The Moroccan Hercynides

The Moroccan Hercynides By Christian Hoepffner, Abderahmane Soulaimani, Alain Pique Department of Geology, Faculty of Sciences, University Mohammed V, B.P. 1014 Rabat, Morocco Department of Geology, Faculty of Sciences, University Cadi Ayad, B.P. S 20, Marrakech, Morocco 21 Rd Point de l'Esplanade, 67 000, Strasbourg, France Received 5 April 2004; accepted 18 July 2005 Available online 18 November 2005 Abstract In Northern Africa deformed Paleozoic rocks are observed, mainly in Morocco where they are present in two structural domains: (i) the southern domain, i.e. the Anti-Atlas belt. In this northern rim of the West African craton, the Paleozoic sequences are mildly deformed; (ii) the northern Mesetan domain, itself subdivided into several structural subzones, corresponds—with its eastern prolongation in Algeria- to the Hercynian /Variscan belt of Northern Africa. In the Meseta, the study of the sedimentological history and the structural analysis of the various subzones allow to discuss the tectonic characters of the Hercynian/Variscan orogeny in Northern Africa: – The deformation was realized through three main events: (i) the Late Devonian, Eovariscan Phase, which developed in the eastern zones of the Moroccan Meseta, northwestern Algeria and in the presently Alpine allochthonous domains of the Rif and Kabylias; (ii) The Visean Phase, which was restricted at the limit between the Moroccan eastern and western Meseta. The two preceding compressional events were contemporaneous with the development of Late Devonian-Early Carboniferous transtensive sedimentary basins; (iii) the

Late Carboniferous Phase, during which the regional shortening affected the entire Hercynian domain, including the Moroccan western Meseta and Anti-Atlas. – The Anti-Atlas differs fundamentally from the Mesetan domains by: (i) its relatively mild deformation; (ii) the vergence of its regional structures, directed toward the West African shield, whereas the main vergence is toward the west in the Meseta domains. – In the Anti-Atlas like in the weakly deformed zones of the Meseta, the deformation is heterogeneous, being concentrated along several regional shear zones. Sedimentological and stratigraphic evidences point out the control exerted by these long-lived weakness zones through the sedimentation, and the deformation. – No direct evidence can be found to invoke the development of a Paleozoic oceanic lithosphere in the considered domains. Therefore, the Hercynides/Variscides of North Africa are considered to be outside the inner zones of the European belt, at the northern border of the Paleo-Gondwana, and probably related to the Appalachian belt of North America.   2005 Published by Elsevier Ltd. 1. Introduction More than one century ago, some workers penetrated, with strong difficulties, the Moroccan territory and they began to decipher its then ignored geology. Among them Thomson crossed the High Atlas Mountains in 1888. He described eruptive rocks (the Atlasic Palaeozoic massif) as an island inside the Cretaceous sea, and the red lacustrine Nfis sandstones, which are folded (Thomson, 1889). From this onwards, the reality of the Hercynian and the subsequent Atlasic deformations was ascertained. During the beginning of the 20th century, Gentil performed an extensive field work north of the High Atlas Mountains. ‘‘The structure of the plateaus is characterized by a folded Palaeozoic basement, unconformably covered by transgressive Mesozoic deposits, which remained mostly horizontal. Due to the erosion, we see that a wide chain, developed by the end of Carboniferous times (i.e. the Hercynian chain) has been completely eroded. This structure of western Morocco has to be compared to the Iberian Meseta'' (Gentil, 1918; translated). Following Gentil, Lecointre (1926) carefully mapped northwestern Morocco while other geologists, most of them belonging to the newly constituted Geological Survey of Morocco, spread the knowledge of the country in Northern Morocco and south of the High Atlas as well. A complete list of the references is given by Morin (1964, 1970, and 1979). As shown by the ancient authors, the Hercynian (=Variscan) chain of Northern Africa, extending from western Mauritania to Northern Algeria, is best exposed in Morocco where the extended outcrops of Palaeozoic rocks allow to distinguish several structural domains (Fig. 1). – The Saharian domain: in southern Morocco the Anti-Atlas domain presents Precambrian inliers cartographically surrounded by more or less deformed Palaeozoic rocks. Hercynian folds are known also in the Algerian Ougarta and in western Mauritania. In the extreme south, the Tindouf basin is the undeformed Palaeozoic cover of the West African craton (Reguibat Rise). – Middle Morocco, where the existence of the Hercynian deformation has been first recognised (Gentil, Lecointre, etc.), is subdivided into two zones: (i) the Meseta, where several massifs made of deformed Palaeozoic rocks are inliers, cartographically separated by a thin and tabular Mesozoic and Cenozoic cover; (ii) the High and Middle Atlas where the Palaeozoic massifs, similar to those of the Meseta, are separated by a thick and folded sedimentary cover. The Atlasic shortening remained weak and correlations between the Palaeozoic massifs of the Meseta and of the Atlas are possible. – The Rif, a part of the Alpine chain of western Mediterranean: the shortening was important and renders difficult, although not impossible, comparisons between the Rifean Palaeozoic series and the other Palaeozoic massifs of Morocco. The Algerian Alpine Tell belt bears Palaeozoic blocks, for instance the Kabylias, which are very similar to those of the Moroccan Rif. The existence of the Hercynian deformation throughout Morocco and adjacent Algeria lead to distinguish several structural zones (Michard, 1976; Pique´ and Michard, 1981, 1989; Michard et al., 1989; Pique´, 1984, 1989, 1994, 2001), which are described below. The definition of the structural zones will in turn allow to present the main characteristics of the Hercynian orogeny in Northern Africa and to tentatively replace the Hercynian belt of North Africa within the tectonic frame of the Hercynian orogeny of Western Europe. Fig. 1. Structural subdivisions of North Africa and location of the Paleozoic terranes. 1: Rifian-Tellian belt, a: southern front of the chain; b: Paleozoic allochtonous terranes of the internal zones. 2: Atlasic belt (HA: High Atlas, SA: Saharian Atlas, TA: Tunisian Atlas, MA: Middle Atlas). 3: Paleozoic, a:deformed by variscan orogeny, b: undeformed. 4: West African craton (Archean and Proterozoic massifs). 5: Mauritanides allochtones. 2. The palaeozoic evolution of the Hercynian structural domains 2.1. The Saharian domain 2.1.1. The palaeozoic sedimentation (Table 1) Between the northern limit of the West African craton and the Hercynian orogenic domains of central Morocco (see below), the Anti-Atlas (Choubert, 1947, 1963) is a large and open antiform, bent during the Atlasic orogeny. Its structural grain trends WSW–ENE in its western part, from which it prolongates toward the Zemmour belt, E–W in its central part, and ENE–WSW in the east, where it connects to the Algerian Ougarta (Figs. 1 and 2). It is separated from the High Atlas by the recent Ouarzazate and Souss troughs. Its main characteristics are the wide outcrops of Precambrian rocks, visible in several inliers (‘‘boutonnie`res''), which are covered by Palaeozoic rocks. The Precambrian times in Anti-Atlas have been marked by the development of the Eburnian orogeny, at about 2000 Ma and the Pan-African orogeny, at about 700–600 Ma. The oldest granitoids and metamorphic episodes are related to the Eburnian orogeny (Charlot, 1978; A?¨t Malek et al. 1998; Thomas et al. 2002; Walsh et al, 2002). The most obvious traces of the Pan-African orogeny are seen in the central Anti-Atlas, where an ophiolitic sequence has been described (Leblanc, 1972, 1975; Saquaque et al., 1989). This ‘‘Pan-African suture'' is traced southeasterly in Algeria, as far as the Hoggar (Black and Lie´geois, 1993) although its actual signification is currently discussed (Ennih and Lie´geois, 2001). After the deposition of the latest Proterozoic volcanic series and redbeds (Ouarzazate series, 575–560 Ma; Thomas et al., 2002), at least partly related to crustal extension (Pique´ et al., 1999; Soulaimani et al., 2003), an eastward-directed transgression started at the very beginning of the Cambrian. This event can be observed all over the Anti-Atlas domain. The first sediments were detrital, but open marine conditions rapidly developed, inducing during the Lower Cambrian, at least in the western and central Anti-Atlas, and the development of a shallow platform, more subsident in the western Anti-Atlas (Choubert, 1963; Benziane et al., 1983). During this period, the so-called Lower and Upper Limestones were deposited, separated by purple shales (Lie-de-vin series) representing a brief regressive episode. After a regression (and an emersion?) at the end of the Cambrian, the sea invaded again the domain for a long time at the beginning of the Ordovician. The region was still a shallow and epicontinental