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RESEARCH PAPER

Late Hercynian tectonic evolution of the Jebilet Massif (Western Meseta, Morocco) based on tectono-sedimentary analyses of related Permian continental deposits

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Abstract
The Jebilet Massif (Western Meseta, Morocco) consists of Hercynian polyphase deformed basement rocks that are, locally, unconformably overlain by a thick series of Permian siliciclastic sediments. New tectonic and tectono-sedimentary analyses offer the opportunity to propose a refined chronology of late Hercynian events of the study area and to specify the sedimentary environment and geodynamic context of related Permian deposits. In addition to the primary Hercynian structuring, three tectonic episodes are distinguished. (1) A compressive episode of Late Hercynian pre-Permian deposits is expressed by kink bands and chevron folds associated with irregular spaced cleavage. The orientation of the kink bands, their geometry and concentration along the regional faults are in favor of a compression episode in NNE-SSW direction. This deformation is ended by the Permian deposits and also marked by reworked pre-Permian deposits with kink-bands in the basal conglomerates of these deposits. (2) The early Permian tectonic episode is responsible for the opening of N-S striking intramontane basins (Koudiat El Hamra-Haiane, KH-H, and Oulad Maachou, OM) due to E-W extension. These basins are formed as submeridian graben and hemi-graben, delimited by normal faults that separate Permian red-beds from the surrounding Paleozoic basement. The sedimentary basin fillings are mainly represented by alluvial deposits with a late early Permian (Artinskian) to middle Permian (Capitanian) ichnofauna. (3) A post-Permian compressive episode, dated to the upper Triassic-pre-Kimmeridgian, is indicated by folded Permian deposits of KH-H and OM (fold axes striking N0°–N20°), as well as reverse faults representing reactivated submeridian normal faults.

Keywords Late Hercynian events · Permian basins · Sedimentology · Geodynamic · Jebilet

Resumen
El macizo de Jebilet (Meseta Occidental, Marruecos) está formado por rocas de basamento polifásicas hercínicas que, localmente, están superpuestas de manera inconforme por una gruesa serie de sedimentos siliciclásticos pérmicos. Nuevos análisis tectónicos y tectonosedimentarios ofrecen la oportunidad de proponer una cronología refinada de los eventos hercínicos tardíos del área de estudio y de especificar el entorno sedimentario y el contexto geodinámico de los depósitos pérmicos relacionados. Además de la estructuración hercínica primaria, se distinguen tres episodios tectónicos 1) Un episodio compresivo de los depósitos prepérmicos del Hercínico tardío se expresa mediante bandas de pliegues y chevrones asociados a un clivaje irregularmente espaciado. La orientación de las bandas de pliegues, su geometría y su concentración a lo largo de las fallas regionales están a favor de un episodio de compresión en dirección NNE-SSW. Esta deformación está terminada

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por los depósitos del Pérmico y también marcada por los depósitos pre-Pérmicos retrabajados con bandas de pliegues en los conglomerados basales de estos depósitos. 2) El episodio tectónico del Pérmico temprano es responsable de la apertura de cuencas intramontanas de dirección N-S (Koudiat El Hamra-Haiane, KH-H, y Oulad Maachou, OM) debido a la extensión E-O. Estas cuencas se forman como graben y hemigraben submeridianos, delimitados por fallas normales que separan los lechos rojos del Pérmico del basamento paleozoico circundante. Los rellenos sedimentarios de las cuencas están representados principalmente por depósitos aluviales con una icnofauna de principios del Pérmico (Artinskiano) a mediados del Pérmico (Capitaniano). 3) Un episodio compresivo post-permiano, fechado en el Triásico superior-pre-Kimmeridgiano, está indicado por depósitos plegados del Pérmico de KH-H y OM (ejes de plegado con dirección N0° a N20°), así como por fallas inversas que representan fallas normales submeridianas reactivadas.

Palabras clave Eventos hercínicos tardíos · cuencas pérmicas · sedimentología · geodinámica · Jebilet

1 Introduction

The Moroccan Meseta domain known also as the Moroccan Varisc belt represents the southwestern extension of the European Variscan belt, which is partially obliterated by younger Alpine orogeny (Michard et al., 2010). The Meseta domain was structured mainly between the upper Devonian and early Carboniferous during the Laurentia-Gondwana collision (Délchini et al., 2018; Hoepffner et al., 2005, 2006; Michard et al., 2010). It is subdivided into several structural zones, separated by major fault corridors of regional extension (Piqué & Michard, 1981, 1989; Ferrandini et al., 1987; Hoepffner et al., 2005, 2006; Simancas et al., 2009; Michard et al., 2010). From the oldest to the youngest age of the paroxysmal deformation, these structural zones are: the Sehoul block, the Eastern Meseta and the Western Meseta. The latter is further subdivided into the nappe zone, the central zone and the coastal block (Fig. 1). The main Paleozoic basement Massifs in the Western Meseta (study area), lies below the Meso-Cenozoic cover, within the Moroccan Central Massif, Rehamna and Jebilet massifs. Here, the Paleozoic basement is strongly deformed and granitized before the Triassic (Chopin et al., 2014; Marcoux et al., 2015; Michard et al., 2010; Piqué, 1979), and this deformation reaches its maximum intensity in the vicinity of the major fault corridors and in the central areas of Rehamna and Jebilet Massifs. Regarding the latter, which is subject of this study, Délchini et al. (2018) propose an age between 310 and 280 Ma for the major Variscan structuring (D1/D2). The D1 phase is marked by synschiste folds (P1) with axial plane direction N20°–N45°, associated with epizone grade metamorphism along the major fault corridors of Oulad Delim or Western Meseta Shear Zone (WMSZ). The D2 phase is expressed by a crenulation schistosity S2 taking over the S1, accompanied by the emplacement of the leucogranitic intrusions. The global shortening admitted during this major phase is oriented NW-SE to WNW-ESE (Délchini et al., 2018; Lagarde & Michard, 1986; Mayol, 1987).

Following the major Variscan deformation, fracturing phases of Stephano-Permian age has controlled the opening of intramontane basins in the High Atlas, in Jebilet, in Rehamna and in the Central Moroccan massifs (Khenifra, Chougrane, Koudiat El Hamra-Haiane, Argana, Mechra Ben Abbou, Souss and other basins). These basins hosted red-bed detrital sediments from the erosion of deformed basement (Huvelin, 1977; Muller et al., 1991; Aassoumi, 1994; Saber et al, 1995, 1998; Saber et al., 1996; Hmich, 2006; Zouicha et al., 2021). The model proposed for the opening of these basins are still debated, particularly those of the Central Moroccan massifs and the High Atlas, where the tectonic regime during their formation is interpreted as a transtensive regime (Cailleux et al., 1983, 1986; Zouine, 1986; El Wartiti, 1990; Youbi, 1990; Saidi et al., 2002; Domeier et al., 2021).

In the Jebilet Massif, three basins of Permian age are known: the Senhaja Basin in Eastern Jebilet, and the Koudiat El Hamra-Haiane (KH-H) and Oulad Maachou (OM) basins in Western Jebilet (Fig. 2b). These red-bed detrital sediments have been attributed, without paleontological evidence, to the Westphalo-Permian time-interval by facies analogies (Huvelin, 1977). However, ichnological discoveries in the KH-H basin recently provided a late early Permian (Artinskian) to middle Permian (Capitanian) age (Zouicha et al., 2021).

2 Material and methods

The present study focuses on tectono-sedimentary analysis of the late hercynian events in the Jebilet massif. The structural analysis is based on the observation of tectonic structures in different scale (outcrops samples, thin sections, geological map and satellite photos) and the measurements of orientation, plunge and dip (of planes and lineations) of folds and faults. This data was projected on the Wulff canvas—Southern Hemisphere, using the software "Stereonet" for statistical treatment. The interpretation is based on integrating our new data with previous work to establish the chronology of tectonic events.

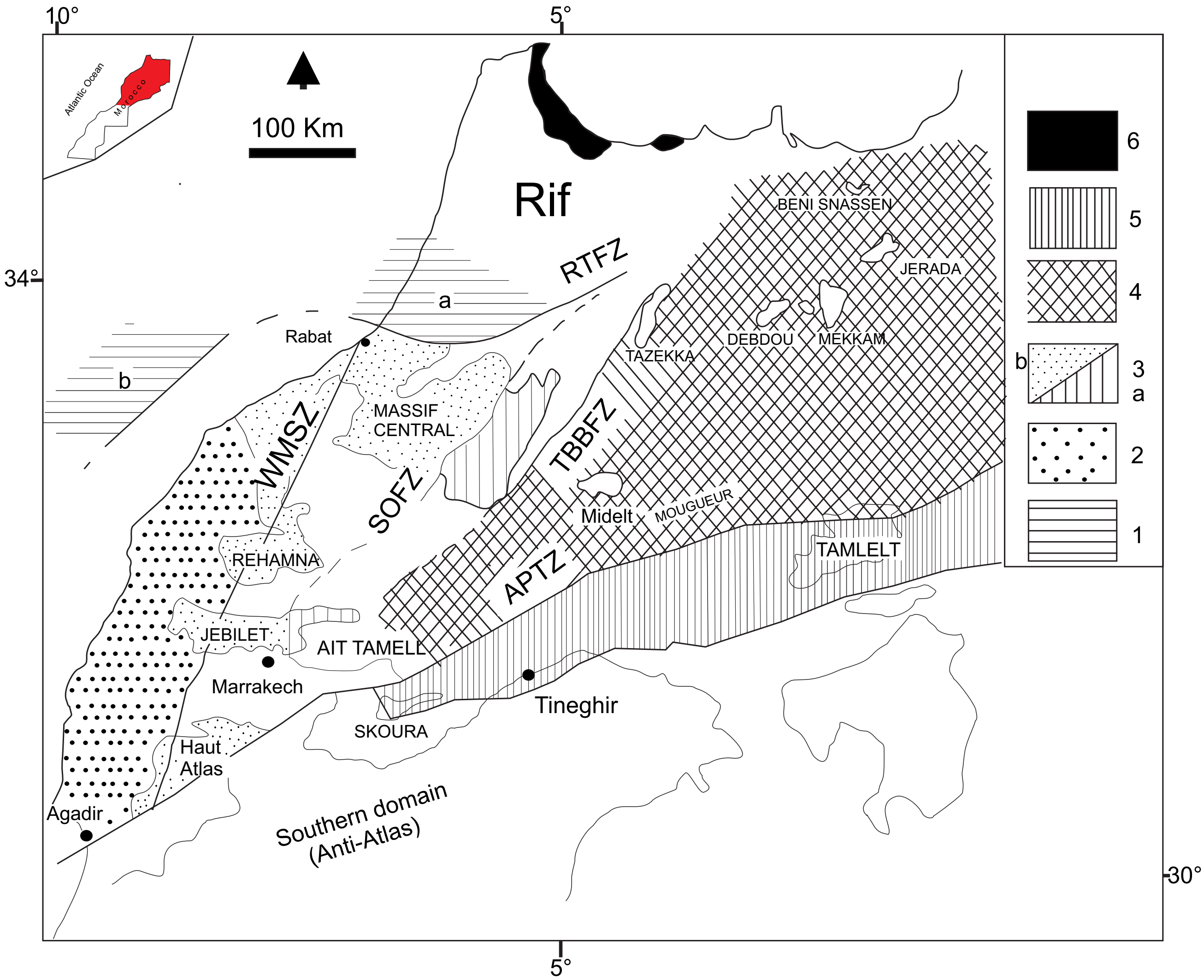


Fig. 1 The main structural zones of the Moroccan northern domain (Meseta) with the most important Variscan inliers (After, Hoepffner et al., 2005). 1: Sehoul Zone (**a**) and its likely prolongation to the west (**b**) with "Caledonian" events. 2: Coastal Block: lower and middle Paleozoic, weakly deformed. 3: Central Meseta; (**a**) foreland basins, strongly deformed by Variscan phases: (**b**) lower to upper Paleozoic with Carboniferous pull-apart basins? 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 calc-alkaline volcanism. 6: Internal zones of the Rifan chain. Main structural limits: *RTFZ* Rabat-Tiflet Fault Zone, *WMSZ* Western Meseta Shear Zone, *SOFZ* Smaala-Oulmès Fault Zone, *TBBFZ* Tazekka–Bsabis–Bekrit Fault Zone, *APTZ* Atlas Paleozoic Transform Zone

The sedimentological study is based on detailed analysis of lithology, grain sizes and sedimentary structures from KH-H and OM basins and three formations are designed: Koudiat El Hamra, Haiane and Oulad Abberahman formations and this formations names are derived from the closest villages. The interpretation of sedimentary data is based on facies association according to Miall (1977–1988) and completed by Freyete (1964, 1969, 1984) for the lacustrine environments. The integration of tectonic and sedimentological data allow reconstituting the tectono-sedimentary evolution of Permian basins in relation with late-hercynian tectonic evolution of Jebilet massif.

