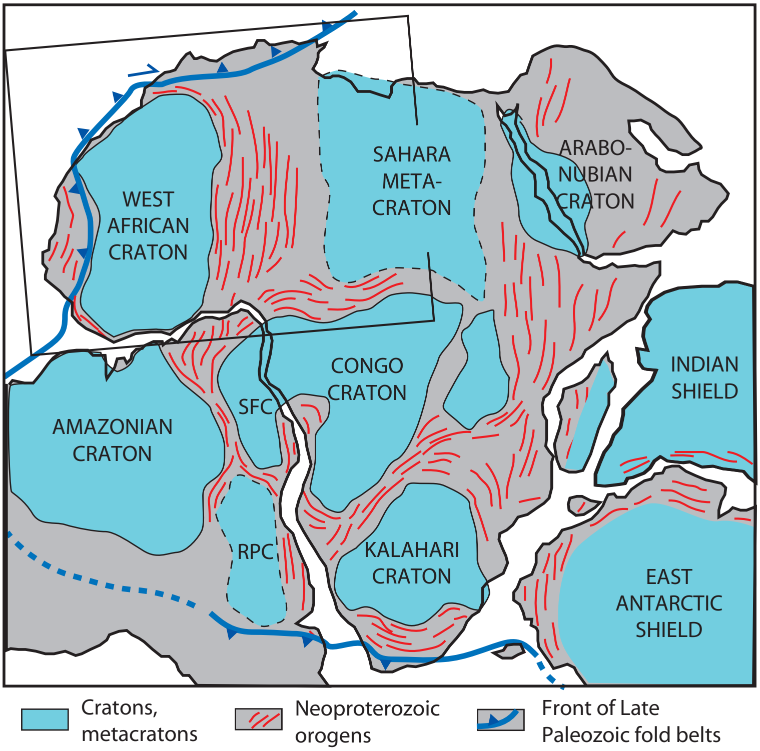

Fig. 10.1 Sketch map of the African Continent in the framework of the supercontinent Gondwana, after Meert & Lieberman (2007), modified. The Neoproterozoic orogens criss-cross the supercontinent, being associated with its progressive amalgamation. In Northwest Africa, the "South Variscan Front" indicates the front of the Variscan displaced terranes (Mauritanide thrust nappes, Meseta Domain). This front runs west and north of the Anti-Atlas and Ougarta foreland fold belts, respectively (not shown; see next figure). The Alpine belts of North Africa (Atlas and Maghrebides) are not differentiated north of the South Atlas Fault. Likewise, the Andes Orogen of South America is not shown south of the South Gondwana Paleozoic Orogen

10.1 Continental Building/Break Up Alternations

In line with L. Gentil (1912), G. Choubert and J. Marçais (1952) outlined the geological structure of Morocco as consisting of a succession of east-west fold belts bordering the Saharan platform, and being superimposed through time, the youngest being located progressively further to the north. Nowadays, this ancient paradigm of "continental growth" has to be substituted by a more complex geodynamic conception, which recognizes alternating phases of continental building and break-up controlled by plate tectonics. This is well illustrated in Morocco since about 2 Ga (Fig. 10.2).