platform. The Ordovician sediments were typically detrital, being composed of sands and clays, all issued from the Saharian continent (Destombes et al., 1985). At the end of the Ordovician a regional glaciation developed (Ouanaimi, 1998), the Anti-Atlas being located not far from the ice cap that spread over western Africa (Deynoux, 1978). The end of the glaciation occurred at the beginning of the Silurian and it was the cause of a glaciogenic transgression over Morocco. Black shales were deposited in confined marine environments and poorly oxygenated waters. At that time the African shield, eroded since a long time and covered by the marine transgression, did not provide more than very fine argillaceous minerals. Furthermore, during the Lower Devonian, even those fine detrital sediments lack in the Anti-Atlas marine basin, and limestones, often reefal, were deposited onto the carbonate platform. During the extensional regime that had characterised the first part of the Palaeozoic, the clastics were issued from the West African craton. From the Devonian, the extensional regime changed to a compressive one, expressing the development of the Hercynian orogeny. The Proterozoic axis of the Anti-Atlas rose up and became the source of the clastics (Wendt, 1985; Hassenforder, 1987). As a consequence, the Late Devonian and Carboniferous sequences deposited in the Anti-Atlas are typically detrital: sandstones, clastic limestones and argillites. Table 1 Simplified paleozo?¨c evolution of the main structural zones of the Northern (Mesetian) domain   1: panafrican basement (Anti-Atlas); 2: sandstones and quartzites; 3: shales and greywackes; 4: shales and psammites; 5: basin deposits (deltaic or deep sea fan sequences); 6: continental redbeds (conglomerates, sandsones); 7: limestones; 8: black shales; 9: volcanoclatic deposits with calk-alkaline volcanism; 10: alkaline to tholeitic volcanism; 11: chaotic deposits (olistostromes, debris flows, rock falls); 12: granites; 13: strong tectonic event: folding and metamorphism; 14: moderate tectonic event: faults, folding; 15: main uncomformities.   1998), the Anti-Atlas being located not far from the ice cap that spread over western Africa (Deynoux, 1978). The end of the glaciation occurred at the beginning of the Silurian and it was the cause of a glaciogenic transgression over Morocco. Black shales were deposited in confined marine environments and poorly oxygenated waters. 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The Hercynian deformation The Hercynian deformation was weak in the Anti-Atlas, when compared to its effects in central and Northern Morocco, where emplacement of granites, regional metamorphism and penetrative deformation occurred. However detailed examination leads to distinguish several structural zones: 2.1.2.1. The western Anti-Atlas (Figs. 2 and 3).   West of the Bas Draa inlier, the Cambrian rocks are involved in NNE–SSW folds and thrusts, all of them being east-vergent (Choubert, 1963; Mattauer et al., 1972; Soulaimani, 1998; Belfoul et al., 2001). In the westernmost part of the area, near the Atlantic coast, the folds are tight and overturned. At the scale of the outcrop, their axial plane is underlined by a metamorphic foliation with an E–W stretching lineation, compatible with the sense of transport (Belfoul et al., 2001). The intensity of the deformation decreases rapidly eastward and the Cambrian strata are only affected by large tens of meters-scale folds with a westward steeply dipping fracture cleavage, mainly visible in pelitic levels. Further east, in the Goulmine Plain, 15 km from the Atlantic shoreline, the Middle Cambrian strata are only slightly tilted. In the Bas Draa inlier, the crystalline basement remained practically undeformed in the course of the Variscan orogeny. By contrast, the base of the sedimentary cover was deformed due to the uplift of the rigid basement along the southeastern limit of the inlier (Soulaimani et al., 1997). In the Bani area (Fig. 3), disharmonic folds affecting the Cambrian limestones are concentrated in some detachment levels at the base of the cover (Helg et al., 2004). Above, the Cambrian-Ordovician sandstones are affected by kilometre- scale open and box-folds, slightly overturned southeastward and associated with an incipient cleavage in their hinges. The Jbel Rich tens of meters-scale wavelength folds developed in the Devonian sandstones is often asymmetric: their southern flanks are sub-vertical or in reverse position, their axes are subhorizontal and they display a regional en-echelon structure. South of the Oued Draa, the Upper Devonian shales are the southernmost formation of the Anti-Atlas that is affected by metre-size folds; the Jbel Ouarkziz Carboniferous strata is only slightly tilted toward the south, at the northern border of the Tindouf bassin. North of the Bas Draa domain, the Lakhsass Plateau area is located between the

Ifni and Kerdous inliers. There, the Hercynian structures result from an E–W regional shortening. They are particularly developed along old reactivated fractures in the centre of the area, as on both limbs of the Jbel Inter anticline. The prominent fabric in the cover rocks is a pervasive cleavage, axial-plane to tight or isoclinal upright folds. On both sides of this zone, the deformation decreases laterally toward the inliers around which the unconformable Palaeozoic sedimentary cover is only gently tilted to the centre of the plateau. Northeast of the Kerdous inlier, the Irherm-Tata area is a large-scale open folded zone where wide synclines cored by Middle Cambrian are separated by narrower uplifted inlier anticlines. The structural pattern of the Variscan folds seems erratic and it would suggest successive folding episodes. However, no refolded axis or cleavage plane is observed in the field. Moreover, there is a regional distribution of the various trends that are controlled by vertical dominant motion of reactive crustal faults like, for instance, the Tata fault (Hassenforder, 1987; Faik et al., 2001; Caritg et al., 2004). Fig. 3. Geological sections across the north western part of the Anti Atlas domain (see location on Fig. 2). 2.1.2.2. Central and eastern Anti-Atlas. In the Bou Azzer inlier, the crystalline basement did not suffer any noticeable ductile deformation in the course of the Hercynian orogeny. By contrast, its sedimentary cover was folded, locally affected by an incipient cleavage and, more importantly, it was detached by a decollement from its basement. The resulting Hercynian structure is a large scale NW–SE box anticline. Vertical reactivation of basement fractures is suggested by the concentration of the deformation along the inlier borders, which laterally decreases toward the adjacent Cambrian syncline (Leblanc, 1975). South of the Tinghir oasis, the Palaeozoic rocks are affected by several thrust faults that dip gently northwards. After Hindermeyer (1954) and Choubert (1959); Michard et al. (1982) distinguished several allochthonous units overlapping a southern autochthonous sequence apparently undetached from the Sahgro Precambrian basement. Such southward overthrusting tectonic structures extend to the east, since several thrusts affect the Neoproterozoic cover along the northern side of the Ougnate inlier and in the Tafilalt subsurface. Generally, in the Anti-Atlas domain, the Hercynian metamorphism is weak, from very low grade to low grade, in the range of 150–300 [1]C (Buggisch, 1988; Soulaimani, 1998). It may be explained by deep sedimentary burial beneath more than 10 km of Paleozoic overburden. 2.2. The northern domains (Fig. 4 and Table 1) 2.2.1. The Sehoul zone Initially defined by Pique´ (1979, 1982), the Sehoul zone outcrops to the east of Rabat in a small area but it can be followed northward under the Gharb Cenozoic deposits. Its contact with the Meseta is a faulted zone trending N80–120[1] E (The Rabat Tiflet Fault Zone, RTFZ). The Sehoul zone is made of Cambrian pelites and greywackes, with a minimum exposed thickness of several hundred metres. Sedimentological observations suggest a shallow but subsident deltaic environment (El Hassani, 1990). The rocks have been subjected to a tectono-metamorphic episode that gave way to the development of E–W trending folds, recumbent and overturned to the south, accompanied by a cleavage contemporaneous with a low-grade regional metamorphism. Deformation and metamorphism increase towards the south, from anchizonal domain (illite crystallinity data, Pique´, 1979) with spaced cleavage to epizonal domain (chlorite and biotite) with slaty cleavage. The metamorphism has been dated at 453 ± 8 Ma (K/Ar on micas; El Hassani et al. 1991). The Tiflet granite emplaced within the slates at 430 ± 3 Ma (Rb–Sr method; Charlot et al., 1973). These data indicate an orogenic episode, coeval with the Caledonian orogeny. This is the only evidence for a Caledonian imprint in Morocco, except in the continental margin off El Jadida, where borehole data show that a Cambrian granodiorite has been mylonitized around 455 Ma (K–Ar method, Kreuzer et al., 1984 in Ruellan, 1985). This suggests that a ‘‘Caledonian'' beltwraps around the northwest Meseta (El Attari, 2001; Fig. 4). The folded and metamorphosed Cambrian slates and the Tiflet granite were thrust upon the Meseta prior to the deposition of Late Silurian strata that unconformably lie upon the granite. Elsewhere, the slates are unconformably covered by fluviatile conglomerates of Lower Visean age (Pique´, 1979; El Hassani, 1990). In the Sehoul zone S.S., the Hercynian deformation was weak and limited to its southern margin, reactivated and also thrust onto the Meseta; it can be connected with the slight thermal event which has been dated at 320 Ma (K/ Ar on mica) in the Sehoul region and in the El Jadida margin.   