3 Geological setting

The Variscan Jebilet Massif located to the north of Marrakech town is one of the main Paleozoic massifs of the Moroccan Meseta domain. It consists of folded and metamorphosed Paleozoic rock basement, unconformably overlain by

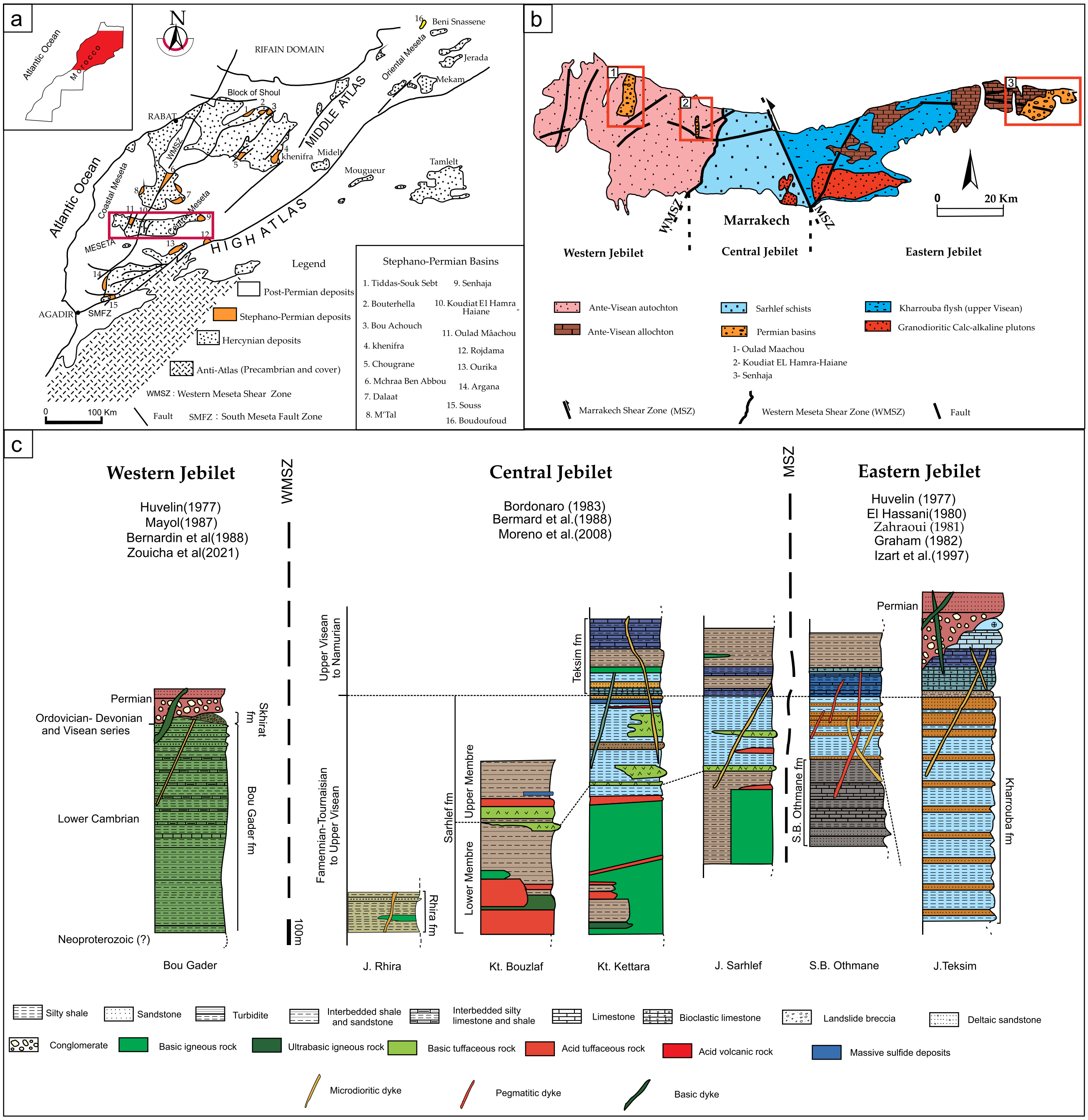


Fig. 2 Geological maps synthetic lithostratigray of the Westphalo-Permian basins of the Jebilet Massif. **a**: location of the study area (red square) in the center of Morocco. **b**: Simplified geological map of the Jebilet Massif with location of studied areas signaled by red squares. **c**: Synthetic lithostratigraphic logs of the Jebilet massif for each tectonic zone (Western, Central and Eastern Jebilet) according to previous studies (Huvelin, 1977; El Hassani, 1980; Zahraoui, 1981; Graham, 1982; Bordonaro, 1983; Mayol, 1987; Bernardin et al., 1988; Bermard et al., 1988; Izart et al., 1997; Moreno et al. 2008; Zouicha et al., 2021) and refined by our observations in the field

Permo-Mesozoic and Cenozoic cover. Based on lithology and deformation intensity, the Jebilet Massif has been subdivided into three structural units, separated by major shear zones (Bouloton & Le Corre, 1985; Essaifi et al., 2001; Lagarde & Choukroune, 1982; Lagarde et al., 1989; Le Corre & Bouloton, 1987) (Fig. 2c).

(1) The Eastern Jebilet Unit, located eastward of the NNW-SSE Marrakech shear zone (MSZ), consists of a succession of marine sedimentary formations (Sidi Bou Othmane, Kharrouba and Taksim formations), ranging in age from Tournaisian to upper Visean-Namurian (Hollard et al., 1977; Huvelin, 1977; El Hassani, 1980; Beauchamp, 1984; Délchini et al.,

2018). This unit is characterized by synsedimentary tangential tectonic (Huvelin, 1977), and by a weak post-Variscan deformation. In the easternmost part of this unit, the deformed pre-Permian basement is unconformably covered by Permian red-beds of Senhaja basin (Fig. 2b) (Essamoud, 1989; Huvelin, 1977).

(2) The Central Jebilet Unit is delimited by WMSZ and MSZ and is formed by the thick late Visean-Namurian or late middle Visean schist-dominated Sarhlef Formation (Bordonaro et al., 1979; Huvelin, 1977; Playford et al., 2008). According to a biostratigraphic study based on conodonts, Lazreq et al. (2021) recently showed that the age of the Sarhlef Formation is upper Devonian which is, in turn, overlain by the late Visean-Namurian schisto-calcareous Taksim Formation (Bordonaro et al., 1979; Gaillet, 1986; Gaillet & Bordonaro, 1981). The central Jebilet Massif is deformed by intense Variscan deformation (Essaifi et al., 2001; Huvelin, 1977; Lagarde, 1985), associated with outpours of syn- to late-tectonic intense magmatism between 360 and 280 Ma (Délchini et al., 2018; Dostal et al., 2005; Essaifi et al., 2003; Marcoux et al., 2008; Mrini et al., 1992).

(3) The Western Jebilet Unit is made by a thick, weakly deformed Cambro-Ordovician series (Bernardin et al., 1988; Huvelin, 1977). The easternmost border of the Western Jebilet is formed by the lower Cambrian Bou Gader Formation, overlain by the poorly studied Skhirat Formation. The latter consists of Ordovician, Devonian and Visean series (Mayol, 1987). Locally, this basement is covered through a major unconformity by Permian conglomerates (Huvelin, 1977; Zouicha et al., 2021).

4 Variscan and late-Variscan events

The Jebilet Massif as well as other massifs of the Western Meseta is deformed by successive Variscan and late-Variscan phases during the upper Carboniferous to lower Permian. These deformations are geographically heterogeneous and marked by local anomalies in major fault zones (WMSZ, Meserat fault: MF, MSZ) (Lagarde, 1985; Lagard & Michard, 1986; Mayol, 1987; Essaifi et al., 2001; Délchini et al., 2018). The present work suggests that the major Variscan event is the result of a W-E to NW–SE compression developed in a collisional-transpressional context controlled by ductile shear zones (submeridian and ENE). The major Variscan event (D1) in the entire Western Meseta corresponds to axial plane schistosity (S1) of folds (P1) oriented N10°–N45° and regional metamorphism that reaches epizone grade in the central Jebilet (Bernard et al., 1988; Bordonaro, 1983; Délchini et al., 2016; Essaifi et al., 2003; Huvelin, 1977; Playford et al., 2008). The D2 phase is characterized by a crenulation S2 taking over the S1 that has been reported from some areas of the Jebilet Massif in relation to the emplacement of leucogranitic intrusions (Huvelin, 1977; Mayol, 1987). For Délchini et al. (2018), the Variscan deformation in the central Jebilet ends with a localized transpressive event along NNE reverse faults and an anastomosed network of conjugate N70 and N130 shear zones. Based on geochronological data (Mrini et al., 1992; Tisserant, 1977) and metamorphic analysis, Délchini et al. (2018) suggest an age between 310 and 280 Ma for the Variscan deformation, referring to S2 as the late progressive evolution of S1 under a WNW-ESE to NW-SE horizontal shortening.

Despite the numerous previous works in the Jebilet Massif, few data are available on the late- Variscan structures and their relationship with the Permian deposits. According to Huvelin (1977), after the major Variscan folding and granitization in the central Jebilet (Jbel Sarhlef), kink-bands and crenulation have been formed. Late kink-bands have also been reported from some localities of Western Jebilet (Jbel Zaouata) with N70-100 axial planes and are related to late to post-schistosity fracturing (Mayol, 1987). This event producing folds and kink-bands, which also occurs in the central Rehamna (Chopin et al., 2014; El Attari, 2001) and in the Western High Atlas (Ferrandini et al., 1987; Saber, 1998), has not been related to the Westphalo-Permian deposits. Indeed, the Westphalo-Permian detrital deposits exposed in the Western Jebilet are the only units that permit to establish an age limit for the Variscan deformations and to clarify the chronology of late events. This red-bed sedimentary succession was deposited above a major unconformity on the older deformed basement in intramontane depressions and grabens (KH-H and OM basins) bordered by faults, during a late Carboniferous-early Triassic distension episode (Huvelin, 1977; Muller et al., 1991; Zouicha et al., 2021). Saidi et al. (2002) suggest that an NNE-SSW transtensional episode is responsible for the development of these basins along the N70-110° sinistral strike-slip faults, associated with the N05-40° synsedimentary normal faults. This episode is followed by a WNW-ESE compressive one of Permian age, which leads to the closure of the basins and ends the late-Variscan compressive movements.

In order to establish a chronology of these late-Variscan structural events in the Jebilet Massif, the present work focuses on the study of the major post-Variscan deformations and structures in the basement and on the tectono-sedimentary analysis of the unconformably overlying Westphalo-Permian deposits. Thus, and in the light of the new structural and biostratigraphic data, it is possible to calibrate the late-Variscan events with respect to the Permian succession and to specify better the sedimentary environments and the geodynamic framework of these basins.

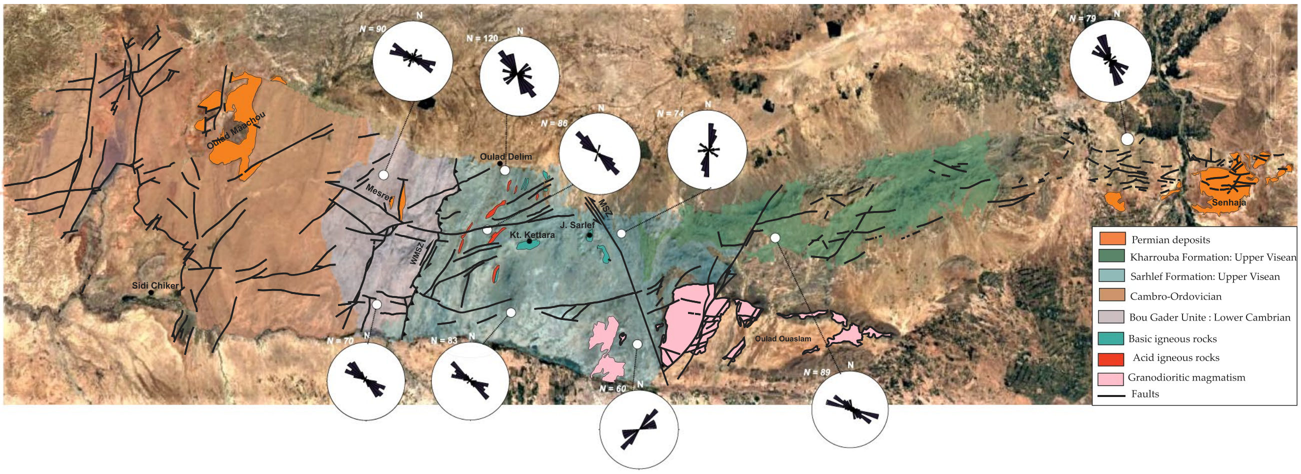


Fig.3 Simplified structural map of the Jebilet Massif showing the orientation of the axial planes of the kink-bands (Google maps)

5 From late variscan to post variscan episode

Three episodes posterior to the major Variscan deformation have been distinguished in the Jebilet Massif. In order to align with the nomenclature of tectonic events described by previous work in the study area (Delchini et al., 2018), we adopt: (i) a compressive phase (D3) occurring during late-Variscan times and before the deposition of the Permian red-beds; (ii) an extensive Permian tectonic episode (D4); and (iii) a post-Permian compressive episode (D5). In the following we describe in particular the D3 episode, then we proceed with a sedimentological and stratigraphic analysis of Permian deposits in the KH-H and OM basins in order to specify their depositional environment and to clarify the relation between these deposits and the D4 tectono-sedimentary structures.