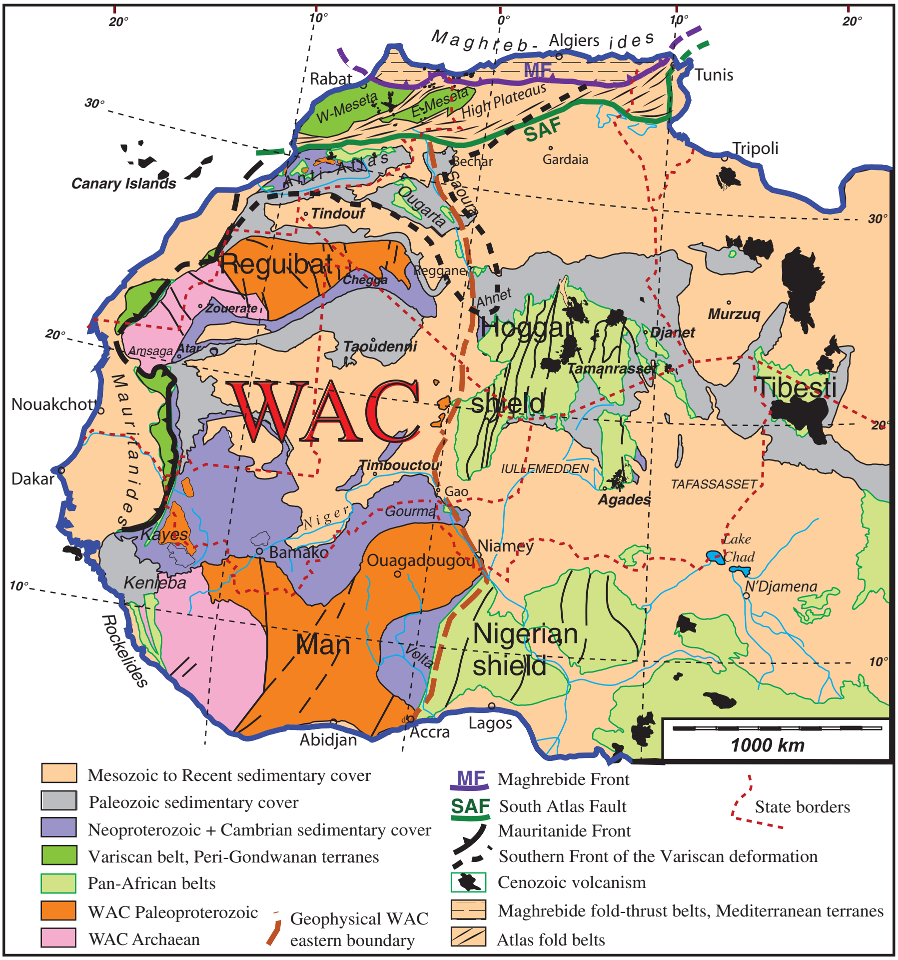

Fig. 10.2 Structural map of NW Africa. Location: see Fig. 10.1. After Fabre (2005), Liégeois et al. (2005), Ennih & Liégeois (2008). State borders of the Maghreb and Saharan countries are indicative. The Cretaceous-Cenozoic intraplate deformations (e.g. Reggane area; Smith et al., 2006) are not shown for lack of regional data

10.1.1 From 3 Ga to 800 Ma (cf. Chap. 1)

The southernmost lowlands of Morocco correspond to the Archean-Paleoproterozoic lithosphere of the West African Craton (WAC), which extends widely in the neighbouring Saharan regions of Mauritania and Algeria (Fig. 10.2), and to the south up to the Ivory Coast (a chip of the WAC forms the Sâo Luis Craton of North Brazil). The WAC subsurface is not homogeneous: its northern part displays a large basement rise, the Reguibat Shield, and two synformal basins, namely the Tindouf-Reggane and Taoudenni Basins. South of the latter basin, the southern counterpart of the Reguibat Shield, namely the Man Shield, takes place. These basins are filled up with virtually undeformed Neoproterozoic to Neogene deposits, as it is typical for a cratonic area.

The WAC lithosphere itself is also heterogeneous. The western half of the Reguibat Shield consists of 3 Ga-old Mesoarchean terranes, whereas its eastern half is made up of 2.1–2.0 Ga-old Paleoproterozoic terranes. This involved the collage of two wandering continents and building of a larger continent through a collisional tectonic phase referred to as the Eburnian Orogeny. The corresponding NW-trending "suture zone" is seemingly devoid of ophiolite.

The WAC behaviour during the Mesoproterozoic remains mysterious (simply drifting and weathered during 1 Ga?) as no geological event at all is recorded during that period. By the early Neoproterozoic, the WAC was probably included in the Rodinia supercontinent, whose rifting may have triggered the subsidence observed in the Taoudenni Basin and southwest Anti-Atlas. The provenance of the clastic input in the WAC shallow water depocenters has not been studied until now (uplifted parts of the WAC or neighbouring Mesoproterozoic belts?). The break-up of Rodinia resulted in the insulation of the WAC, which was surrounded by oceanic domains until the Pan-African convergence took place.