Fig. 4. The main structural zones of the northern domain (Meseta s.l.) with the most important variscan inliers 1: Sehoul Zone (a) and its likely prolongation to the west (b) with ‘‘Caledonian'' events. 2: Coastal Block: lower and middle Paleozoic, weakly deformed. 3: Central Meseta: lower to upper Paleozoic with carboniferous pull-apart and foreland basins, strongly deformed by variscan phases. 4: Southern Zone: lower to upper Paleozoic similar to the southern domain (Anti-Atlas), moderately folded by the variscan phases. 5: Eastern Zone: lower and middle Paleozoic deformed by eovariscan events, small carboniferous basins with calcalkaline volcanism. 6: Internal zones of the Rifian chain. Main structural limits: RTFZ: Rabat-Tiflet Fault Zone, WMSZ: Western Meseta Shear Zone, SOFZ: Smaala-Oulme`s Fault Zone, TBBFZ: Tazekka–Bsabis– Bekrit Fault Zone, APTZ: Atlas Paleozoic Transform Zone. 2.2.2. The coastal block This zone corresponds to the coastal Meseta, i.e. the western parts of the Central, Rehamna, Jbilete and Atlasic Ancient massifs. Subsurface data of the Palaeozoic basement hidden by the flat and thin younger sedimentary cover allow drawing the main structures between these massifs (Fig. 2). The main characteristics of this zone are the following: – The Precambrian basement is scarcely present at the outcrop. It is represented by acidic and intermediate volcanic and volcano-clastic formations, the El Jadida rhyolites (Gigout, 1951; Corne´e et al. 1984, 1985). These rocks can be compared to the Anti-Atlas Ouarzazate formations with which they share the same geochemical high K calc-alkaline affinity (El Attari, 2001). – The Lower Cambrian rocks are, like in the Anti-Atlas, limestones and dolomites. These thin strata are dated by Archeocyaths in the western Jbilete massif. Above, the Middle Cambrian is represented by greywackes and pelitic rocks. Their variable thickness (1000–6000 m) and the distribution of the depocentres suggest that they accumulated in a NNE–SSW trending graben (Bernardin et al., 1988). Indeed, the intercalated volcanic flows and basaltic dykes (Gigout, 1956) yield the characters of a within-plate alkaline series (El Attari, 2001; Ouali et al., 2000). This extensive episode took place within the post-rift deposition of uppermost Mid-Cambrian sandstones and quartzites and thin politic and sandy Upper Cambrian horizons (Andre´ et al, 1987). – After a sedimentary hiatus during the Tremadocian, the Ordovician strata (800–1000 m thick) were deposited in a shallow marine platform submitted to the storm waves (Hammoumi, 1988). They begin with Arenigian micaceous shales, followed by Llandeilian and Caradocian sandstones and quartzites. Ashgillian microconglomeratic shales are indicative of a periglacial environment (Destombes and Jeannette, 1966). – The Silurian sequence is thin (100–150 m) and mainly represented from the Llandoverian by Graptolitic black shales directly lying on the Ashgillian or even Caradocian strata. Some carbonates are present in the Wenlockian and especially the Ludlowian. The beginning of the Silurian corresponds to a marine transgression during which shallow and non oxygenated waters invaded again the considered area. Mafic lavas are intercalated in the Silurian rocks in the Oum er Rbia valley (Corne´e et al., 1985). They are intraplate, anorogenic, alkaline Basalts (El Kamel et al. 1998). – The Lower Devonian (Lochkovian-Praguian) is represented by limestones and shales deposited in a more or less subsident marine shelf. A true carbonate shelf with many reefal buildings developed since the late Emsian and it lasted during the Mid-Devonian (Eifelian- Givetian) and the beginning of the Frasnian Its central part rose up and constituted a NNE–SSW oriented emerged ridge during the Late Devonian. Note that such a positive trend occurred since the Silurian, as indicated by the transgressive direct contact of the Lower Devonian strata upon the Caradocian rocks in western Jbilete (Beun et al., 1986). Anyway, west of the emerged area, a subsident zone acted during the Famennian and at least the Tournaisian as a large dépocentres the latter is known from seismic and subsurface data (Barbu, 1977; Echarfaoui et al., 2002; Echarfaoui, 2003). Broadly speaking, the Hercynian deformation was weak in the Coastal block. The kilometric-scale folds, NNE–SSW trending, are ordinarily upright or overturned towards the west, rarely towards the east. From west to east, the rocks are affected by an increasing penetrative cleavage and metamorphic grade (Pique´ and Wybrecht, 1987) (Fig. 5). The eastern limit of the Coastal block is therefore affected by an important deformation, especially in the Rehamna and Jbilete massifs, where folds and west-verging thrusts are associated to right-lateral wrench-faults, allowing defining theWestern Meseta shear zone (WMSZ: Pique´ et al., 1980). The timing of the tectono-metamorphic activity is not precisely determined. Affecting Late Devonian rocks, it should be post-Devonian. However, a recent interpretation of seismic data in the Doukkala basin suggests that the Devonian and Carboniferous rocks, only mildly deformed, unconformably blanket a substratum affected by NNE–SSW folds and thrusts identical to the structures known at the surface (Echarfaoui et al., 2002). This observation suggests that at least a part of the Hercynian structures of the Coastal block have developed early.   Fig. 5. Simplified geological section across the northern mesetian domain (see location on the Fig. 2). P3: Neoproterozoic; Cb: Cambrian; O: Ordovician; Si–D: Silurian to Middle Devonian; UD–LC: Upper Devonian, Lower Carboniferous; V–N: Visean–Namurian; W: Upper Westphalian; A: Autunian; c: granito?¨ds. S1: eovariscan cleavage, S2: main variscan cleavage. SBB: Sidi-Bettache Basin, AKB: Azrou-Khe´nifra Basin. 2.2.3. The Central Meseta This zone covers the main parts of the Central, Rehamna and Jbilete Mesetian massifs, the Atlasic Ancient massif and the Tamlelt inlier in the Atlas Mountains. It is limited to the west by the Western Meseta shear zone; to the north by the Sehoul zone, to the south by the Tizi nTest fault zone; and to the east by the Tazekka– Bsabis–Bekrit fault zone (TBBFZ). Two subzones must be distinguished, separated by the Smaala-Oulmes fault zone (SOFZ) the Western Central Meseta and the Eastern Central Meseta (Figs. 2 and 4). The Precambrian basement is, like in the Coastal block, represented by felsic volcano-clastic rocks. Neoproterozoic granitoids crop out scarcely in the Eastern Central Meseta (Za?¨an Block; Morin, 1960, 1962, in Michard, 1976; Allary et al., 1976; Bouabdelli, 1989; Verset, 1988; Cailleux, 1994). Above, the Lower and Middle Cambrian strata (600 m) are limestones and marbles covered by slates and greywackes with intercalated tuffs and tholeiitic basaltic flows (Ouali et al., 2001, 2003). They are themselves covered by a thick series (3000 m) of quartzites in which Acritarchs date from the lowermost Ordovician (Cailleux, 1994). In the Western Central Meseta, the Neoproterozo?¨c basement is visible as metarhyolites in the Rehamna (Corsini et al., 1988a), dated at 593 ± 8 Ma (U/Pb on zircons, Baudin et al., 2003) and granodiorites in the High Atlas of Marrakech dated at 598 ± 5 Ma (U/Pb on zircons Eddif, 2002); and the Cambrian is represented by thick slates in the core of the anticlines. Like in the Coastal Block, the first Ordovician rocks have an Arenigian age and their deposit succeeded to a hiatus during the Tremadocian. In the Western Central Meseta, the stratigraphic succession (Llanvirnian and Llandeilian pelitic rocks followed by Caradocian quartzites) is similar to that of the Coastal block facies, indicating a similar shallow marine platform. Further to the east, however, in the Eastern Central Meseta, the sedimentary facies are more distal and deeper; the Caradocian and the Ashgillian facies are argillaceous and turbidites are present in the autochthonous series of the Eastern Jbilete (Hammoumi, 1988). North of the Meseta, in a narrow stripe in tectonic contact with the Sehoul zone (The Rabat Tiflet zone, Table 1), the Ordovician is only represented by Arenigian-Llanvirnian pelitic rocks. Its main characteristic is to yield evidences of a mafic magmatic activity, basaltic flows and doleritic dikes (Pique´, 1979). The Silurian rocks are similar to those of the Coastal Block, with Llandoverian black shales and phtanites. To the west, the first levels are detrital. Above, the limestones beds increase in importance up to the Ludlowian and Pridolian. South of the Sehoul zone, the upper Silurian rocks lies