5.1 Compressive episode (D3) pre-Permian deposits

5.1.1 Description

The deformation structures of the D3 episode are heterogeneously distributed throughout the Jebilet Massif. They are expressed mainly as centimetric to decimetric kink-bands and chevron folds (P3), occasionally associated with irregularly spaced cleavage (S3) and reworked regional schistosity (S1) and crenulation schistosity (S2). The geographical distribution of kink-bands in the Jebilet Massif show an extremely high concentration and intensity near the main regional faults: (MSZ) (N160°–N150°), (WMSZ) (N10°) and (MF) (N70°). The structural analysis shows two main groups of kink-bands with subvertical axes: a dominant group with axial planes oriented N120°–N150° and a minor group oriented N20°–N80° (Fig. 3). Their geometry is often simple with monoclinal axial planes, or rarely, with conjugate axial planes (Fig. 4a,c).

The chevron folds range from decimetric to metric scale and are tight close to the major fault zones and their axial planes are oriented N100°–N130° (Fig. 4c–d). The spaced cleavage (S3) is associated with the kink-band and chevron folds in the vicinity of major faults (Fig. 4e), whereas it appears alone away from the major fault (Fig. 4f). In both cases, spaced cleavage (S3) is oriented N120–150° parallel to the axial plane of the kink-band and chevron folds. In addition to isolated or en-echelon quartz veins can be observed in different parts of this zone, their planes are sub-perpendicular to the axial planes of the dominant kink-bands (N120°–N150°) (Fig. 4 g); most are oriented N5° and N45° (Fig. 4 h). Locally, these veins show a shearing movement by their deformation style.

5.1.2 Correlation and discussion of D3

The structural data show that the D3 episode is compatible with a late compressive episode, probably contemporaneous with shearing movements along some major faults. The stereographic distribution of the axial planes of the kink-bands and associated with irregularly spaced cleavage are in favor of NNE-SSW to NE-SW shortening. The quartz veins with planes stretching parallel to this shortening could be related to the episode D3. Elsewhere, further south, in the Western High Atlas, Ferrandini et al. (1987) and Saber (1989) describe simple and conjugate kink-bands favoring a N10°–N30° late-Variscan compression. Similarly, to the north, from central Rehamna, El Attari (2001) reports asymmetric kink-bands that he links to a sinistral component of the N120°–130° strike-slip fault. In addition, kink-bands N70°–N100° trending are also described from the Upper Mouloya and Anti-Atlas where they are related to a shearing movement (Vauchez, 1976; Hoepffner, 1994; Belfoul et al., 2001).

Comparable post-S1 fold structures are reported from the Rehamna and Jebilet massifs with an axial plane oriented NNE (Chopin et al., 2014; Délchini et al., 2018). These authors admit a WNW-ESE to NW-SE shortening, of late early Permian age (280 Ma). Furthermore, the kink-bands described in the present work are also found in reworked pebbles in the basal conglomerates of the Permian deposits. Therefore, we consider the episode D3 as pre-Permian deposits, or, more specifically, pre-Artinskian, according to Zouicha et al. (2021).

5.2 Permian episodes

The end of the Variscan cycle is marked by the deposition of continental red-beds of Permian age that lie unconformably on the intensely deformed Paleozoic basement. The main outcrops of these deposits in the Western Jebilet Massif belong to the Koudiat El Hamra-Haiane (KH-H) and Oulad Maachou (OM) basins (Huvelin, 1977; Saidi et al., 2002; Zouicha et al., 2021). The detailed mapping and tectono-sedimentary study of these two continental basins allow to highlight two tectonic episodes in their geological history: (1) an episode (D4) related to the opening of these basins by distensive regime, (2) an episode (D5) of folding according to a compressive regime, we describe sedimentological and stratigraphic details of the Permian deposits of the KH-H and OM basins in order to clarify their depositional environments.

5.2.1 Sedimentology and stratigraphy of Permian deposits

The KH-H basin is located about 40 km northwest of Marrakech. It is subdivided into two sub-basins: (i) the Haiane sub-basin, about 5 km long and 1 km wide, bounded by N-S faults and (ii) the Koudiat El Hamra sub-basin, triangular in shape and directed N-S with about 2 km long and 500 m wide, and bounded to the west by a submeridian fault. The two sub-basins are separated by an ancient Paleozoic horst (Bou Gader unit and Skhirat unit) that was deformed and metamorphosed before the Permian (Fig. 5a). The Haiane sub-basin is filled by Haiane Formation, which consists of 474 m thick succession of monoclinal layers with a moderate dip of 50° to the west (Fig. 6). The Koudiat El Hamra sub-basin is filled by a heterogeneous siliciclastic sediment of Koudiat El Hamra Formation, with thickness reduction of north to the south (90–200 m). In order to detail the sedimentological characteristics of the Koudiat El Hamra Formation, three S-N oriented stratigraphic sections were described in the Koudiat El Hamra sub-basin (Fig. 7). The Oulad Maachou basin (OM) located at 20 km eastward of KH-H basin, is a residual basin located at a distance of 7 km from Chemaîa city (Fig. 5b). This basin is covering a large area in the middle part of the Western Jebilet Massif, with a very rare exposed outcrops and the bedding planes measured on the isolated beds are trending NNE and dipping either to SE or to NW. The best stratigraphic profile in the OM can be observed near the Oulad Abderrahmane village and exposes up to 240 m thick sedimentary deposits (Fig. 8).

5.2.2 a Facies characterization

The measured sections were subdivided into nine different facies (Table 1) according to the characteristic lithology, primary sedimentary structures and geometry (Miall, 1977, 1978).

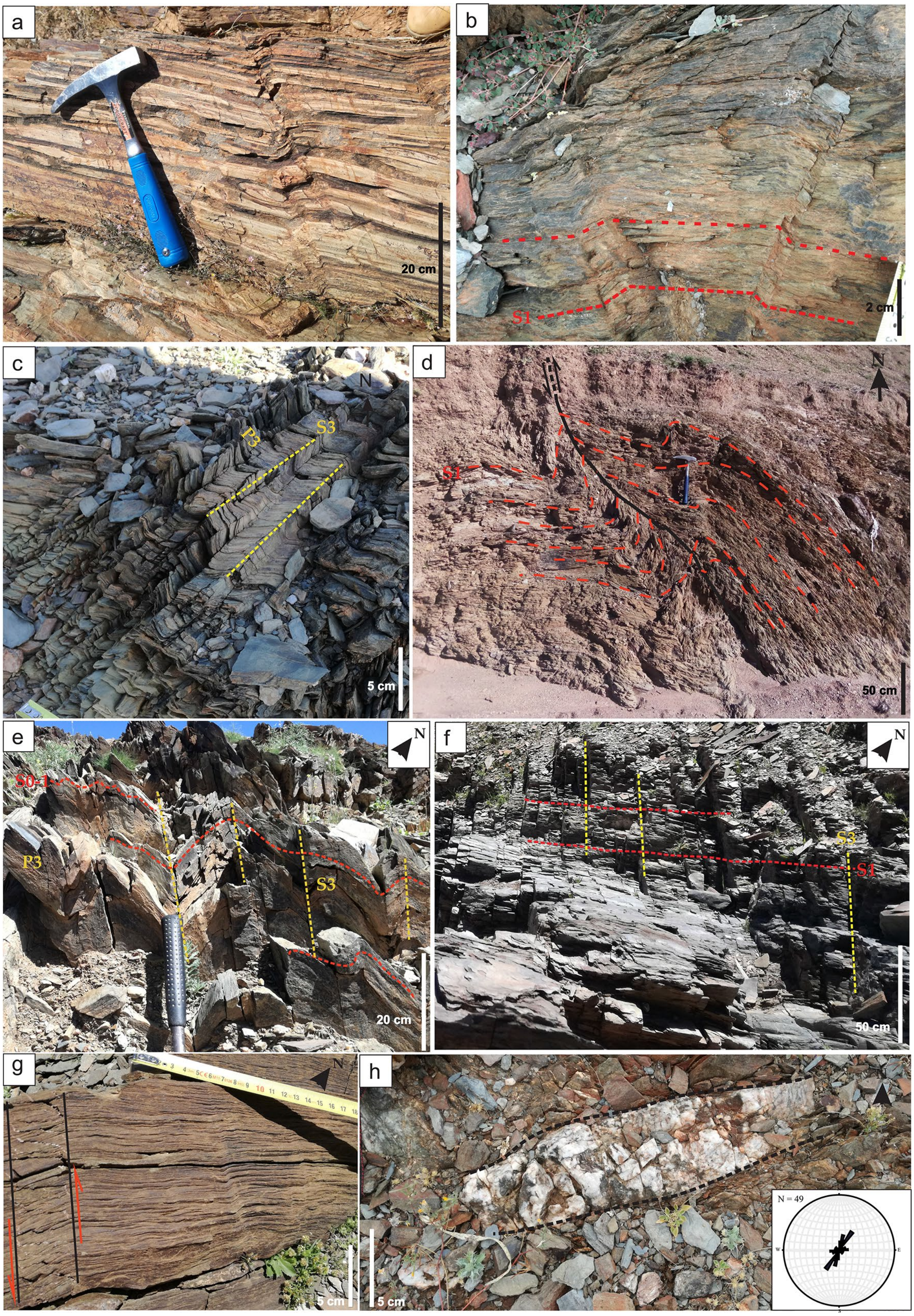
5.2.3 b Facies association

The nine facies described are grouped into five facies associations: Alluvial Fan (FA1), Channel fill (FA2), Crevasse splay (FA2), Flood plain (FA4), Lacustrine to palustrine (FA5).

Alluvial fan facies association (FA1)

This facies association is generally characterized by tabular, massive, matrix-supported conglomerates (Fc1) with normal graded from conglomerate to micro-conglomerate (10 cm–5 m thick) and associated frequent centimetric to decametric lenticular intercalations of massive sandstone (Fc4a) (Fig. 9a). The conglomerate can be laterally traced over hundreds of meters with local erosive base. It consists of poorly sorted gravel elements 0.2–8 cm of meta-sediments (schist, quartzite) and magmatic rocks (gabbro, dolerite and granite) with angular to sub-angular shape, floating in sandstone matrix (Fig. 9b). The bed thickness and size of conglomerate are increasing upward. This facies association is common in Haiane formation, Oulad Maachou formation and in lower part of Koudiat El Hamra formation.

The facies Fc1 is characterized by absence of sedimentary structures with mixture of fine and coarse materials. It suggest that this conglomerate is deposited by high-stream gravity flows at proximal alluvial fan environment (Gms) (Miall, 1978, 1985, 1988; Nemec et Steel, 1984; Oplustil et al., 2005), near steep slopes of lifted structural blocks along the faults (Longwell, 1930; Beaty, 1961; Bull, 1977). The increase in bed thickness and grain size of Gms towards the top of the formation is linked to growing tectonic activity and increasing subsidence (Crowell, 1954). The associated Sm is interpreted as sediments gravity flow deposits, which mainly formed in alluvial fan environment when the hydrodynamics of the flows descended (Blair & McPherson, 1992).


a
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◂**Fig. 4** Field photos showing the deformation event D3 in the Central Jebilet Massif. **a**: simple kink-bands in Kettara area. **b**: conjugate kink-bands in the Ouled Delim area. **c**: chevron folds (P3) in the Sarhlef area. **d**: chevron folds related to strike-slip fault movement in the Sidi Bou Othmane area. **e**: chevron folds (P3) associated irregularly spaced cleavage (S3) Koudiat Aîcha area. **f**: irregularly spaced cleavage (S3). **g**: distorted quartz veins at Jebel Rhira associated with Kink-bands folds. **h**: example of isolated veins quartz with its directions

Channel fill facies association (FA2)

The facies association FA2 consist mainly of 4–20 m thick sandstone facies and occasional associated with conglomeratic facies.