10.1.2 From 760 to 560 Ma (Cf. Chap. 2)

The 760–560 Ma-old Pan-African Belt has surrounded continuously the WAC to the north (Anti-Atlas and Ougarta inliers), east (Western Hoggar or Pharusides, Iforas, Gourma), southeast (Dahomeyides), southwest (Rokelides) and northwest, as Pan-African terranes with both felsic and ophiolitic lithologies are included in the Mauritanide nappes finally emplaced during the Variscan orogeny (see below). This is consistent with a major collisional event responsible for the agglutination of the wandering continents into a single Pannotia supercontinent (Gondwana + Laurentia + Baltica + Siberia). For the first time in the geological record, the plate tectonics with subduction and collision is well illustrated by obducted ophiolites and oceanic arc (Siroua and Bou Azzer inliers in the Anti-Atlas), and HP-LT coesite-bearing metamorphism in the eastern suture zone (Mali). The putative "northern continent" involved in the collision along the Anti-Atlas segment is unknown. It could be hidden beneath the Atlas and Meseta system but could also be included in some of the Peri-Gondwanan terranes now dispersed in Europe and America.

This phase of continental building is also characterized by a huge magmatism, intrusive and effusive, firstly calc-alkaline, then potassic and finally alkaline. Part of the magmas is anatectic, resulting in the recycling of older continental crust, but another part is mantle-derived, thus adding fresh material to the continent. Besides of the nappe tectonics and of the folding of the detached foreland cover (e.g. Bou Azzer, Kerdous), the tectonic regime coeval with the main magmatic accretion was dominated by wrench faulting, either transpressive or transtensive, in a large metacratonic zone fringing the WAC.

10.1.3 From 550 to 270 Ma (cf. Chap. 3)

Pannotia was no more that a transient, unstable continental configuration. As far as NW-Gondwana is concerned, extensional tectonics affected the Pan-African Belt during the late Ediacaran, then rifting increased during the Cambrian and continued during the Ordovician, basically along the western and northern deformed borders of the WAC. This resulted in the formation of thinned crust/oceanic domains at the emplacement of the present-day Mauritanide Belt and Meseta Domain. However, the WAC itself subsided contemporaneously, and extensional faulting operated until the Devonian-Early Carboniferous. By the end of this time, 5–10 km of dominantly clastic deposits had been accumulated over the northern WAC and former Pan-African Belt. The source of this huge clastic sedimentation may be found in the large Tuareg (Hoggar) Shield, still affected by magmatism and uplift during the Cambrian.

The driving force responsible for this continuous or recurrent Paleozoic extension is a matter of debate: plate divergence or back-arc extension associated with subduction? In every case, this resulted in the dismembering of the metacratonic margin of the WAC into terranes which drifted toward the NW (present coordinates): Avalonia and the Hun/Armorica terranes. Was the Meseta Domain part of the latter, or did it remain at short distance from Africa? This is also controversial.

A new phase of continental building corresponds to the Variscan Orogeny (350–270 Ma). More or less exotic terranes were accreted then to NW Africa: the Mauritanide Belt on the west border, and the Meseta Variscan Domain on the north border. The latter domain includes a northward, Caledonian-Sardic terrane (Sehoul Block) characterized by Ordovician felsic magmatism and metamorphism, and brought against the undeformed Central Meseta during the Late Silurian. Late Devonian-Tournaisian shortening events are recorded within the Meseta Domain. However, the final collage of both the Mauritanide and Meseta terranes against Africa occurred during the Late Carboniferous-Early Permian, in the framework of the building of the Pangea supercontinent. Thus, the small part of the Variscan Belt which remained in Africa after the Pangea break-up outlines a new “orogenic aureole” around the WAC to the North and West. It is notable that this “aureole” is widely open eastward, as the Meseta Variscides are accreted, not only to the WAC, but along the entire Saharan Precambrian platform. Remarkably, the Ougarta Pan-African segment was reactivated during the Variscan collision, giving birth to an intracontinental belt. The latter belt is connected to the Anti-Atlas, and together these belts represent the foreland fold-belt of the main Variscan segments, i.e. the Mauritanides and the Mesetan Variscides.