directly upon the Arenigian rocks, indicating an earlier uplift of this area. Toward the west of the Cent ral Meseta, the Lower Devonian is represented by clastic, conglomeratic and locally by fluviatile deposits, characteristic of the development of a tectonic instability (Corne´e et al., 1987a, b; Corne´e, 1989; Mayol and Muller, 1985; Hollard et al., 1982). Toward the north of the Central Meseta, the Lower Devonian is not represented. The first Devonian deposits are Emsian in age. They contain conglomerates with granitic pebbles probably extracted from the Tiflet granite (Charrie`re and Regnault, 1989). Elsewhere in the Western Central Meseta, the observed Lower and Middle Devonian facies suggest an open marine shelf. Undifferentiated at the beginning, its paleogeography became more complicated through time. The limestones were predominant since the Praguian and reefal buildings were widespread from the Emsian to the Frasnian, with a maximum extension during the Givetian (Termier, 1936; Pique´, 1979; Zahraoui, 1991; Tahiri, 1991; Chakiri, 2002). Some clastic, often turbiditic sediment indicate deeper areas within the shelf (Razin et al., 2001). In the Eastern Central Meseta, Allary et al. (1976); and Bouabdelli (1989), among others, distinguished autochthonous and allochthonous Devonian series. The autochthonous facies are indicative of a shelf, inner or outer, and a slope where evidences of sedimentary gliding and resedimentation increase during the Upper Devonian. The allochthonous facies correspond to sediments which were deposited further to the east: the Praguian and Emsian rocks are thick turbiditic sequences; the Middle and Upper Devonian are slope deposits similar to those of the autochthonous series. At the end of Devonian times, rapid changes, known as the ‘‘Famennian revolution'' (Pique´, 1975) occurred in the Western Central Meseta. In the Central Massif, where they have been extensively studied, and coarse clastic rocks: conglomerates, rock fall deposits, debris flows, olistostromes and proximal turbidites were deposited during the Famennian and the Tournaisian upon Devonian limestones. These Devonian limestones are often involved as olistholiths in the chaotic sedimentation. Laterally, these deposits grade to more distal argillites and sandstones (Pique´, 1979; Zahraoui, 1991; Tahiri, 1991; Tahiri and Hoepffner, 1988; El Hassani, 1990; Izart et al., 2001a). Since Pique´ (1979), these chaotic facies are considered to delineate the borders of the incipient late Devonian-Carboniferous Sidi-Bettache basin (SBB). The basin limits are the western boundary of the Coastal Block, the southern limit of the Sehoul zone and the Zaer-Oulmes anticlinal zone (Figs. 3 and 6). Some volcanic flows are associated to the peripheral zones of the SBB. Their geochemical affinity is transitional to alkaline (Kharbouch et al., 1985; Kharbouch, 1994). The SBB is thought to have a southern prolongation in the Rehamna (Hollard et al., 1982; Destombes et al., 1982) and Jbilete (Bordonaro et al., 1979; Mayol and Muller, 1985) massifs. In the Eastern Central Meseta, the Tournaisian is represented by conglomerates, discordant upon the Middle Devonian rocks (Bouabdelli, 1989). During the Lower Visean, clastic rocks (1000–2000 m) were deposited in the SBB inside a shallow but subsident shelf (Pique´, 1979; Izart, 1991) and in the Eastern Central Meseta, inside another subsident area, named the Azrou-Khenifra basin (AKB; Bouabdelli, 1989). The Upper Visean transgression deposited a wide range of sediments that cover all the areas of the Central Meseta, with variable facies and thicknesses. Several environments are distinguished: (i) marine shelves where clastic sediments were deposited and reefs built. Such deposits are often discordant on the underlying strata from the Lower and Middle Palaeozoic. They occur in the Eastern Central Meseta (Zaian area) and in the Western Central Meseta (Zaer-Oulmes area) (Table 1); (ii) basins or elongated NE–SW trending depocentres, where thick clastic sequences of Upper Visean and Namurian ages accumulated. In Western Central Meseta, the SBB was still active, from the Central Massif to the Jbilete (Bordonaro et al., 1979; Beauchamp and Izart, 1987). Eastward, beyond the Smaala-Oulmes fault, the AKB is marked by an important tectonic activity, especially at its eastern margin. Here, the olistostromes that were deposited have been related (i) to the emplacement of gravity-driven nappes gliding toward the AKB from its eastern uplifted margin (Huvelin, 1977; Allary et al., 1976; Bouabdelli, 1989; Jenny and Le Marrec, 1980; Jenny et al., 1989), (ii) to some extension faults (Beauchamp and Izart, 1987; Izart et al., 2001b; Verset, 1988; Berkhli et al., 2000), or (iii) to the dislocation of shelves by extension faults at the nose of a duplex complex moving from east to west during the Visean–Namurian (Benabbou, 2001a,b; Benabbou et al., 2001). A mafic magmatism accompanied the development of these basins. Within and near the Jbilete massif intrusive rocks, trondhjemites, gabbros and dolerites were emplaced (Bordonaro et al., 1979; Aarab, 1995; Kharbouch, 1994; Essaifi, 1997). Further to the north (Rehamna, Fourhal), volcanic flows and doleritic sills and dykes (Hoepffner, 1982; Kharbouch, 1994; Remmal et al., 1997; Remmal, 2000; Benabbou, 2001a,b; Roddaz et al., 2002; Ntarmouchant, 2003) yield a transitional to tholeiitic affinity (Kharbouch, 1994; Remmal, 2000), although a calc-alkaline trend is evidenced in the northeast of the Fourhal area (Roddaz et al., 2002). Fig. 6. Simplified geological section across the Tamlelt inlier (from Houari and Hoepffner, 2000; location on Fig. 2). P3: Neoproterozoic, Cb: Cambrian; O–Si: Ordovician and Silurian; Cb–O: Cambrian-Ordovician (eastern zone); M: mesozo?¨c cover (High Atlas). S1: eovariscan cleavage, S2: main Variscan cleavage. The final filling of the Mesetan basins occurred during the Namurian and the Lower Westphalian, when the very shallow, marine shelf emerged and when the Meseta was subjectedto the last stage of the Hercynian deformation. The Upper Westphalian is represented in Central Morocco by the Sidi Kassem continental red beds (Termier, 1936). Resting unconformably upon the Hercynian folds, they are affected by open folds and thrusts, suggesting that the Late Westphalian was still a period of syntectonic sedimentation (Benabbou, 2001a, b; Hoepffner et al., 2000; Razin et al., 2001). The true post-tectonic strata are continental beds dated from the Stephanian in the Atlas Palaeozoic massif (Broutin et al., 1989) and the Jbilete and Haouz massifs (Essamoud and Courel, 1996). Elsewhere, the first discordant sequences are red conglomerates, sandstones and argillites (El Wartiti, 1990; El Wartiti et al., 1990) that were deposited in restricted basins during the Autunian (Lower Permian). These sedimentary rocks are associated to andesites, dacites, rhyolites and ignimbrites (Cailleux et al. 1986; Youbi et al. 1995). The geochemical affinity of these magmatic rocks evolves from calc-alkaline for the oldest to alkaline for the youngest, according to variations in the mechanisms responsible for the opening of the Permian basins (Doblas et al., 1998). The Hercynian deformation started early, at the end of Devonian times, and lasted during most of the Carboniferous. – An Early Variscan phase corresponds to the opening of the SBB and AKB at the limit between the Famennian and the Tournaisian-Visean period. Pique´ (1979); and Bouabdelli and Pique´ (1996) interpreted these basins as transtensive areas bounded by NE–SW transcurrent faults or faulted zones: the Western Meseta shear zone, the Smaala-Oulmes fault and the Tazekka–Bsabis–Bekrit fault (Figs. 2 and 7), which acted at that time as positive flower structures and determined the development of sedimentary ridges. Besides, a tilted block tectonics is often assumed (Tahiri, 1991; Zahraoui, 1991; Bouabdelli and Pique´, 1996). Compressive deformations, responsible for the development of cleavage, folds (Tahiri, 1991) and limited thrusts (Cailleux, 1985), attributed to the stacking of slices (Benabbou, 2001a,b), can be reconciled with the flower structure model along these faults. – The Visean deformations (330–320 Ma; K/Ar on micas, Huon et al., 1987, 1988) are depicted in the Eastern Central Meseta. At the eastern margin of the AKB, the structure is a conspicuous cleavage, axial plane of N30[1]E folds, recumbent toward the west, followed by thrusts directed towards the same direction. The eastern part of the AKB was deformed at that time. Its dépocentres migrated toward the west, in the Fourhal basin, which was attained during the Namurian-Westphalian (Bouabdelli and Pique´, 1996). Propagating folds in a duplex system (Benabbou et al., 2001) may have play a role in this deformation migration. In the southern part of the Fourhal Basin, the pre-Visean (Neoproterozoic to Ordovician) rocks of the ‘‘Zaian block'' display N–S folds (Fig. 2). The associated cleavage, more or less developed, is flat-lying. Upper Visean sequences unconformably cover the pre-Visean deformed rocks (Fig. 5). The pre-Visean structures are interpreted as the result of the deformation of the basin bottom during its initiation. East of the AKB, and in its southern prolongation (Jbilete and Ait Tamlil massifs), several nappes, respectively verging to the NW and the SW were emplaced between the end of the Upper Visean and the Namurian-Westphalian. The mechanism of their individualization is attributed to gravity slidings (Allary et al., 1976; Huvelin, 1977; Bouabdelli, 1989; Jenny and Le Marrec, 1980; Jenny et al., 1989). These allochthonous units are made of Ordovician, Silurian-Devonian and Visean rocks. All of them are free of any pre- or Visean deformation, suggesting therefore the initial decollement of the sedimentary sequences predated the development of these deformations in their original location, i.e. the eastern zones. Fig. 7. Opening model of the Carboniferous basins (from Bouabdelli and Pique´, 1996) 1: Sidi-Bettache and Azrou-Khe´nifra basins. 