The dominant facies is massive, fine to pebbly sandstone with 3–4 m thick beds that characterized by lenticular shape with concave-up erosional basal (Fc5). The fine to coarse sandstone is organized as 40–80 cm thick bed with parallel lamination (Fc4). The coarse to fine sandstone is massive and show flat boundaries and abundant bioturbation and root of plants (Fc3). The fine sandstone with ripple marks (Sr) constitutes a minor facies of this association (Fc6) (Fig. 9c, d). Massive clasts supported conglomerates (Fc2) are found associated with this facies association. It consists of 0.5–2 m thick lenticular beds with restricted lateral extension and typically poorly to moderately sorted with frequent erosional basal and flattop (Fig. 9e, f). This association are very common in the Koudiat El Hamra and Oulad Maachou formation.

Typically, this facies association started by Fc5 (Ss) or Fc2 (Gcm), graded to Fc4 (Sh) or Fc3 (Sm) and ended by Fc6 (Sr). This association is interpreted to reflect a multi-storey channel-fills deposit of a braided fluvial system (Miall, 1977). This channel is characterized by a high-flow regime, then decease progressively to lower flow regime during the deposition of Fc6 (Sr).

Crevasse splay facies association (FA3)

The FA3 association corresponds to a minor facies, typically less than 2 m thick. It is composed of coarse–fine sandstones (Fc3, Fc4), which are always interbedded with fine sediments of the massive and laminated siltstone-mudstone (Fig. 9g, h).

The fine-medium, massive sandstone is the most dominated facies in this association. It consists of 30–70 cm thick beds with sparse quartz fragments. The upper bedding show desiccation cracks, abundant plant root traces, horizontal straight and sinuous traces ichnofossils bioturbation (*Helminthoidichnites tenuis*, *Scoyenia gracilis*, *Sphaerapus larvalis* and cf. *Spongeliomorpha* isp.). The fine-coarse sandstone is a minor facies of FA3 association. It is characterized by 20–70 cm thick beds with horizontal lamination and planar boundaries. This association is present in Koudiat El Hamra formation and OM. In the Koudiat El Hamra formation, the proportion of FA3 increase from the south to the north.

This deposit is the result of rapid deposition and interpreted as crevasse splay deposits. The presence of structureless sandstone Fc3 (Sm) and Fc4 (Sh) indicate high rates of sediment and rapid deposition (Allen, 1983). The presence of bioturbation as *Scoyenia gracilis* and *Spongeliomorpha* isp indicate a low energy environment.

Floodplain facies association (FA4)

The FA4 association is dominated by laminated mudstone (Fc7) (Fig. 10a) with minor beds of massive siltstone-mudstone (Fc8). The facies (Fc7) is 1.5–12 m thick with large lateral extension (up to hundred meters). It is characterized by horizontal lamination, rare bioturbation and the presence of raindrops impression and mud cracks (Fig. 10b). The massive siltstone-mudstone consist of 2–7 m thick beds extend for up to hundred meters in lateral extension. This facies is highly bioturbated (Fig. 10d) with abundant burrows, plants roots, vertebrate tracks and show the calcareous concretions. It is very developed in the northern part of the Koudiat El Hamra formation and in OM, whereas it is very reduced in the Haiane formation.

This association is deposited in a floodplain environment (Miall, 1985). Facies Fc7 is the equivalent of Fl in Miall (1996) and indicates suspension deposits from a long-lived stagnant water body in a floodplain (Miall, 1985, 1988). Desiccation cracks, raindrops and bioturbation indicate the periodic subaerial exposures (Bull 1977). Fc8 with calcareous concretion, devoid of lamination and traces of root plants indicates the effect of pedogenesis (Freytet, 1964). This facies is equivalent to the Fp of Miall (1977) and is interpreted as a paleosole or floodplain with pedogenesis ascendants.

Lacustrine facies association (FA5)

This facies association is composed of massive limestone to sandy limestone (Fc9). The massive limestones is limited to the southern part of the Koudiat El Hamra sub-basin and consists of a 6 m thick succession of 20–40 cm beds (Fig. 10e, f). The external geometry of the beds is generally lenticular and its lateral extension is restricted (maximum of 20 m). Sporadically, the limestone beds are intersected by centimetric lenses of conglomerate (Fig. 7H). The sandy limestone is observed in the southern part of the Koudiat El Hamra sub-basin, but also present episodically in the northern part. It is a succession of 1–6 m thick, with each bed delimited by a flat to undulating horizontal surface.

This facies association is interpreted as the deposits of lacustrine to palustrine environments (Freyted 1964, 1969, 1984; Freytet & Plaziat, 1978). The considerable thickness of FA5 might be the result of successive tectonic subsidence (Freyte, 1964). This lacustrine environment is marked by an episodic gravitational influences presented by an erosive

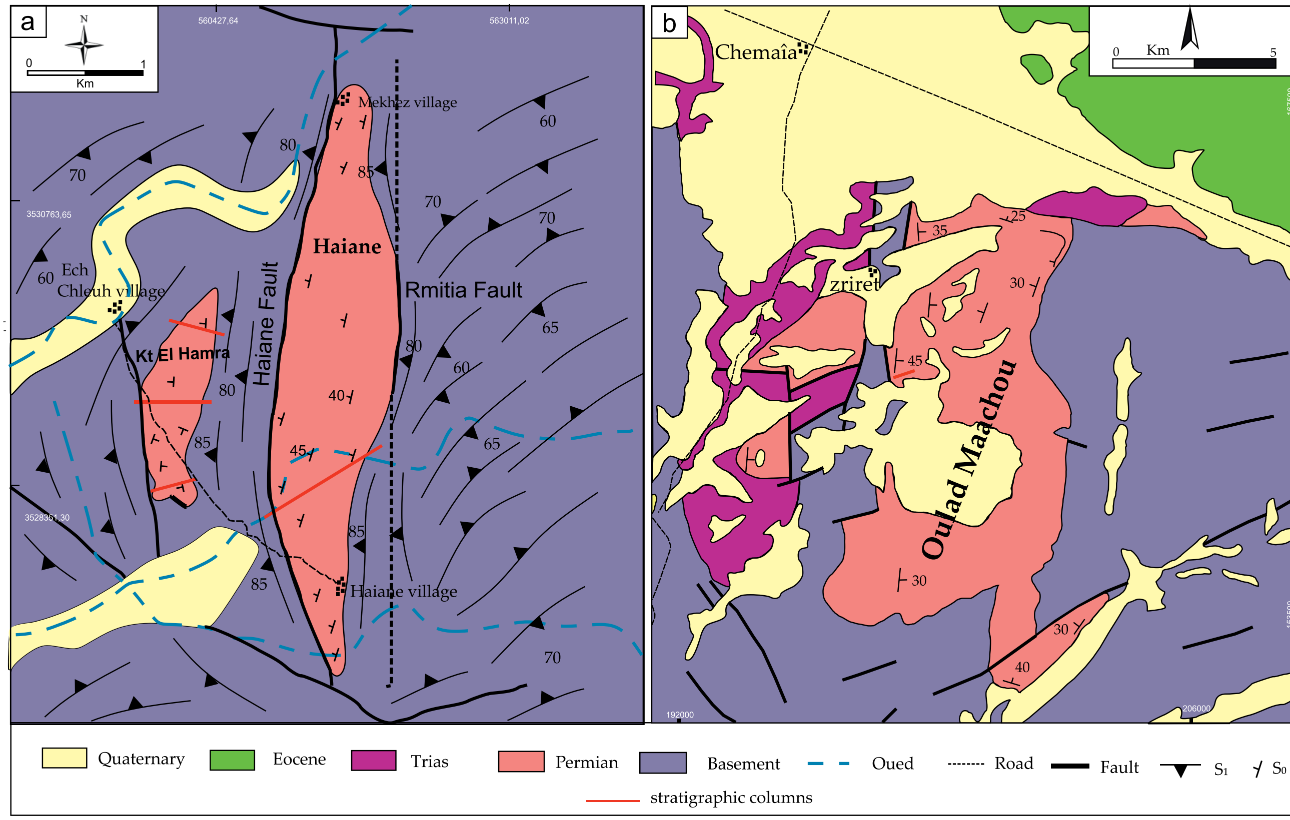


Fig. 5 **a**: Simplified structural map of the Koudiat El Hamra-Haiane (KH-H) basin. **b**: Simplified geological map of the Oulad Maachou (OM) basin (Huvelin, 1977 modified)

conglomerate lenses, deposited by subaquatic gravity flows. These deposits record carbonate deposition and cementation in a small, deep-water lake of tectonic origin.

c Discussion

The sedimentological analysis of Permian basin of the Western Jebilet massif reveal nine facies grouped in five facies association. The Haiane Formation is composed by Alluvial fan facies as main association with Floodplain facies as a minor association. The coarse sediments (conglomerate) are interpreted as the proximal part of alluvial fans controlled by tectonic activity. Fine sediments (siltstone and mudstone) indicate low-energy flows and deposition of stagnant long-lasting water masses in floodplain environments, with periodic subaerial exposure.

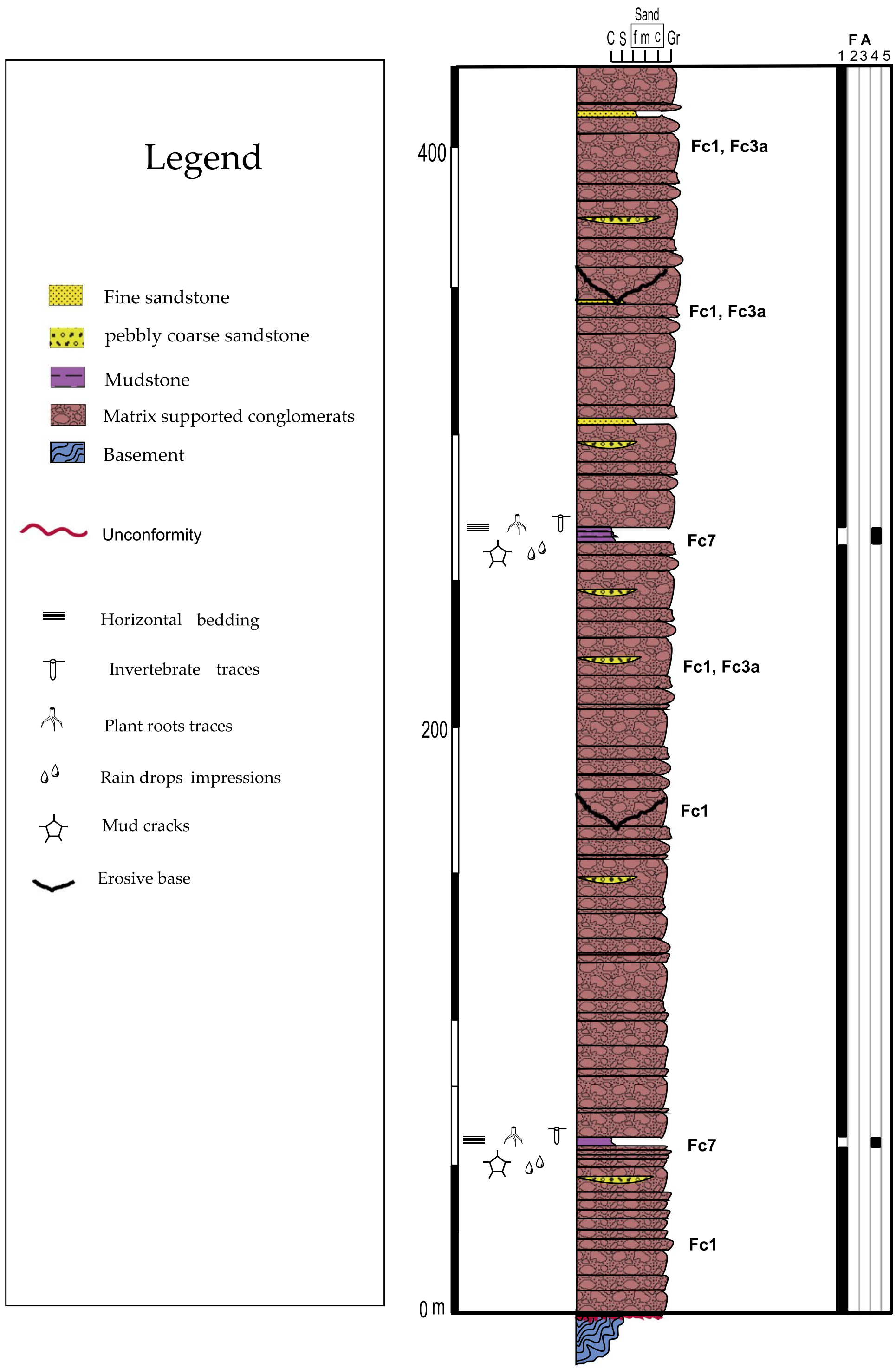
The Koudiat El Hamra Formation includes four depositional environments: alluvial fan (FA1), Channel fill (FA2), Crevasse splay (FA3), Floodplain (FA5) and Lacustrine to palustrine (FA5). The basal unit consists of alluvial fan facies association. It is interpreted as debris flow deposit linked to proximal alluvial fan areas controlled by tectonic activity. The upper unite is composed by channel fill, Crevasse splay and floodplain facies association reflecting a braided fluvial environment, evolving to an overbank environment (Crevasse splay and floodplain), with carbonates deposits (Fc5) interpreted as lacustrine environments. The dominance of lacustrine facies in the southern part of the Koudiat El Hamra sub-basin is probably the result of repetitive tectonic subsidence by syn-sedimentary N-S faults (Fig. 11).