Overall, the Variscan Orogeny brought back to Africa continental fragments formerly rifted from Gondwana. They were accreted to the continent together with metasediments whose clastic elements had been mostly taken from the Saharan massifs. Only few mafic and felsic magmatic rocks, either pre-, syn- and post-orogenic added some fresh material to the previous continental mass.

10.1.4 From 250 Ma to Present (cf. Chaps. 1 and 4–8)

The break-up of Pangea disconnected definitively Africa from the Americas, resulting in the formation of the Atlantic margin of Morocco. This is one of the oldest passive margin preserved worldwide, being only perturbed offshore in the western continuation of the Atlas belt and along the Gibraltar Arc. Rifting began as early as the Late Permian, whereas spreading began during the Early Liassic. The 200 Ma-old magmatic event of the giant Central Atlantic Magmatic Province (CAMP) added a significant mass of basaltic trapps and gabbroic intrusions to the Moroccan crust.

Unlike the wide Atlantic spreading, the coeval, Jurassic-Early Cretaceous Tethyan opening hardly separated Africa from Europe. It was characterized by a strong left-lateral movement parallel to the NW Africa margin. The latter margin encroached obliquely onto the Variscan domain: it is located within the Variscan domain in the Moroccan transect and south of it, i.e. within the metacratonic domain, in the eastern Maghreb. The opening of the western Tethys Ocean (Ligurian-Maghrebian Ocean) resulted in the splitting up of the Variscan Belt between Africa and Europe (Iberia). The future Internal Zones of the Betic-Maghrebide belts, i.e. the AlKaPeCa Domain, was either the southern distal part of the Iberian margin or an isolated block within the Tethyan realm.

The Tethyan rifting also affected the Variscan and metacratonic domains south of the African passive margin itself. From the Triassic to the Middle Jurassic, extensional faulting created a mosaic of elongated basins (troughs) and highs (platforms) which prefigured the future Atlas Mountains and Meseta/Plateaus areas. Rifting aborted in this domain during the Middle-Late Jurassic, after the emplacement of a tiny volume of gabbroic rocks (Central High Atlas). A conspicuous shallow structure, namely the West Moroccan Arch (WMA), developed between the Atlantic Coastal Basins and the Tethyan Atlas Gulf. This block acted firstly as a common shoulder between both rift basins, then as a poorly subsident high from the Late Triassic to the Middle Jurassic, before suffering uplift and erosion during the Late Jurassic- Early Cretaceous. From this point of view, the western half of the Maghreb is very different from its eastern half (Eastern Algeria, Tunisia) characterized by a continuous subsidence since the Liassic.

The North Africa passive margin (i.e. the future External Maghrebides) was particularly wide. In its western part, it is characterized during the Jurassic-Early Cretaceous by the occurrence of an elongated zone of thinned crust/oceanic crust between the proximal margin (Prerif, Mesorif) and a distal continental block (Intrarif). This type of wide, dislocated passive margin compares fairly well with that of western Apulia.

From the Late Cretaceous onward, the Africa-Europe convergence tended to close the Tethys oceanic hiatus. Subduction was initiated along the Iberian plate margin (possibly two successive subductions, one beneath Iberia, the other one beneath the Alboran Domain?). In North Africa, few if any shortening did affect the Atlas and External Maghrebide domains before the Middle-Late Eocene. However, large wavelength folding affected probably the entire lithosphere during the Senonian-Eocene interval, being responsible for the individualization of E-trending rises: (1) between the Maghrebide and Atlas Domains (the so-called North Moroccan Bulge, cf. Chap. 4); (2) on the site of the Anti-Atlas and (3) on the site of the Reguibat Shield (Frizon de Lamotte et al., 2008). The general inversion of the Atlas paleofaults began during the Middle-Late Eocene, i.e. before the docking of the AlKaPeCa terranes (Internal Maghrebides) against Africa. The climax of Alpine shortening occurred during the Neogene in the External Maghrebides. It is the direct result of the development of an accretionary prism in front of the moving AlKaPeCa and finally of the "collision" of AlKaPeCa against Africa, which occurred at 18 or 15 Ma. The collision-related deformation propagated progressively from the Mediterranean coast southward up to the South Atlas Front. At the moment, the deformation is clearly concentrated in the Maghrebides, but diffuse deformation also occurs in the Atlas System and even in the Anti-Atlas. On the other hand, the convergence had far-distant intraplate consequences in Africa, marked by swells (Hoggar, Tibesti) and volcanism in several areas including the metacratonic margins of the WAC, but not in the WAC itself.