2: Eovariscan structures and vergence (eastern zone—EZ). 3: Suspected eovariscan structures in the anticline zones. 4: Strike-slip along the main faults. CB: Coastal Block; SZ: Sehoul Zone. – The Late Carboniferous deformations affected the whole Central Meseta. Considered as the ‘‘major phase'' by Michard (1976), they post-dated the Westphalian and they predated the Stephanian-Permian. Small neoformed micas developed during this deformation yielded K/Ar isotopic ages between 300 and 290 Ma (Huon et al., 1987). This deformation is complex and polyphased. The general direction of the folds is NNE–SSW to NE–SW (Fig. 2). The regional anticlines and synclines correspond, respectively to the former sedimentary ridges and depocentres that had previously controlled the sedimentation, even for the N70[1] E to N110[1] E folds along the Sehoul zone, and the N–S to N140[1]E folds in the western part of the SBB. The folds and the ductilebrittle associated thrusts are verging to the west and the NW from the High Atlas to the Rehamna massif. In the Central Massif, the structures are SE facing from the Sidi Bettache syncline to the Fourhal syncline (Fig. 5). This can be interpreted: (i) as the result of a polyphased deformation; the SE facing structures are more recent since they affected the Upper Westphalian rocks, which are discordant upon NW vergent folds (Razin et al., 2001); (ii) as a change in the dip of the deep structures that controlled the deformations (Cailleux, 1987); or (iii) as antithetic folds and thrusts in a globally NW facing regional structure (Bensahal, 2001; Benabbou, 2001a, b; Benabbou et al., 2001). The intensity of the deformation is highly variable. Generally, cleavage and metamorphism are absent in the Carboniferous rocks of the synforms, while both grade towards the antiforms, where a conspicuous cleavage is observed, coeval with a low-grade metamorphic evolution. The most important deformations are located in the Rehamna massif, where they are associated to a medium-grade metamorphism (kyanite-staurotide). This culmination of the metamorphic grade and of the associated deformation has been related to a high thermal gradient during the deformation that combined ductile thrusts and wrenchfaulting (Hoepffner et al., 1982; Lagarde and Michard, 1986; Pique´ and Michard, 1989; Essaifi et al., 2001). Moreover, the piling up of symmetamorphic nappes or slices likely played a role in the burial of the Palaeozoic rocks (Corsini et al., 1988b; Diot, 1989). A subsequent exhumation resulted from the inversion of the ductile thrusts (Baudin et al., 2003). The Late Carboniferous tectono-metamorphic events were accompanied by the emplacement of granitoids whose ages are considered to be between 320 and 270 Ma (Mrini et al., 1992). The granitic magmas injected in the upper crust along the sinistral

NNE–SSW and dextral ENE–WSW crustal shear zones, interfering with the regional deformation (Diot, 1989; Lagarde, 1989; Lagarde et al., 990). Three magmatic associations (calc-alkaline, subalkaline and peraluminous) are distinguished by Gasquet et al. (1996). They characterize a post-collisional tectonic regime and the granitoids are mainly of crustal origin. The most recent granites are Permian in age and they present an alkaline (Mabkhout et al., 1988) or nearly alkaline (Gasquet et al., 1996) affinity. – The last Hercynian compression affected the Stephanian and Permian deposits. They are weak and consist of open folds and brittle shears in a compressive regime oriented first E–W then NW–SE to N–S (A?¨t Brahim and Tahiri, 1996). 2.2.4. The eastern zone The eastern zone corresponds to the Eastern Meseta inliers from Midelt to Oujda, further east in Western Algeria, and to some Atlasic inliers such as the Tazekka and north Tamlelt massifs (Figs. 2 and 4). The oldest rocks, attributed to the Cambrian on the basis of facies similarities (Hoepffner, 1987), crop out in the Tazekka, Midelt and north-Tamlelt massifs. They are made of slates and greywackes with mafic intercalations. Among them the Midelt amphibolites correspond to old intraplate alkaline basalts (Ouali et al., 2000). The Ordovician is represented by sedimentary rocks indicative of a shallow sea. Sandy pelitic rocks, dated from the Arenigian-Llanvirnian in several inliers (Hoepffner, 1977; Rauscher et al., 1982; Torbi, 1996), are covered by sandstones and quartzites attributed to the Upper Ordovician. The Silurian sequences are thin (150 m) and they often have been squeezed by the Hercynian deformations. Their base is made from Llandoverian phtanites. Then the Wenlockian and the Ludlowian are represented by argilites and graptolitic black shales (Hoepffner, 1987). Note the lack, here, of the limestones present in more western Upper Silurian strata. The Devonian sequence starts with Lochkovian rocks identical to those of the Ludlovian. Here, slumps and ball and pillow sedimentary structures in the sandstones testify the instability of the shelf. Above, a thick detrital sequence, sometimes turbiditic, is made of argillites and greywackes. It is represented in most of the inliers, from the Tazekka to western Algeria. Their age, determined by palynomorphs, is Praguian to Givetian-Frasnian (Marhoumi et al., 1983), suggesting the development of a turbiditic basin during the Devonian. The clastic character of the Devonian sedimentation distinguishes the eastern zone from the Western Meseta and its carbonate shelf. The only turbiditic Devonian sequences observed in the Western Meseta arepresent in the allochthonous units of central Eastern Meseta, which originated in the eastern zone. Note that, in spite of the volcano-clastic facies of the greywackes, no true volcanic rock, tuff or flow, has been observed. The oldest Carboniferous rocks are conglomerates and bioclastic limestones, unconformable upon older rocks deformed by the Eo-Variscan Phase (Hoepffner, 1987). They are dated from the Upper Visean (Me´dioni, 1980; Huvelin and Mamet, 1989; Berkhli et al., 1999). Above them, a thick volcano-clastic sequence is made of pyroclastites and epiclastites associated to intermediate to felsic flows: andesite, dacite, rhyolite and ignimbrite (Hoepffner, 1981; Huvelin, 1986; Chalot-Prat, 1990). The volcanic activity lasted up to the beginning of the Namurian. A contemporaneous faulting is deduced from chaotic facies developed at that time (El Ghazi and Huvelin, 1981; Huvelin, 1986; Torbi, 1996), the faults having controlled the development of the volcano-clastic basins (Chalot-Prat, 1990). The magmatism is calc-alkaline, similar to that of the active margins (Kharbouch, 1994). However, there is no other evidence for an active subduction of the oceanic lithosphere during the Carboniferous and its occurrence is therefore questionable, consequently, the geodynamical setting of this calc-alcaline magmatism remain in debate (See Section 3.2.1). Anyway, the sea withdrew to the East, in the Jerada basin, from the Namurian to the upper Westphalian. Initially marine, the sedimentation became paralic since the Westphalian B (Izart, 1991; Desteucq et al., 1988; Essamoud and Courel, 1998). In the eastern zone, the Hercynian deformation was polyphased. – The oldest compressive events are attributed to the socalled Eo-Variscan phase. They gave way to flat-lying and stretched folds, accompanied by a well developed slaty cleavage. The axes are oriented NNE–SSW, N–S, and NW–SE (Figs. 2 and 5). Their vergence is generally towards the west (Hoepffner, 1987; Houari and Hoepffner, 2000). The metamorphism, generally lowgrade, was more intense at Midelt, where biotite and garnet crystallised. The age of the Eo-Variscan phase is dated at 366 Ma in Midelt (Rb/Sr, Clauer et al., 1980) and at 368–372Ma in Debdou-Mekkam (K/Ar on micas: Huon et al., 1987). – The Visean deformations are evidenced in the Tazekka massif, at the limit between the Western and Eastern Central Meseta. Folds and west-vergent thrusts with small displacements are associated to a conspicuous cleavage and a low-grade syntectonic metamorphism dated at 330 Ma (K/Ar on micas: Huon et al., 1987). Note that elsewhere in the Eastern Meseta; this period corresponds to the initiation of the volcano-clastic basins. This is also at that time that the oldest granitoids of eastern Meseta were emplaced: in the Tazekka (Huvelin, 1992), in Midelt (333–319 Ma; U–Pb on zircons: Oukemeni et al., 1995), and SW of Oujda (328– 321 Ma; Rb/Sr, Mrini et al, 1992). – The late Hercynian deformations affect the Carboniferous rocks and overprint their substratum. They are folds and thrusts, NE–SW to E–W oriented (Fig. 2). Their vergence is often to the north like at Jerada (Erraji, 1997). The associated metamorphism remained weak. These deformations post-dated the Westphalian, as confirmed by isotopic ages at 300 Ma (K/Ar on micas; Huon et al., 1987). Following Mrini et al. (1992), granite emplacement ended afterwards, since the isotopic ages given by these authors are within the 286–247 Ma age interval. 