The palaeocurrent analysis indicates a dominant N15-30° direction with a northward flow. This indicates that the proximal and distal parts of the stream are located in the south and north of the basin respectively, in agreement with the sedimentological analyses which show that the coarse sediments in the south are deposited in the proximal zone.

The Oulad Maachou basin reflects a braided fluvial environment with debris flow deposited related to tectonic activity and the establishment of short-lived floodplains. The existence of horizontal traces fossil, such as *Spongeliomorpha,* is an indicator of low energy environment, with prolonged phases of exposure and non-deposition. Paleosole developed between debris flow episodes and fluvial sediments, evidencing long periods of non-deposition.

The depositional environments in the KH-H and Oulad Maachou basins are similar. They are dominated by sandstone (Sm, Sh) and conglomerate (Gcm) are formed under higher energy conditions. The association of facies and the absence of St and Sp indicate that the basin fillings are made

Fig. 6 Sedimentary log of Haiane formation with the lithofacies and facies association



at higher energy in the very proximal part of the braided system controlled by tectonic activity (Miall, 1985).

5.2.4 Permian extensive episode (D4) the red beds

The mapping survey carried out in the Permian deposits of the KH-H basin allows describing two submeridian tectonic sub-basins separated by a Paleozoic basement horst (Fig. 5a). The Koudiat El Hamra sub-basin is a hemi-graben bordered to the west by the N-S normal faults of Koudiat El Hamra that separate the Permian deposits from the deformed pre-Permian basement (Fig. 5a). The basal conglomerates of the Koudiat El Hamra Formation crop out along its Western edge and show a decreasing thickness and

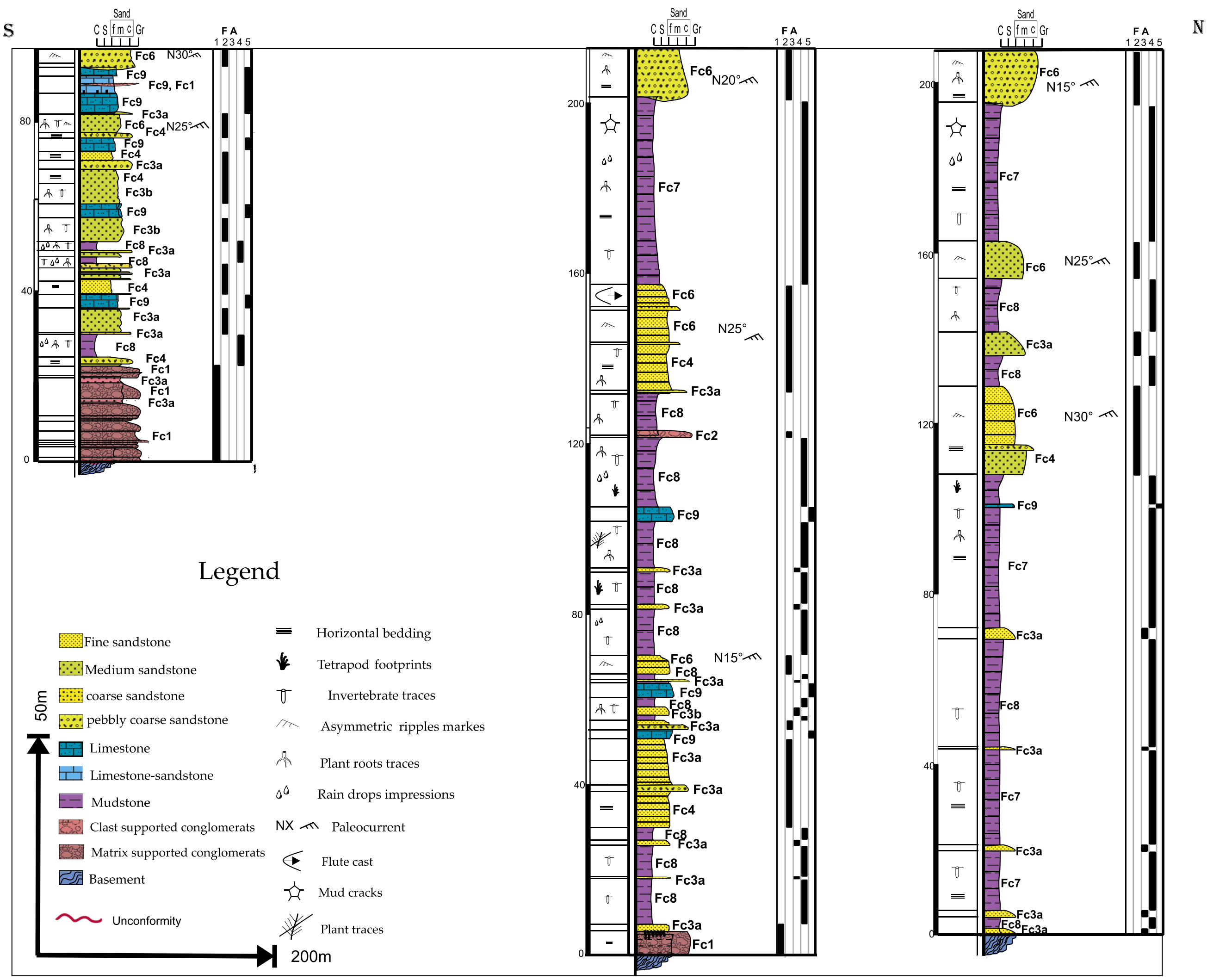


Fig. 7 Sedimentary logs in the south, center and north of the Koudiat El Hamra formation with lithofacies and facies association

pebbles size toward the east. The lateral variation of sediments can be observed also from the south to the north of the hemi-graben, where the southern side is dominated by coarse sandstone, while in the north, the sedimentary secessions are dominated by siltstone. The basal conglomerates are exclusively associated with the border fault and are likely related to the erosion of the shoulder along the active normal fault during sedimentation (Fig. 12a). The direction of water flow measured from flute casts and ripple marks on the sandstone levels indicates a N15 to 30° drainage, implying a deepening of the basin toward the North.

The Haiane graben is mainly filled by conglomerate deposits. It is limited to the west by the submeridian normal fault of Haiane, and to the east by N-S normal faults of limited extension, which separate the basin from the uplifted pre-Permian basement (Fig. 12b). These latter faults probably represent a branch of the Rmitia fault described by Mayol (1987). The Haiane conglomerate are steeply tilted to the west. This tilting could be the result of synsedimentary activity of the Haiane fault.

Synsedimentary tectonics are present in these sub-basins. Several metric to decametric synsedimentary faults, bordering hemi-graben structures are observed in the southern part of Koudiat El Hamra (Fig. 12c–d). They are oriented N170°–175°, dipping 70–80° to the east (Fig. 12e). To the west, in the Oulad Maachou basin, similar sub-vertical extensional faults were observed and create metric N170–175° trending mini-grabens (Fig. 12f, g, h).

The structural data are consistent with an E-W extensional regime along the N-S synsedimentary normal faults. The absence of horizontal striations on the fault mirrors excludes the presence of strike-slip movement, which was proposed by Saidi et al. (2002). It could be a regime related to a simple gravitational re-adjustment during post-orogenic

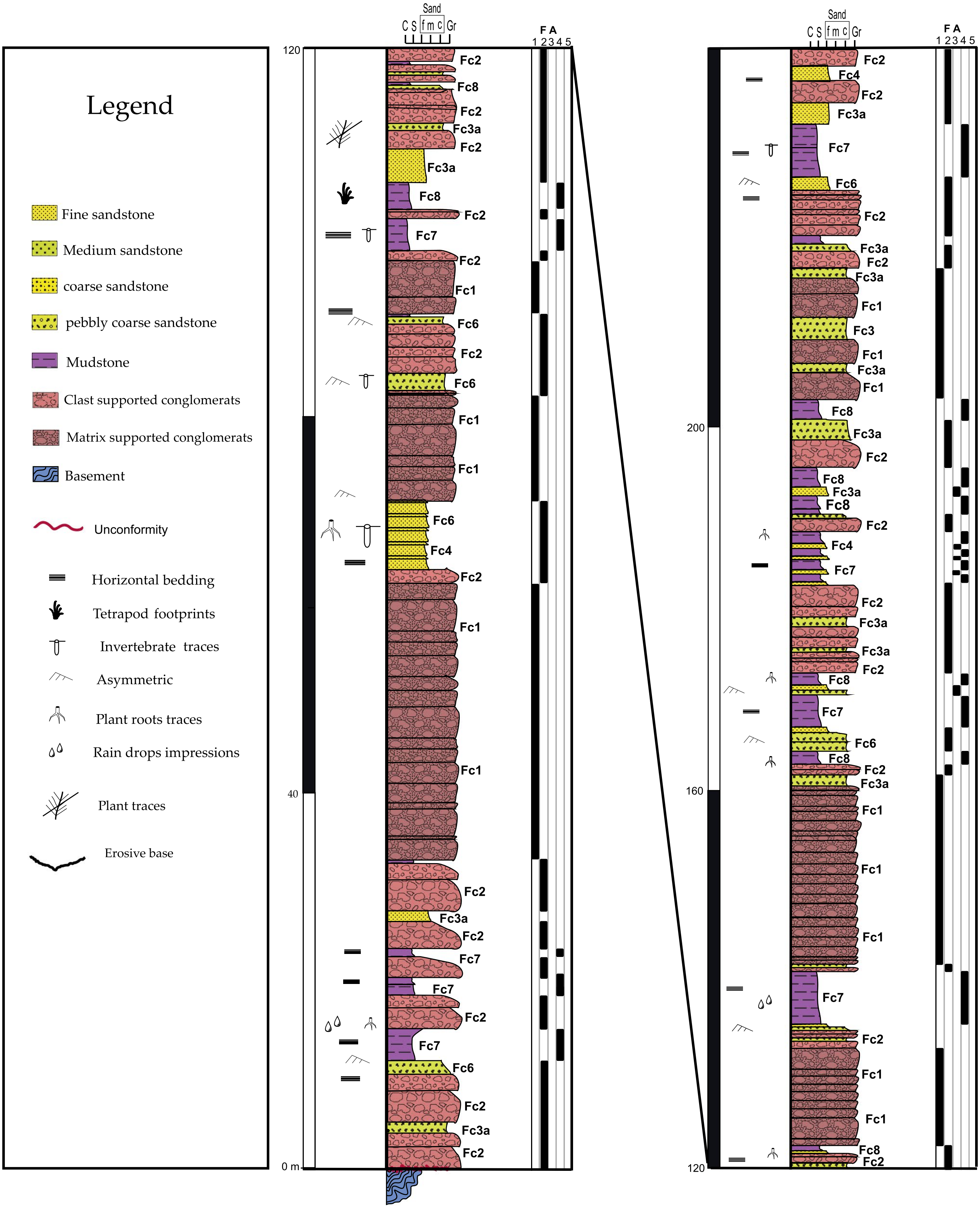


Fig. 8 Sedimentary log of Oulad Abderrahmane formation with lithofacies and facies association

Table 1 Description and interpretation of sedimentary facies of Permian basins of Haiane Formation, Koudiat El Hamra Formation and Oulad Maachou basin based principally on Miall (1977, 1978, 1985, 1988) and completed by the others authors (Freyete 1964; Allen 1983)