Thence, the Alpine Orogeny of the Maghrebide Belt corresponds to a new phase of continental accretion, due to the collage of exotic terranes. The observed continental growth remained very limited, as the collage of Iberia against Africa was hampered by the efficient roll-back process which carried the AlKaPeCa terranes toward Africa, then toward the Gibraltar Arc, and opened contemporaneously the Mediterranean Sea between the converging continents.

10.2 Continental Deformation and Topography

Topography is the surface expression of the 2 Ga-long continental evolution reported above. At first glance, the topography of NW Africa offers two strongly contrasting domains (Fig. 10.3). The southern and largest domain consists dominantly of low lands with smooth topography except in the Hoggar (Ahaggar) and Tibesti swells. In contrast, to the north, the Maghreb strip shows a rugged topography with high mountain ranges including lozenge-shaped plateaus and basins.

It is clearly tempting, and indeed largely correct to correlate this contrasted topography with the age of the orogens, which form the corresponding crustal domains. On the one hand, in the main continental domains, the crust consists of Precambrian orogens, almost totally erased during the Paleozoic. Both the Variscan and Alpine deformations have been negligible there, relative to the northern domain. Only the Anti-Atlas and Ougarta belts show significant deformations as foreland

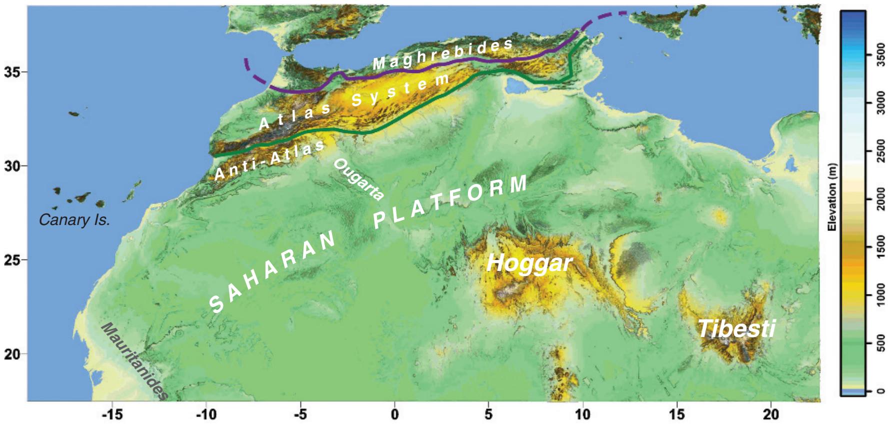

Fig. 10.3 Topography of NW Africa (GTOPO30 database) showing that the main current relief is concentrated in the NW fringe of the continent, i.e. in the Maghreb (Atlas Belts) but that major swells (Hoggar, Tibesti) also occur within the continent itself, in the Pan-African and metacratonic regions of the Saharan platform (compare with Fig. 10.2)

fold belts during the Variscan Orogeny. On the other hand, the Maghreb rugged topography correspond to the continental rim which suffered the superimposed Variscan and Alpine orogenic cycles, each one involving successively rifting and collisional events. The youngest and still ongoing collision affected a weak, deeply fractured continental crust, resulting in the observed mountainous topography.

However, this scheme does not account for all the topographic particularities in these regions of NW Africa, neither qualitatively or quantitatively. One of the issues in debate concerns the origin of the Hoggar and Tibesti swells in the main, cratonic-metacratonic domain. As they coincide with the distribution of Cenozoic (Late Eocene-Pleistocene) volcanic centres (Fig. 10.2; Dautria et al., 2005), they have been classically considered to be the products of mantle plumes (e.g. Aït Hamou et al., 2000, with references therein). However, Liégeois et al. (2005) argue that at present, several observations and data including geological, heat flow and tomographic results do not support the mantle plume model (cf. Chap. 1, Fig. 1.21). They emphasize the volcanic centres close relationship with fractures zones in the Pan-African basement. Thence, they suggest that intraplate stress induced by the Africa-Europe convergence reactivated the Pan-African mega-shear zones inducing linear lithospheric delamination, asthenospheric upwelling and melting due to pressure release. This debate certainly deserves new studies, in particular more accurate tomographic images and geophysical models.