2.2.5. The Rifian–Kabylian zone This zone includes the inner massifs of the Alpine Rifian–Kabylian belt, which are made of Palaeozoic sequences and probably older crystalline rocks. These rocks are included in several Alpine allochthonous units; such are for instance the Ghomarides and Sebtides in the Rif's belt. All these rocks belong to the allochthonous Alboran ‘‘terrane''. However, they present several similarities with the autochthonous NE Moroccan and NW Algerian units. In the Ghomarides, the Ordovician and Silurian are represented by shelf sequences where a volcanic activity is noted, becoming important at the Silurian-Devonian boundary. In Kabylia, the oldest dated Palaeozoic rocks represent the Cambrian (Baudelot and Ge´ry, 1979) or the Tremadocian (Baudelot et al., 1981). According to Bossie`re (1980), they unconformably cover an older basement. They are covered by Arenigian-Llanvirnian sequences. The Lower Paleozoic shelf was disrupted during the early Devonian. Bourrouilh et al. (1980); and Chalouan (1986) described from north to south a carbonate and reefal shelf, a slope and a turbiditic basin. Contemporaneous volcano-clastic and volcanic rocks are known in the Middle Devonian of Kabylia (Ge´lard et al., 1978). In the Rifian Ghomarides, the Upper Visean–Naurian beds unconformably overlie deformed older Palaeozoic rocks. The succession of the environment was the same as in the Devonian, leading again from proximal turbidites and olistostroms to the north to distal turbidites in the south, indicating therefore the southward deepening of the basin (Chalouan, 1986). The Hercynian deformation was polyphased. The EO- Variscan phase, pre-Upper Visean in age, is described in the Kabylia (Bouillin and Perret, 1982) and analyzed in the Rif (Chalouan, 1986). It developed folds facing to west and northwest, and a low-grade regional metamorphism. The Upper Carboniferous phase was mild. The folds are NW–SE and E–W and their vergence is variable. In Kabylia, late Hercynian granitoids were emplaced around 270–280 Ma (U–Pb on zircons, Peucat et al. 1996). The similarities between the Rifian–Kabylian Palaeozoic zones and the eastern Morocco and northwestern Algeria have been emphasised by Chalouan (1986); Hoepffner (1987); and Pique´ et al. (1993). The correlations are based mainly on the existence of a Devonian turbiditic basin and the development of the Eo-Variscan phase. They suggest that the Rif and Kabylia were the prolongation of NE Morocco and NW Algeria during the Palaeozoic, at the northwestern margin of the Paleo-Gondwana. Note, however, that the crustal extension revealed by the mafic volcanic activity was probably more important in the Rif and the Kabylia. On the other hand, the Carboniferous calcalkaline magmatism was less important there than in NE Morocco and NW Algeria. 2.2.6. The southern zone This zone includes the centre and the south of the Tamelelt inlier, the region of Tineghir and the Skoura inlier (Figs. 2 and 4). It marks the transition with the Anti-Atlas domain. It is situated in the High Atlas and its southern border. Its limit with the Central Meseta zone and the Oriental Zone is not observable except in the north of the Tamelelt inlier (Fig. 6). The Precambrian is represented by Neoproterozoic flows and volcanoclastic rocks. During the Lower Palaeozoic, from Cambrian to Devonian, the considered area received detrital and carbonate sediments that were deposited on a platform showing more analogies with the Anti-Atlas than with northern domains (Destombes et al., 1985; Wendt, 1985; Houari, 2003) with the notable absence of any of magmatic activity. Carboniferous rocks are absent in the Tamelelt, Tineghir and Skoura areas. However, during the Carboniferous detrital sediments were deposited on the subsident northern margin of the Saharan shield. From the Tournaisian to the Namurian-Westphalian, deltaic deposits grade northward into olistostromes and turbidites (Michard et al., 1982; Izart et al., 1989; Soualhine et al., 2003). A communication probably existed north of Skoura with the Ait Tamlil turbiditic basin, and therefore with the Central Meseta zone. The absence of the Carboniferous magmatism is another distinctive feature of this zone which is a thus rather part of the sub-cratonic domain. The Hercynian structures are E–W folds and overlaps directed towards the craton. At Tamelelt (Fig. 6), the deformation resulted from a combination of thrusting and strike-slip faulting. The folds are overturned to the SSE and associated to E–W dextral shears, parallel to the contact with the eastern zone (Houari and Hoepffner, 2000, 2003). The cleavage is rough or slaty, the metamorphic grade is weak (sericite-chlorite). At Tineghir, the folds and thrusts, southward-directed, are typical of a foreland deformation (Michard et al., 1982). At Skoura the structures are also E–W. Beyond, the Southern Zone links westward with the N80[1] E Tizi nTest fault zone, through the N120[1] E Skoura fault (Ouanaimi and Petit, 1992). These faults underline the direct contact between the northern Mesetan domain and the Anti-Atlas domain. These deformations are attributed to the Late Carboniferous phase known in the other zones. 3. The North African Hercynides: Geological and tectonic characters 3.1. The development of the Hercynian orogeny 3.1.1. The deformation 3.1.1.1. Ages Within the Hercynian belt of Morocco and adjacent areas, stratigraphic and structural arguments issued from field observations and isotopic datings lead to distinguish four major tectono-stratigraphic events (Pique´ and Michard, 1989; Pique´, 2001): (1) a first event, coeval with the Caledonian deformation of Europe, is dated at 450–430 Ma. It is known in the Sehoul zone, in the northernmost part of the Moroccan Meseta. Besides, some disturbances occurred at that time in the Coastal Block and the Northern Moroccan Meseta. The docking of the Sehoul zone with the Moroccan Meseta by thrusts and/or transcurrent faulting occurred prior to the Late Silurian; (2) the Eo-Variscan deformation, 372–366 Ma in age, is well developed in the Eastern Meseta of Morocco, in western Algeria and in the Rifian–Kabylian blocks; (3) the Intra-Visean deformation developed at 330 Ma in the Tazekka and the Eastern Central Meseta of Morocco; (4) the Late Carboniferous event, between 300 and 290 Ma, corresponds to the second folding phase in the eastern zones of Morocco and in the western Algeria, and to the main folding in the Western Moroccan Meseta. This suggests that the deformation became younger from east to west, since the Late Devonian to the Late Carboniferous. Exceptions to this general rule are the Pre-Upper Visean deformations in the Central Moroccan Meseta basins, which probably initiated the development of sedimentary ridges bordering the depocentres. Such a deformation is also suspected in the subsurface of Western Morocco. Actually, the isotopic ages suggest a continuum of the regional shortening, moving westward rather than discontinuities between distinct tectonic events separated by episodes of stress relaxation. In the Anti-Atlas, the age of the Hercynian deformation is not accurately determined. The regional contrast between the Bani and Rich folded strata and the Ouarkziz unfolded sequences is not an unconformity but a progressive transition from the weakly deformed domain of the southern Anti-Atlas to the undeformed Carboniferous sequences at the northern border of the Tindouf platform (Soulaimani et al., 1997). The Hercynian deformation could be contemporaneous with a thermal event depicted at around 290 Ma (Bonhomme and Hassenforder, 1985). 