Facies code		Lithology and sedimentary structures	Depositional process	Interpretation
Fc1		Matrix-supported conglomerates. Poorly sorted clasts floating in a sandstone matrix, showing some in grading clasts with sharp contact	Gravity flows, Mass flow deposits	Equivalent to Gms of Miall (1977) and interpreted as high-stream debris flow at a proximal alluvial fan
Fc2		Clast-supported massive conglomerates with lenticular shape beds of decametric to metric in extension. The clasts are sub-angular and the matrix is formed mainly by fine to coarse sandstone	Progradational deposit	This facies can be assimilated to Gcm Channel fill conglomerates (Miall 1977)
Fc3	a	Massive coarse to fine sandstone with lenticular bedding and devoid of sedimentary structures	Rapid deposits, gravity flow deposits	Similar to Sm of Miall (1977) and is interpreted as sediment gravity flow
	b	Massive sandstone with planar lower and upper boundaries. This facies is practically bioturbated with many root of plant	Gravity flow deposits	It is interpreted as rapidly deposited sandstone during flood events
Fc4		Fine to coarse sandstone characterized by horizontal laminations	High-flow regime	Equivalent to Sh of Miall (1985). It is interpreted as upper flow regime deposits in channel (Miall 1985, 1996) or as crevasse splay deposits (Allen 1983)
Fc5		Fine pebbly sandstone with, erosive basal, (3–6 m)	Progradational deposit	Equivalent to Ss of Miall (1977). It is interpreted as channel deposits
Fc6		Fine to coarse sandstone, sometime becoming pebbly sandstone. It is characterized by oscillatory ripple-marks and flute-casts	Lower flow-regime	Equivalent to Sr of Miall (1977). It is interpreted as lower flow regime or shallow and crevasse channel
Fc7		Reddish siltstone and mudstone with fine lamination. Associated sedimentary structures are desiccation cracks, yellowish calcareous concretions, raindrop impressions and abundant bioturbation	Deposit suspension associated with, frequent emergence and desiccation	This facies is associated to Fl of Miall (1977). It is interpreted as flood plain, or waning flood within calmer aqueous environment
Fc8		Massive mudstone with traces of rootlets and some bioturbation. Sedimentary structures consists of rain drops, vertebrate and invertebrate traces	Deposition not homogenized by pedo-genesis or rapid sedimentation	Equivalent to Fp of Miall (1996) and interpreted as paleosol or flood-plain with pedogenesis ascendants (Miall 1985)
Fc9		Yellow-color massive carbonate and sandy limestone with, lenticular bedding of restricted lateral extension (1–6 m in thick)	Carbonate precipitation on the basin floor	This is interpreted as lacustrine- palustrine deposits (Freyete, 1964)

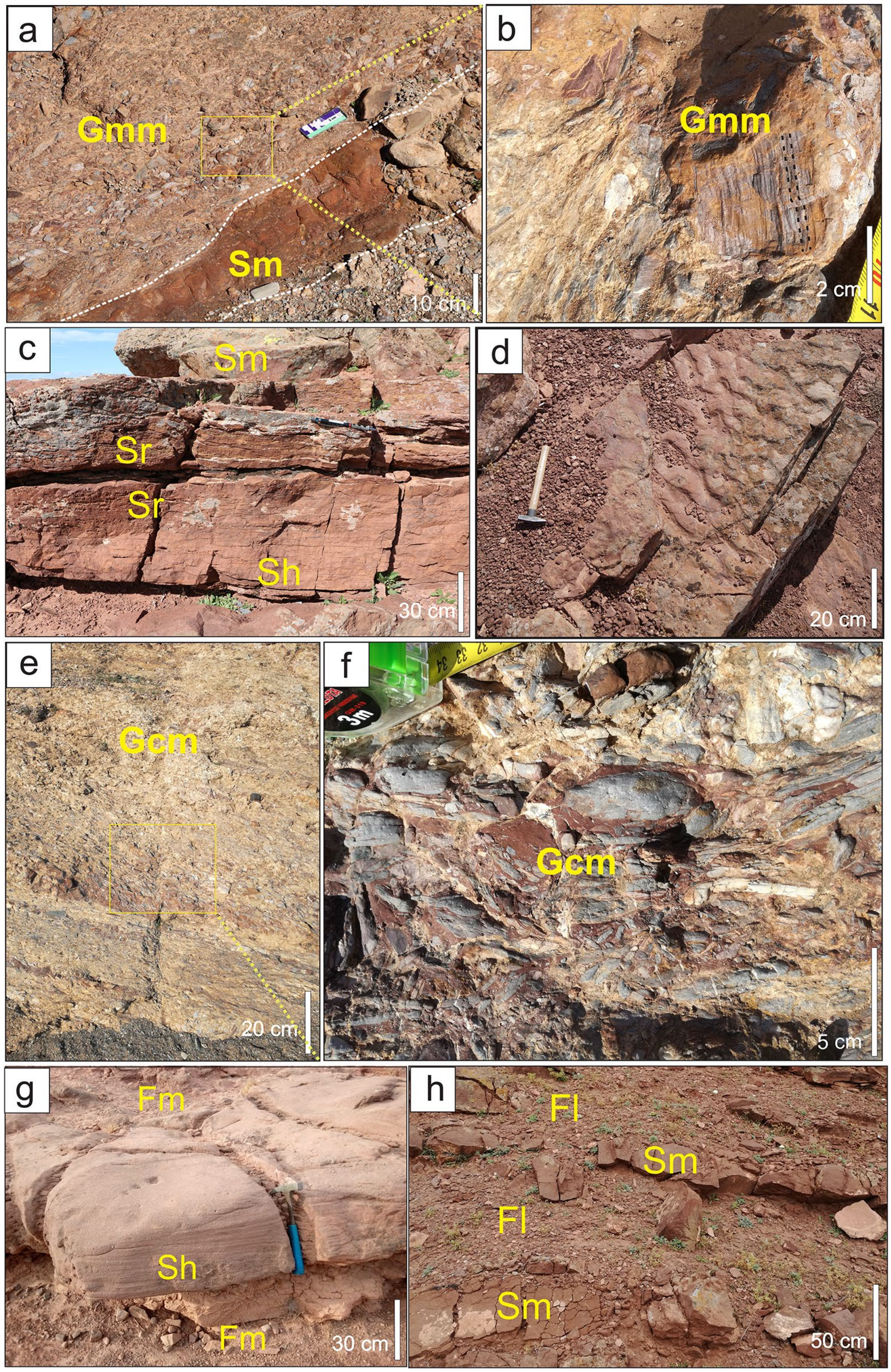


Fig. 9 Field photos **a**: matrix supported Conglomerate (Gmm) with sandstone lenses (Sm). **b**: angular gravels with kink-band deformation deposited in the conglomerate of Koudiat El Hamra and Haiane formation. **c**: sandstone facies association formed by sandstone with parallel lamination (Sh), massive sandstone (Sm), sandstone with ripple marks (Sr) indicating the fluvial deposit channel. **d**: ripple marks structure in the upper bedding of sandstone facies. **e**: clast supported conglomerates (Gcm). **f**: detailed view of gravels of the clast supported conglomerate (Gcm). **g**, **h**: sandstone facies (Sh, Sm) interbedded with fine sediments indicating the crevasse splay environment

relaxation, creating grabens (Haiane) and hemi-grabens (KE H and OM) separated by deformed basement.

In the Western Meseta, submeridian faults were the major structural lineament that governed its Paleozoic evolution. These faults have been primarily activated during the Cambrian, giving birth to the “Coastal Block basin” (Bernardin, 1987; Bernardin et al., 1988; Mayol, 1987). During the major Variscan deformation, these faults were reactivated again leading to the closure of the basins (Huvelin, 1977; Mayol, 1987; Poutchkovsky, 1978; Sougy, 1976; Tahiri, 1982). Later, during the Permian, these faults were reactivated again, contributing to the opening and subsidence

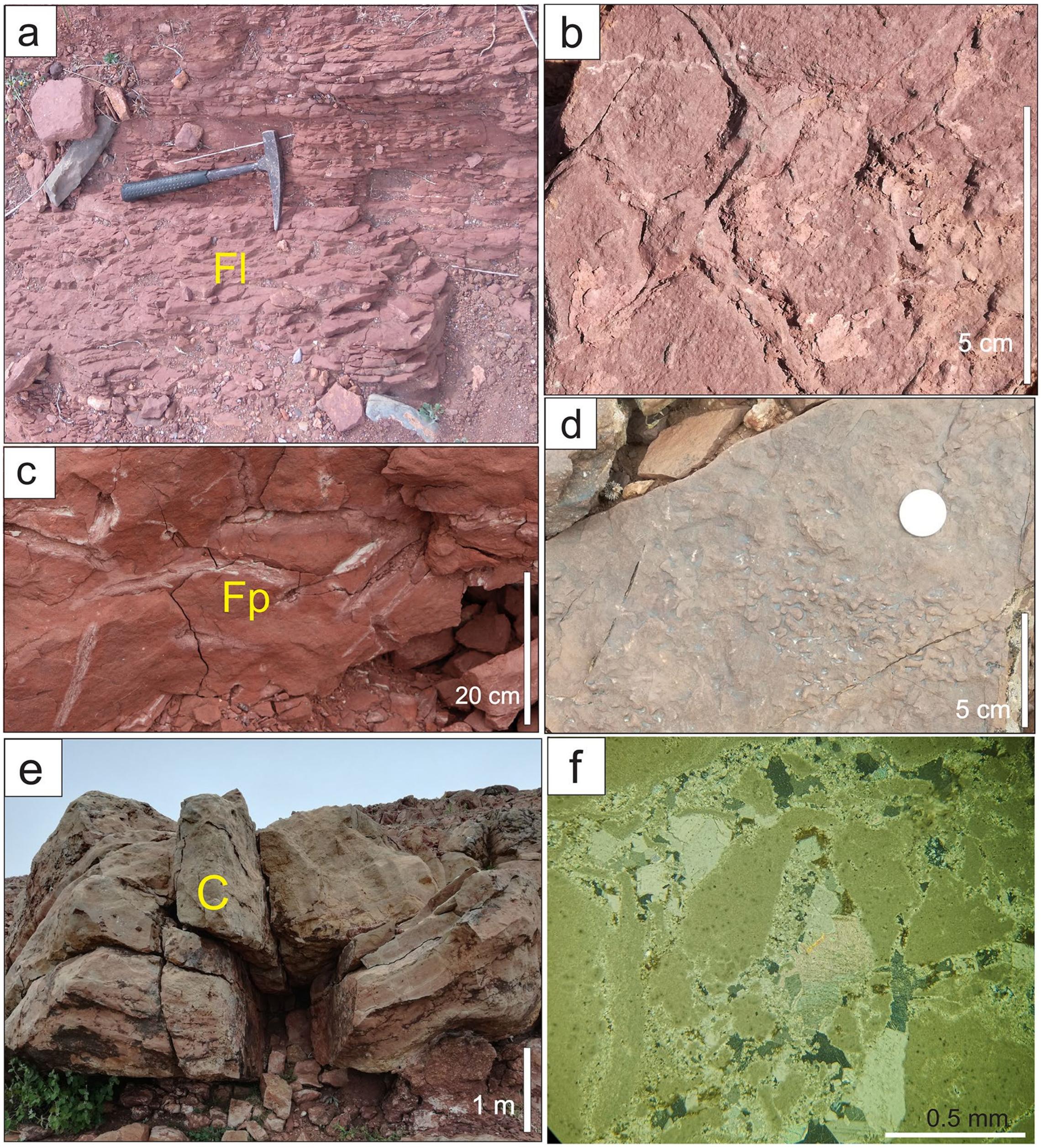


Fig. 10 Field photos of **a**: laminated siltstone –mudstone indicates a floodplain environment. **b**: mud cracks structure in the upper bedding o of Fl. **c**: massive mudstone with roots of plants. **d**: wrinkle structures (Microbially induced sedimentary structures: MISS) in the bedding surface of Fm. **e**: limestone facies. **f**: microscopic view of the limestone facies showing calcite within a micritic matrix

of the KH-H and OM basins in a subequatorial extension. Further evidence of a subequatorial Permian extension is reported along the Rmitia fault (El Attari, 2001; Mayol, 1987).

5.2.5 Age of deposits

The Permian continental red beds of the KH-H basin are still poorly age-constrained due to the lacking of radiometric data (Huvelin, 1977; Mayol, 1987). In our study, we use available tectonic and biostratigraphic data to better precise the chronological development of these basins. Recent biostratigraphic investigations in the Koudiat El Hamra sub-basin have yielded a number of ichnofossils including *Helminthoidichnites tenuis*, *Scoyenia gracilis*, *Sphaerapus larvalis,* cf. *Spongeliomorpha* isp., and vertebrate footprints such as *Dromopus lacertoides*, *Hyloidichnus bifurcatus* and cf. *Tambachichnium* isp. (Zouicha et al., 2021). This ichnofossil assemblage helps to constrain the age to the late early Permian (Artinskian) to middle Permian (Capitanian)

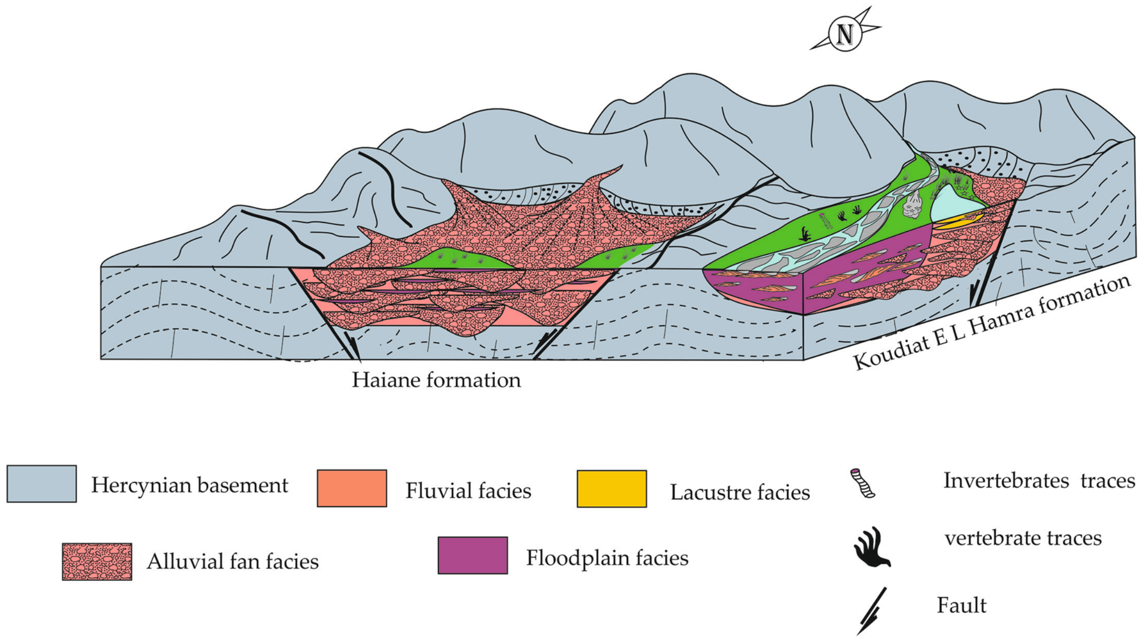


Fig. 11 Schematic model showing the tectonic and sedimentary context during the opening of the KH-H basin and note the normal faults delimiting the basin

(Zouicha et al., 2021). Furthermore, the basal conglomerates of the KH-H basin are largely made up of basement pebbles, which record the D3 deformation. In the Jebilet Massif this last episode (D3) ended at around 280 Ma (Délchini et al., 2018). Based on these observations, we conclude that the sediments of the KH-H basin were deposited between 280 and 260 Ma.