Another issue concerns the asymmetry of the Maghreb topography from west to east. Why do the highest mountains occur in Morocco (Marrakech High Atlas)? Why the only mountain range south of the South Atlas Fault (SAF) is the Moroccan Anti-Atlas? An intuitive cause should be the presence there of the West African craton that induced a larger rheological contrast that has been used already during the Jurassic rifting. Rift weakening and craton rigidity could have concentrated the shortening effects. However, it is known for long that the crustal root created by the Alpine shortening beneath the Atlas Mountains is not thick enough to isostatically support the topography. Different authors modelled the lithospheric structure taking into account gravity, geoid, heat flow and topography. They showed that the lithosphere is thinned to 60 km below the Anti-Atlas and High-Atlas (see Chap. 1, Fig. 1.19). Modelling the effect of such lithospheric thinning shows that the whole topography of the Anti-Atlas and up to half of the relief of central High Atlas is due to lithospheric thinning, not only to crustal shortening (cf. Chap. 4, Fig. 4.46). Moreover, the NE-trending thinned lithosphere strip coincides with the distribution of Miocene to recent alkaline volcanism. This lithospheric structure is oblique on the structural grain of the crust as it crosscuts not only the SAF, but also the Jurassic Atlantic margin up to the Canary Islands to the south, and the Oligocene-Miocene Alboran Basin up to eastern Spain and possibly the French Central Massif to the north ("Morocco Hot Line" hypothesis; Fig. 4.47). Again, this issue deserves further geophysical and geological studies. In this general framework, the asymmetry of the Maghreb topography from west to east is mainly due to the existence of the Cenozoic "Moroccan Hot Line", whose development was probably enhanced by the lithosphere tearing along the Maghrebian margin (Frizon de Lamotte et al., 2008).

10.3 Further Studies

Morocco is certainly one of the African countries whose geology is best known. As shown in the Chap. 9, this results from a long history but above all from an exemplary coordination between the Geological Survey of Morocco ("Service Géologique du Maroc") and the academic research handled in national and foreign universities. By the beginning of the seventies, oil and gas exploration, under the supervision of ONAREP ("Office National pour le Recherche Pétrolière") now included in the ONHYM ("Office National des Hydrocarbures et des Mines"), led to a better knowledge of sedimentary basins, borders of orogenic belts and both Atlantic and Mediterranean margins. The exploration remains very active, in particular the deep offshore targets, which bear the main hopes of discovery. Concurrently, mining exploration and related academic research restarts as a direct consequence of the price of raw materials worldwide.

Beyond these economic stakes, societal stakes are manifold. They firstly concern the question of water resources and environmental problems. Among them, we emphasise the evaluation of seismic hazard. Indeed Morocco is globally subject to a moderate risk. However the recent Ms 6.0 earthquake of Al Hoceima (2004 February 24th) recalls that the Earth remains murderous and that we have to increase our vigilance.

From an academic point of view, Morocco is a wonderful natural laboratory attracting researchers from many countries. This territory offers numerous opportunities for detailed studies. For a better understanding of its geological evolution, we are waiting for more and more data: more geochemical data, more geochronological and thermochronological data, more stratigraphic data (in particular in continental series) etc… One of the main frontiers is the knowledge of the deep crustal and lithospheric structure of the country. Morocco provides a relatively restricted region where a great variety of geophysical, geodynamic and geochemical processes associated with extension, subduction and continental collision can be addressed. To improve our understanding of these processes, we suggest promoting collaborative, international multi-disciplinary projects. The first general objectives could be:

– to determine the three-dimensional structure of the crust and lithosphere through high resolution tomographic images and seismic profile acquisition across the orogenic systems (Rif, Atlas) and the margins (Atlantic and Alboran margins);
– to monitor the motions of crustal blocks in time and space in order to constrain earthquake models as well as mountain building processes;
– to analyse the feedback relationships between tectonics, topography and climate.

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