3.1.1.2. Amount of the shortening. At the scale of Morocco, the southern domain, where the shortening is relatively weak, differs from the northern zones, more intensively deformed. In the relatively strongly deformed northern domain, we distinguish: (1) the pre-Upper Visean phases during which the deformation was homogeneous and accompanied by a generalised metamorphism. West-verging recumbent folds were interpreted as the result of a crustal thickening (Hoepffner, 1987; Pique´ and Michard, 1989). However, the Midelt granitoids have been considered to have emplaced during a Visean crustal thinning (Diot and Bouchez, 1989) that have been thought to moreover control the main deformations (Filali et al., 1999); (2) the Late Carboniferous deformation was heterogeneous, especially in the Central Meseta and the Coastal Block. It was concentrated along relatively narrow and elongated domains generally corresponding to the former sedimentary ridges. There, the main structures are narrow folds, incipient to well developed cleavage, and ductile shear zones, which indicate a transpressive regime. The most noticeable shear zones are the WMSZ dextral and west-vergent thrust, the SOFZ wrench- and thrust fault, and the ATPZ dextral and south-vergent all along the southern limit of the High Atlas (Fig. 4). The resulting pattern is a contrasted orogenic domain, constituted by poorly deformed to undeformed wide areas separated by regional shear zones, themselves characterised by a relatively intense deformation and an important metamorphic grade. At depth, these structures are probably accommodated by ductile thrusts, one of which is exposed in the Rehamna metamorphic zones (Michard et al., 1989; Pique´ and Michard, 1989; Aghzer and Arenas, 1995). In the Anti-Atlas, the Hercynian shortening was at the origin of the reactivation of Precambrian blocks and of disharmonic folds within the Palaeozoic strata. It was also accommodated by many detachment and decollement levels. It differs clearly from west to east. (1) In the Western Anti-Atlas, the southeasterly verging shortening was relatively important, as evidenced by the stacking of metamorphic slices and the ductile deformation affecting the base of the cover, especially beyond the reactiv basement fractures. An amount of about 15–20% for the horizontal shortening is deduced from the restoration of the Western folded Bani (Helg et al., 2004). (2) On the contrary, the Central and Eastern part of the Anti-Atlas are characterized by a very weak and heterogeneous deformation, concentrated along restricted faulted zones that separate undeformed or only tilted wide areas. Values of 5–10% for the Hercynian shortening are given by Leblanc (1975); and Hassenforder (1987). Globally, the amount of deformation decreases progressively towards the south and the southeast and it vanishes within the undeformed and stable Tindouf platform, a part of the West African craton. 3.1.1.3. Vergence and virgations of the structures. During the Eo-Variscan phase in Northern and Eastern Morocco and in Western Algeria, the structures, foliations and thrusts, delineate a regional virgation (Figs. 2 and 7). This virgation seems to have controlled later the Intra-Visean deformation, with a west-directed vergence in the northern part and a south-directed vergence in its southern part. In the Western Central Moroccan Meseta, the trend of the regional structures is NNE–SSW to NE–SW. The variations, locally observed like in the Sidi Bettache basin area (Fig. 2) result from an en-echelon setting between ductile NNE–SSW shear zones, as well as the role play by some rigid buttresses like the Sehoul zone (Fadli, 1990). In the western Anti-Atlas, the folds and thrusts are typically east- to south-east verging. In the Central and Eastern Anti-Atlas, like in the Tinerhir area, the folds and thrusts are south-facing (Fig. 2). Roughly, the structural vergence of the Anti-Atlas Hercynian structures is directed towards the West African craton. From the Zemmour to the Ougarta, the craton acted as an apron, along which the Hercynian folds are moulded. 3.1.1.4. Control of the Hercynian deformation by the basement structures. In the Central Moroccan Meseta, the regional shear zones are located at the limits of the late Devonian-Carboniferous basins such as the SBB (Pique´, 1979). In other words, the wrench/thrust ductile shear zones are reactivations of synsedimentary faults. The magmatic activity recorded along the basin limits suggests that they correspond to deep-seated faults. Similar observations are made for the Smaala-Oulmes fault. Eastward, the Tazekka–Bsabis–Tazekka faulted zone corresponds to the eastern limit of the AKB, intensively deformed (Bouabdelli, 1989). From the Tazekka massif to Oujda, NE–SW to ENE–WSW faults controlled the trend of the compressive structures. There also, the associated magmatism (Kharbouch, 1994) indicates the crustal character of these faults (Hoepffner, 1987; Torbi, 1996). In the Anti-Atlas, the trend of the Hercynian structures was inherited from Proterozoic fractures by the rigid reactivation during the uplift of the basement blocks. This control was strict at the regional scale, allowing therefore partial decoupling of the basement from its cover, where local decollement occurred (Fig. 3). 3.1.2. ‘‘Inner'', ‘‘outer'' zones and pericratonic domains;   The kinematics of the Hercynian deformation by many aspects, the Palaeozoic evolution of the Northern and Southern domains of Morocco presents important differences: – To the South, the Palaeozoic sediments were deposited on a relatively stable shelf, at the northern margin of the Reguibat shield. This cratonic platform, dislocated during the Late Proterozoic-Lower Cambrian rifting, became relatively stable during the Palaeozoic. The heterogeneous Hercynian deformation, globally weak except in the Western Anti-Atlas and the Zemmour, occurred during the development of a very low-grade metamorphism, without any magmatic activity. – To the North, the marine platform was instable during the Cambrian, with the initiation of a graben in the Western Moroccan Meseta. Since the Famennian ‘‘revolution'', it was broken and disintegrated by the development of the late Devonian-Carboniferous subsidents basins. The deformation was largely controlled by the basement architecture. It developed differently in the Eastern and the Western parts of the Moroccan Meseta. The Eo-Variscan phase, which is the main Hercynian deformation event in the eastern zone of Morocco and western Algeria, testifies for the initiation of regional stresses in these areas. It is suggested that the same stress field was also responsible for the initiation of the pullapart SBB and AKB in more western zones, which opened through transcurrent motions along NNE–SSW trending crustal faults (Fig. 7 and Hoepffner, 1987; Bouabdelli and Pique´, 1996) the end of the transcurrent motion along the Tazekka–Bsabis–Bekrit fault was the result of its activation as a west-vergent thrust during the Middle Carboniferous. Then, the deformation moved westward, reaching the Fourhal and Sidi-Bettache foreland basins during the Namurian and the Westphalian. By its earlier deformation and the general vergence of the structures toward the Carboniferous foreland basins, the Eastern Moroccan Meseta (and northwest Algeria) is therefore considered as the ‘‘inner'' zone of the Hercynian belt in North Africa, while the Central and Western Morocccan Meseta represent the ‘‘outer'' zones of this belt. Such a distinction is useful but we must note that the term ‘‘inner zone'' does not imply here the existence of a highpressure metamorphism and of remnants of a continental collision. Even if the deformation is noticeable in its Western part, it is globally weak and no Hercynian granitoids are known in the Anti-Atlas, which can be regarded as a pericratonic domain. It is noticeable that in the Anti-Atlas, the deformation is stronger to the west, which is the opposite of what is observed in the Meseta, where the more deformed zones are located to the east. The actual relation between Anti-Atlas and the Moroccan Meseta is not yet deciphered. However, the boundary is probably the Atlas Palaeozoic transform zone (APTZ): Pique´ and Michard, 1989), which is a very important and long-lived shear-zone. This zone separated these two domains since the Lower Palaeozoic, as a part of a transfer fault joining the southern and the northern branch of the Late Precambrian–Cambrian rift (Pique´ and Jeannette, 1981). The Hercynian shortening, larger to the north than to the south of the fault, was accommodated by a sinistral motion along this fault during the Eo-Variscan and intra- Visean deformations. Later, during the late Carboniferous phase, the collision of the two domains occurred through the reactivation of the APTZ as a right-lateral and southverging thrust. During this deformation, recorded in the Southern Mesetan zones, the Anti-Atlas acted as the Hercynian southern foreland. 3.2. The tectonic development of the Hercynian orogeny 3.2.1. The North African Hercynides: An intracontinental belt   The Hercynian belt results from the continental collision between the Paleo-Gondwana to the south, and the Laurentia-Baltica to the north (in present coordinates) after the disappearance of oceans (Matte, 1986, 2001). Several microcontinents, or microplates, such as Armorica, Avalonia, etc. participated to the general scheme (Fig. 9). A fundamental question concerning the position of the Moroccan and Western Algerian orogenic segment in the Hercynian belt is the presence or not, of remnants of the oceans. From palaeomagnetic studies in Cambrian and Ordovician flows in the Western Meseta and the comparison of data given by stable Africa and the Anti-Atlas, Feinberg et al. (1990) suggested that an ocean, several thousand kilometres wide, separated the Moroccan Meseta from the Anti-Atlas during the Lower Palaeozoic. It would have been progressively resorbed during the Silurian and the Devonian and the subduction-collision process would have been achieved during the Carboniferous. Subsequent palaeomagnetic studies proved the inaccuracy of this model (e.g. Khattach et al., 1995). Moreover, the total lack of volcanic activity during the Devonian testifies for the absence of any subduction of an oceanic lithosphere under the Meseta domain during the Middle Palaeozoic. The study of the Carboniferous flows in the Moroccan Meseta and their relationships with the Hercynian structures afford the most accurate tools to give valuable arguments allowing geodynamical models. The Visean–Namurian volcanic rocks are typically calc-alkaline and associated to early deformations in the Eastern Moroccan Meseta and Western Algeria, while they are transitionalalkaline or tholeiitic and associated to the initiation of sedimentary basins in the Central Moroccan Meseta (Kharbouch, 1994). From this, two models have been proposed (Fig. 8):   Fig. 8. Geodynamical models for the Moroccan Hercynides (Middle Carboniferous). Subducted oceanic crust: A from Kharbouch et al. (1985); B from Roddaz et al. (2002). Intracontinental shear zones, C from Kharbouch (1994); and Pique´ (2001). 