In OM basin, the lack of suitable muddy and plane surfaces does not allow for extensive ichnological exploration. However, the upper surfaces of the silty-clay layers provide few specimens of invertebrate and vertebrate traces. They consist of: (i) *cf. Tambia spiralis* (Müller, 1954) (Found by Sebastian Voigt) and it is the first record of *Tambia* in Africa. This specimen is characterized by twisted burrows displaying successive furrows and fan-shaped ridges (Fig. 13a-c); (ii) cf. *Spongeliomorpha* (Saporta, 1887) appearing as horizontal burrows of 8 mm width, with unlined and deeply striped walls associated with scratch marks (SM) (Fig. 13d–e). In addition, the undetermined tetrapod track, showing a pentadactyl plantigrade manus or pes impression, was also recorded (Fig. 13f, g).

The OM basin preserved lithofacies and tectonic features (submeridian synsedimentary faults and micro-grabens) similar to those of the KH-H basin, in addition to cf. *Tambia* ichnofossils, which are known from the early Permian (Artinskian) Tambach basin in Germany (Müller, 1954). Based on these data, we assume that the KH-H and OM basins opened and filled synchronously during an E-W extensive context.

5.3 Post-Permian compressive episode (D5)

The folding structures affecting the Permian deposits can be observed especially in the southern part of the Koudiat El Hamra hemi-graben, where the strata form an open perched syncline with a submeridian axis (Fig. 14). To the north of this locality, only the eastern flank of the syncline is preserved. At its Western limit, tectonic breccias and disrupted strata are observed locally, showing a truncation of the Western flank of this fold by a tectonic contact. This is most likely a late reactivation of the normal fault bordering the hemi-graben. In the eastern part of the Haiane graben, the steep dip of the conglomerates (60–70°W) may be partly related to this compressive episode.

In the OM basin, the conglomerate layers also show NNE-SSW oriented flexures.

We suggest that these folding structures are induced by a compressive episode (D5) whose mean shortening (Z) is oriented E-W to WNW-ESE. The reactivation of submeridian faults into reverse faults (e.g. Haiane/Rmitia fault) could be related to this episode.

In the western Jebilet, the Triassic basin of Sidi Chiker (Fig. 3) is deformed by a series of folds oriented NNE to NE, whose age is estimated to be between the Upper Triassic and the Pre-Kimmeridgian (Huvelin, 1977) and may be linked to the D5 episode we described in the KH-H and Oulad Maachou basins.

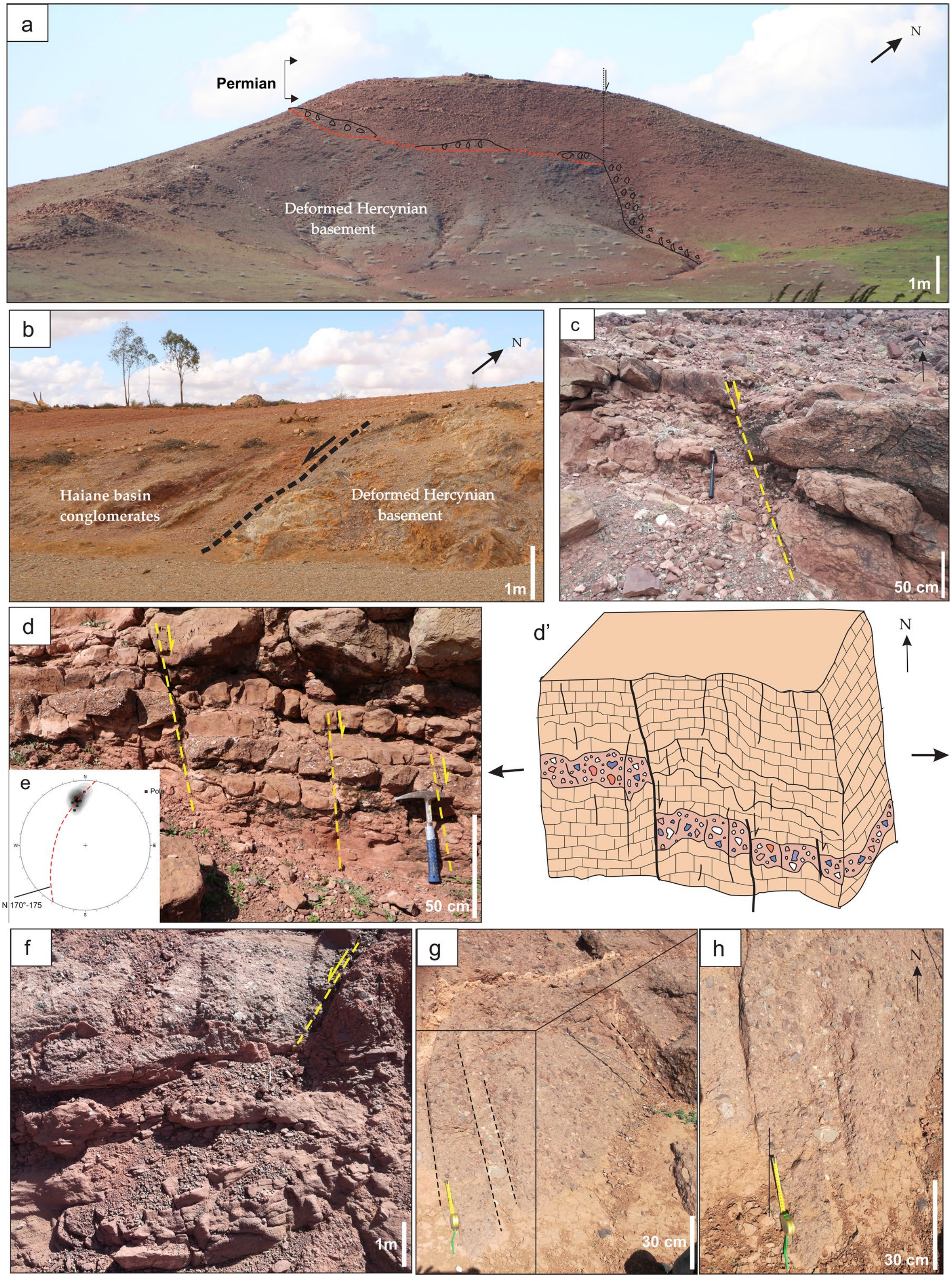


Fig. 12 **a**: a N-S Synsedimentary faults in the southern part of the Koudiat El Hamra sub-basin. **b**: Normal faults at the eastern limit of the Haiane conglomerates. **c**, **d**, d': Decimetric to metric synsedimentary normal faults in Koudiat El Hamra sub-basin. **e**: stereographic projection of normal fault of Koudiat El Hamra sub-basin. **f**, **g**, **h**: Synsedimentary faults in the residual basin OM

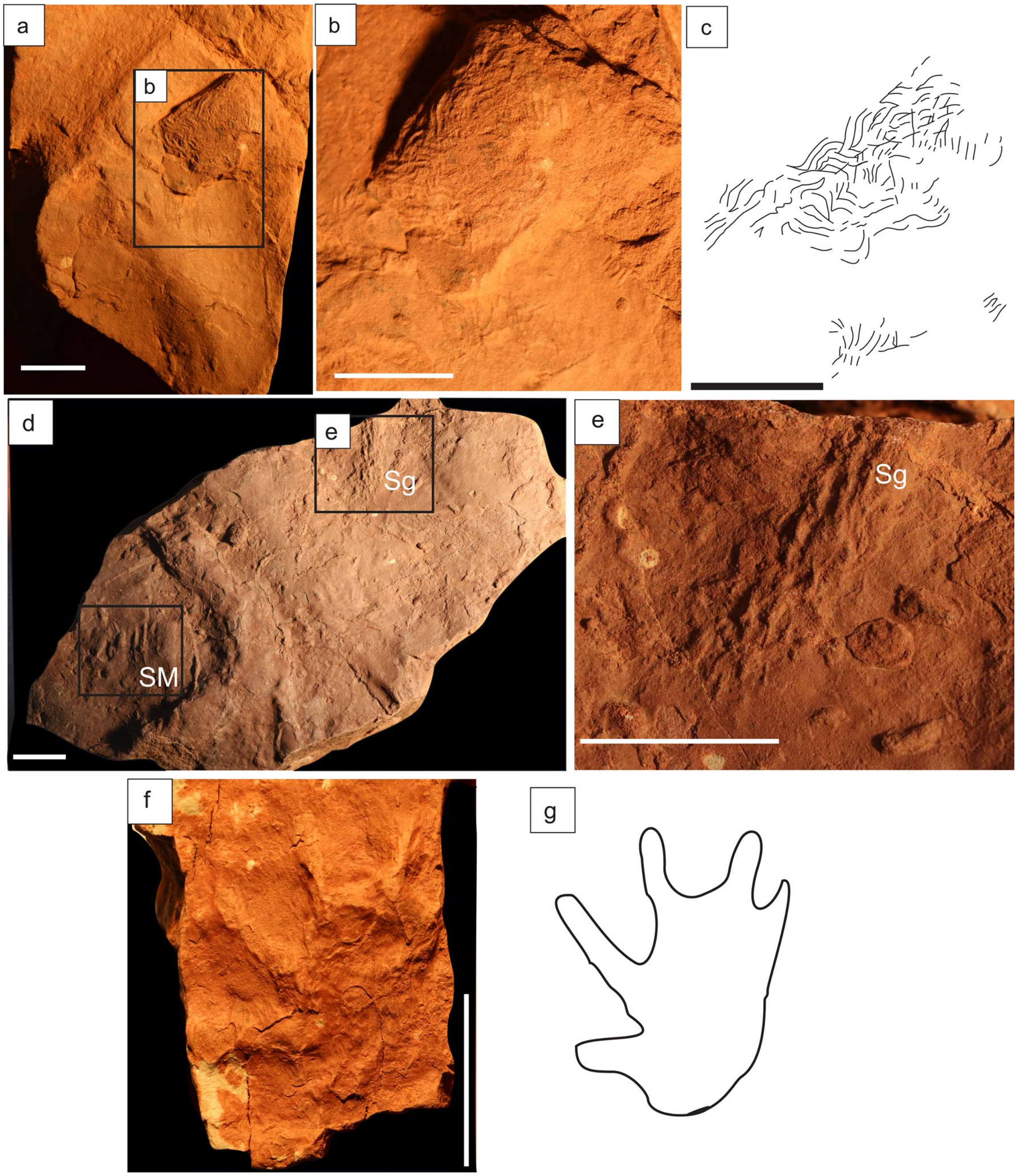


Fig. 13 Invertebrate and vertebrate traces in fine siltstone-mudstone materials from the OM basin. **a** and **b**: cf. *Tambia spiralis* Müller, 1954 with (**a**) shows the overview of specimen and (**b**) show its detailed view. **c**: Interpretive drawing of (**b**). **d** and **e**: cf. *Spongeliomorpha* Saporta, 1887 (Sg) associated with scratch marks (SM). The general view of the specimen is shown in (**b**) and its detailed view in (**e**). **f**: Undetermined tetrapod track from the OM basin, g: Interpretive outline drawing of specimen in (**f**). Scale bars equal 1 cm

6 Discussion

In the Jebilet Massif, we reveal two episodes of the late Hercynian. The first dated between 310–280 Ma is a NNE-SSW compressive episode that induces the formation of kink-band, chevron folds and associated irregularly spaced cleavage and locally a shearing movement along the preferred directions N10°/N20° and N70°. The second is dated 280–260 Ma is an extensive E-W episode allowing the formation of graben and hemi-graben of KH-H and OM in a pure extensive regime (Table 2).