1: continental crust; 2: upper mantle; 3: oceanic crust; 4: calc-alkaline magmatism; 5: alkaline to tholeitic magmatism. CB: Coastal Block; SBB: Sidi Bettache Basin; AKB: AzrouKhenifra Basin. (1) The calk-alkaline magmatism is related to the subduction of a lithospheric plate plunging to the west under the Moroccan Meseta. This subduction would have been active during the Carboniferous (Boulin et al., 1988), or it would have ceased since the Eo-Variscan phase, giving way to a continental subduction (orogenic prism) during the Carboniferous, the oceanic lithosphere being ‘‘fossilized'' under the Meseta (Kharbouch et al., 1985; Roddaz et al., 2002). In this model, all the Meseta is characterized by Carboniferous retro-arc foreland basins where the structural vergence is opposite with regard to the subduction plane dipping. Such a model implies the existence of an oceanic lithosphere to the east of Morocco. This is hardly compatible with the absence of ophiolitic complexes, subduction-related metamorphism and syn-collisional granitoids. (2) The calc-alkaline volcanism of the Eastern Meseta and Western Algeria is related to movements along transcurrent/thrust shears deeply seated in the crust (Lagarde, 1989; Kharbouch, 1994; Pique´, 1994, 2001). This means that the extensive regime, active several times in the considered domain, especially in its eastern zones during the Devonian, did not give way to an oceanic accretion. In other words, in this model—which seems the more realistic—, the Hercynian belt of Morocco and Western Algeria is an intracontinental segment of the Hercynian belt. It belonged to the margin of the Gondwana all through the Palaezo?c. 3.2.2. Relations of the Moroccan Hercynides with the other Hercynian zones By its location at the northwestern corner of Africa, the Hercynian chain of Morocco and Western Algeria appears to be close to other Palaeozoic belts of the circum-Atlantic realm (Fig. 9). To the South, the Western Anti-Atlas extends into the Zemmour and further into the Mauritanides foreland (Le´corche´ and Sougy, 1978; Le´corche´ et al., 1991). To the West, beyond the present Atlantic Ocean, Hercynian Morocco is at the contact with the Eastern Appalachian zones. Similarities between the geological evolution of the Avalon and Meguma Appalachian zones have been recognised a long time ago (Hughes, 1972). They are explained by their Palaeo-Gondwanian origin and their docking to the Appalachians when the Theic Ocean was consumed (Pique´, 1981; Pique´ et al., 1990; Pique´ and Skehan, 1992). To the Northeast, the relationship with the European Hercynian belt is obscured by the Alpine orogeny and the opening of the Mediterranean Sea. Moreover, from Upper Carboniferous to Permian, great dextral wrenchfaults cut up the chain allowing the westward displacement of Africa and the separation between North Gondwana and Western Europe (Bard, 1997). Therefore, it is difficult to connect the North African and European Hercynides, especially the Moroccan and Iberian Mesetas. Comparisons between North Africa and Europe have however been made early (e.g. Gentil, 1918; Lecointre, 1926). Stratigraphical and structural evidence indicate the Paleo-Gondwanian origin of many European zones (Iberian Meseta, Central and Northern French Armorican massif, southern Germany, etc.). Anyway, by its sedimentary column, the age and the intensity of its main deformations, the Hercynian belt of Morocco and Western Algeria is to be compared (even for its eastern zones) to the External zones of the Hercynian belt, devoid of any oceanic signature (Pique´ and Michard, 1989). Finally, according to the similarities between Eastern Moroccan Meseta, Palaezoic Rifian–Kabylia massifs, Western Mediterranean palaezoic blocks and Alpine external massifs, the Morroccan Hercynides belong to the southern limit of the Hercynian belt, near the Gondwana (Pique´ et al., 1993; Bard, 1997).   Fig. 9. Possible configuration of the periatlantic Paleozoic orogens in Permian time (from Matte, 2001; Houari and Hoepffner, 2003). 1: Gondwanan stable blocks (West African Shield); 2: Parts of Avalonia and Armorica microplates; 3: Carboniferous foreland basins); 4: main sutures (Is: Iapetus suture; Ts: Theic suture; Bs: Beja suture; CCsz: Coimbra-Cordoba shear zone; LRHs: Lizard Rheno-Hecynian suture; TPs: Tepla suture; GSBs: Galicia South- Brittany suture). NAF: North Appalachian Front; NVF: North Variscan Front; Me: Meguma Zone and: Caledonian terranes (like Sehoul Zone); CB: Coastal Block; CM: Central Meseta; EZ: Eastern Zone; AA: Anti-Atlas; Ma: Mauritanides belt. 4. Conclusion The present review of the sedimentological evolution and the Hercynian orogeny throughout Palaeozoic areas of Morocco and adjacent Algeria, reported in this paper, lead us to define several structural zones which sedimentological and structural features are briefly summarized below. (1) The Palaeozoic evolution presents important differences between the Northern and Southern domains of Morocco; (i) To the South, the Palaeozoic sediments were deposited on a cratonic platform (Reguibat rise), relatively stable during the Palaeozoic since the Late Proterozoic-Lower Cambrian rifting; (ii) To the North, the marine platform was unstable during the Cambrian Rifting in the Western Meseta and it disintegrated by the development of the late Devonian-Carboniferous subsident basins. The architecture resulting from these extensional episodes is critical for the understanding of the subsequent control of the Variscan structures that individualized in the course of the Eo-Variscan and late Carboniferous compressive deformations. (2) Within the Hercynian belt of Morocco and Algeria, four major tectono-stratigraphic events are recorded: (i) ‘‘Caledonian'' event (450–430 Ma) known only in the Sehoul zone in the northernmost part of the Morocco (ii) Eo-Variscan deformation (372–366Ma) developed in the Eastern Meseta, the western Algeria and the Rifian–Kabylian blocks; (3) Intra-Visean deformation (330 Ma) in the Tazekka and the Eastern Central Moroccan Meseta; (4) Late Carboniferous event (300 and 290 Ma), second folding phase in the eastern zones, and to the main folding in the Western ones and probably in the Anti-Atlas. (3) Two episodes characterised the Major Hercynian shortening, relatively more important in the northern domain than in the Anti-Atlas: (i) the pre-Upper Visean phases in the Eastern Morocco and Eastern Algeria, giving way to a homogeneous deformation accompanied by a generalised metamorphism and west-verging recumbent folds, (ii) the Late Carboniferous heterogeneous deformation, in the Central Meseta and the Coastal Block, concentrated along relatively narrow and elongated domains marked by isoclinal folds, incipient to well developed cleavage, ductile shears zones (WMSZ,APTZ, . . .) and westvergent thrusts (SOFZ). (4) In the Anti-Atlas, the Hercynian deformation is largely governed by the reactivation of Precambrian blocks uplift that induced regionally variable disharmonic folds trend within the Palaeozoic strata. The east-southeast verging fold-and-thrust in its westernmost side contrasts with the folded cover that wraps Precambrian NE–SW linear inliers in the rest of the chain. The southeasterly verging Hercynian deformation decreases progressively toward the southeast and vanishes within the undeformed Tindouf platform, a part of the West African craton. (5) In the lack of any ophiolitic complexes of the Paleo-Tethys Ocean, subduction-related metamorphism and syn-collisional granitoids, the Hercynian belt of Morocco and Western Algeria appears to be an intracontinental segment of the Hercynian belt. (6) By its location at the northwestern corner of Africa, the Hercynian chain of Morocco and Western Algeria is close to other Palaeozoic belts of the circum-Atlantic realm, the Mauritanides belt to the South, the Eastern Appalachian zones to the West and the European Hercynian belt to the Northeast. All these orogenic belts define a broadly synchronous circum-Atlantic Hercynian–Alleghanian belt developed during the Late Paleozoic Paleo–Gondwana–Laurentia–Baltica collision.

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