The late Variscan-Permian deformations described in the Jebilet massif are not localized events in this massif, but rather belongs to the regional evolution of the Meseta

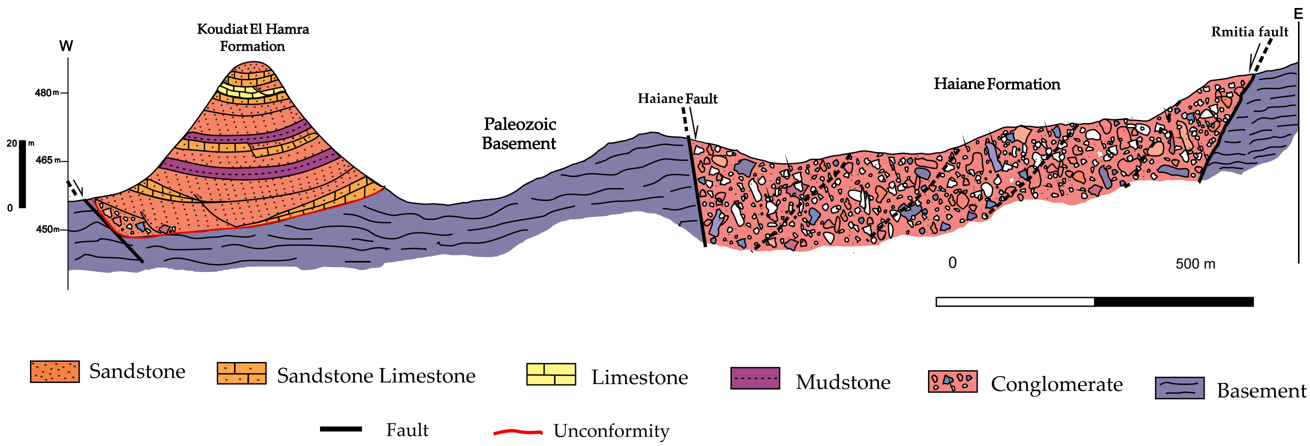


Fig.14 a E-W oriented geological section in the KH-H basin showing the main tectonic structures and facies arrangement

during this period. Indeed, several Permian basins have been described in the Moroccan Meseta and High Atlas domains. These basins have been interpreted as pull-apart basins induced by a NNE-SSW compression (Cailleux et al., 1983; El wartiti, 1990; Youbi et al., 1995; Tahiri et al., 1996; Saber, 1998; Saidi et al., 2002). The fluvial-lacustrine sediments of these basins are interbedded with intermediate to felsic volcanic rocks of calc-alkaline affinity (Cailleux et al., 1983, 1986; Zouine, 1986; El Wartiti, 1990; Youbi, 1990; Saidi et al., 2002; Domeier et al., 2021). These authors agree on the Upper carboniferous-early Permian age of these basins, but this does not necessarily imply that they are coeval with those of the Jebilet massif (KH-H and OM). Indeed, the NNE-SSW shortening that induced the formation of the Permian basin of Central massif and the High Atlas is compatible with our D3 event responsible for the kink-bands and chevron folds reworked in the Artinskian conglomerates at the base of the KH-H basin. Consequently, it is clear that there are two different generations of Permian basin in the Moroccan Meseta as is the case in the neighboring Hercynian fragments.

For example, in Western Europe, two type of basin are recognized in between late stage of Variscan orogeny and initial stage of Pangea break-up: (i) the Upper Carboniferous pull apart basins are controlled by a transpressive regime generated at end of the Variscan orogeny (Arthaud & Matte, 1975; Matter et al., 1988; Burg et al., 1990; Blüm, 1989; Genna & Debriette, 1996; Elter et al., 2020). Fluvial-lacustrine filling of these basins is associated with a magmatic episode of calk-alkaline affinity (Munoz et al., 1986; Lago et al., 2004; Pereira et al. 2014; Rodríquez-Mendèz et al., 2016). This episode is interpreted as the response to strike-slip movement between Laurussia and Gondwana related to the final amalgamation stage of Pangea, (Knight et al., 2000; Gras & Zarza, 2003; Frings et al., 2004; Lago et al., 2004; Arche & Lopez-Gomez, 2005; Lopez-Gomez et al., 2005; Elter et al., 2020). (ii) The early Permian- upper Triasic record the formation of isolated hemi-graben basins filled by alluvial fan sediments in a pure-extensive regime (Châteauneuf and Farjanel, 1989; Ziegler & Stampfli, 2001; Jabaloy et al., 2002; McCann et al., 2006, 2008; Lopez-Gòmez et al., 2019). This episode is completely devoid of magmatism (Cassinis et al., 2012) and linked to the beginning of the Pangea break-up (Van Houten, 1977; Mpodozis & Kay, 1992; Aît Chayeb et al., 1998; Kleiman & Japas, 2009; Edel et al., 2018; Lopez-Gòmez et al., 2019; Elter et al., 2020; Lloret et al., 2021).

Based on our sedimentological and ichonological data combined with published tectono-sedimentary analyses in the late Carboniferous-Permian basins of Morocco (the Meseta and the Western High Atlas), we infer that the Moroccan Meseta and Western Europe share the same Late-Hercynian evolution. This is reflected in a transpressive tectonic regime (our D3) allowing the deformation of the main Variscan structures and the opening of pull-apart type basins in both Meseta and Western Europe. The second stage (our D4) develops in an extensive regime allowing the formation of pure extensional basins (KH-H and OM basins) filled by alluvial sediments.

7 Conclusions

The study in the Jebilet Massif provides new framework to reconstruct tectono-sedimentary history of the Carboniferous-Permian basins of Morocco. It highlighted three main late a post Hercynian tectonic episodes linked to different tectonic regimes (Table 2).

1. A compressive episode (D3) marked by simple and conjugate kink-bands, chevron folds associated with

Table 2 Synthesis and chronology of the Hercynian and late Hercynian events in the Jebilet massif

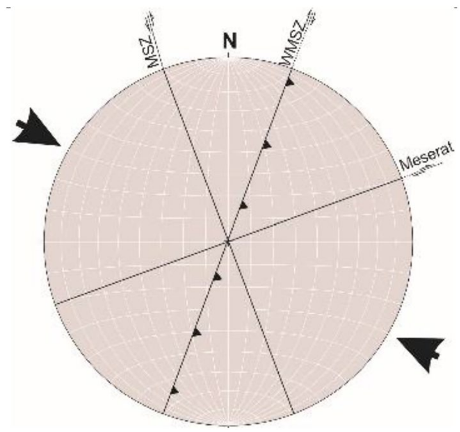
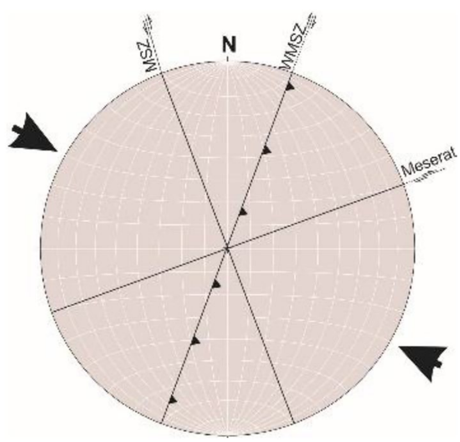
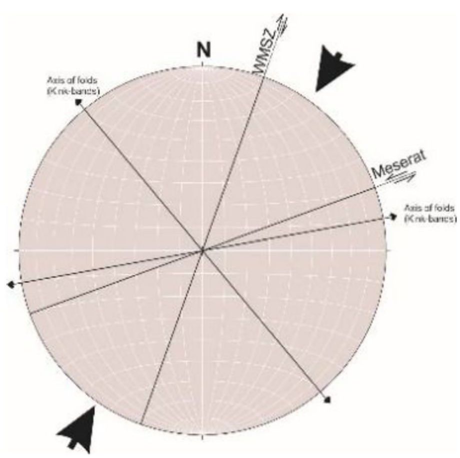
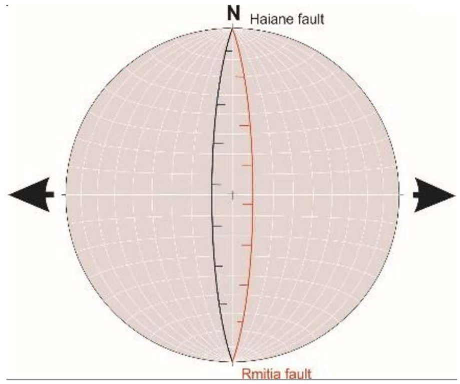
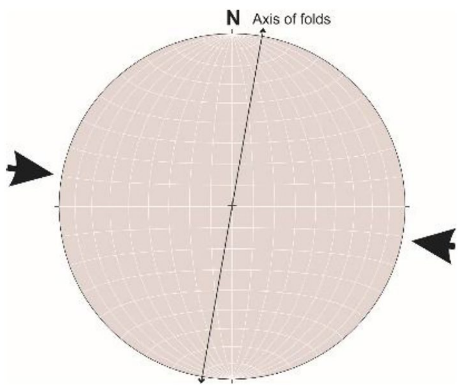
Episode	Age	Orientation	Domaine	References
D1	-D1/D3: 310–280 Ma		Jebilet massif	Lagarde, 1989; Delchini et al., 2018
D2	-D1/D3: 310–280 Ma		Jebilet massif	Tisserant 1977; Mrini et al. 1992;Delchini et al. 2018
D3	-D1/D3: 310–280 Ma (Pre-Artinskian)		Jebilet massif	- Delchini et al. 2018 - This work

Table 2 (continued)

Episode	Age	Orientation	Domaine	References
D4	Artinskian to Capitanian (280–260 Ma)		Koudiat El Hamra-Haiane and Oulad Maachou basins	- Zouicha et al. 2021 - This work
D5	Upper Triassic- pre-Kimmeridgian		Koudiat El Hamra-Haiane and Oulad Maachou basins	- This work

irregularly spaced cleavage parallel to the axial planes of the kink-bands. In addition to locally shearing movements in some corridors N10°/N20° and N70°. Dominant N120°–N150° kink-bands and N05°–N45° extensional veins indicate a NNE-SSW to NE-SW shortening. This NNE stress makes a slight angle with the regional schistosity, resulting in the formation of symmetrical conjugate kink-band bands. Contemporaneous and similar structures have been reported in different parts of the Moroccan Hercynian orogeny (occidental High Atlas, the Upper Moulouya, Rehamna and Guemassa) and associated with late Variscan NNE-SSW shortening (Cornée, 1982; El Attari, 2001; Ferrandini et al., 1987; Saber, 1989; Soulaimani, 1991). This deformation is also marked in the Western European Hercynian orogeny between 310–270 Ma (Bard et al., 1971, 1973; Mattauer et al., 1972; Arthaud &Matte, 1975; 1977; Michard et al., 2010) during the late stage of Pangea amalgamation. Regionally, this compressive event is associated with the reactivation of pre-existing faults in strikes-slip motion and the opening of the Pull-apart basin combined with Calc-alkaline magmatism. In the Jebilet Massif, the deposition of pebbles recording D3 deformation (kink-bands) in the Artinskian basin of KH-H allows to assign a pre-Artinskian age to this event.

2. An extensive episode (D4) 280–260 Ma responsible for the opening of KH-H and OM basins as graben and hemi-graben. The basins formed during this episode are controlled by the reactivation of inherited faults from the Paleozoic basement in a pure E-W extensive regime. Sedimentological analyses of the KH-H and OM deposits reveal that they are filled by coarse debris-flow and lacustrine deposits controlled by faults in the proximal part and by fine sediments in the distal part. Thus, these basins are developed in the proximal part of a high-energy braided river system. The D4 episode in the Jebilet Massif is probably concomitant with extensive episodes in Western Europe during the initial opening of the Atlantic Ocean (Van Houten, 1977; Mpodozis & Kay, 1992; Aît Chayeb et al., 1998; Kleiman & Japas, 2009; Edel et al., 2018; Lopez-Gòmez et al., 2019; Elter et al., 2020; Lloret et al., 2021).
3. A post-Permian compressive episode (D5) dated between the Upper Triassic and Pre-Kimmeridgian is recorded in all Permo-Triassic basins of western Jebilet. This episode is defined by N0° to N20° oriented folds in

the Permian deposits and by reactivation of submeridional normal faults into reverse faults.

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Declarations

Conflict of interest We declare that this manuscript is original, unpublished and not currently being considered for publication elsewhere. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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