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ORIGINAL PAPER

The Plio-Pleistocene evolution of the Southern Middle Atlas Fault Zone (SMAFZ) front of Morocco

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Abstract The South Middle Atlas front constitutes a northeast-trending shear zone, located north of the Neogene Missour basin and east of the Taza Guercif basin. This paper analyses the Southern Middle Atlas Fault Zone (SMAFZ) deformation since the Pliocene. The set of structures observed suggests that reverse and thrust faulting along the central part of the SMAFZ are combined with left-lateral slip along N–S striking faults of its south-western termination and right-lateral faulting along E–NE striking faults of the east–northeast termination. Thrusts and oblique thrust-related anticlines of the two lateral ramps partly accommodate north-west directed motion of the African plate. The Thrusts probably resulted from rejuvenation of Jurassic normal faults; they were active during the Upper Miocene–Pliocene and the Pleistocene. The geometries of positive inversion structures and buttressing effects are clearly dependent on the geometry and sedimentology of the original basin-controlling fault system and on the presence of a décollement level. Field mapping is integrated with Landsat imagery and a digital elevation model to investigate the morphotectonic evolution of the south-eastern range front of the Middle Atlas. Geomorphological features provide significant information on the processes that govern lateral propagation of active anticlines. Both suggest that the deformation front may have been active since Pliocene.

Keywords South Middle Atlas thrust zone · Plio-Pleistocene · Kinematics · Morphotectonics · Indenter · Morocco

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Introduction

The Atlas orogen constitutes the most prominent morphotectonic feature of North Africa, and is an Alpine intracontinental belt that developed during Cenozoic times in the foreland of the Rif-Tell orogenic belt system. It resulted from the closure of the Maghrebian Tethys and the subsequent collision of the European and African plates. These two stages correspond to two phases of uplift of the Atlas system (Frizon de Lamotte et al. 2000). The latter uplift took place in two phases: the first one is of Tortonian age and the second is of Pleistocene age (Morel 1989). This second phase is general to the whole Atlas domain and is a response to the present-day oblique convergence of Africa and Europe (4 mm $year^{-1}$ in a NW–SE direction; Demets et al. 1990). In Morocco, the Atlas belt displays two branches; one extends in a roughly east–west direction from Agadir in the west to the Saharan Atlas in the east and covers about 1,000 ϶ 100 km. The other trends NE and constitutes the Middle Atlas belt that developed from a Mesozoic basin by inversion between the Moroccan Meseta and the High Plateaux (inset Fig. 1). Total shortening of the Atlas has been of the order of about 36 km (28%) since the early Miocene (Gomez et al. 2000); balanced cross-sections across the High Atlas belt show lower shortening values that increase from west to east from 15 to 24% (Teixell et al. 2002). Active thrust movements in the Atlas range are low (~ 1–2.5 mm year^{-1}; Negrado et al. 2002).

This study analyses the Plio-Pleistocene kinematics of the South Middle Atlas Fault Zone (SMAFZ). Along the northeast-trending Main Fault zone, north of the Missour region (segment B, Fig. 1), faults have been interpreted as thrusts and reverse faults (Beauchamp et al. 1996) or transcurrent faults related to a sinistral transpressive tectonics between the Moroccan Meseta and the African indenter (Bernini et al. 2000). At the terminations of the Main Thrust, *en échelon* folds and disrupted folds extend in a east–north-eastwards direction along its north-eastern tip (segment A, Fig. 1) and in N–S direction along its south-western tip (segment C, Fig. 1). This direction is oblique to the overall trend of the Middle Atlas fold-and-thrust belt. These sets of structures suggest that reverse and thrust faulting may be combined with strike-slip movements. Pleistocene activity in this region has been previously discussed by Gomez et al. (1996); however, no significant information has been published on recent morphotectonic evolution of the south-eastern range front of the Middle Atlas to establish whether the modern geomorphological features represent a rapid response to tectonic motion that result from the NW–SE convergence.

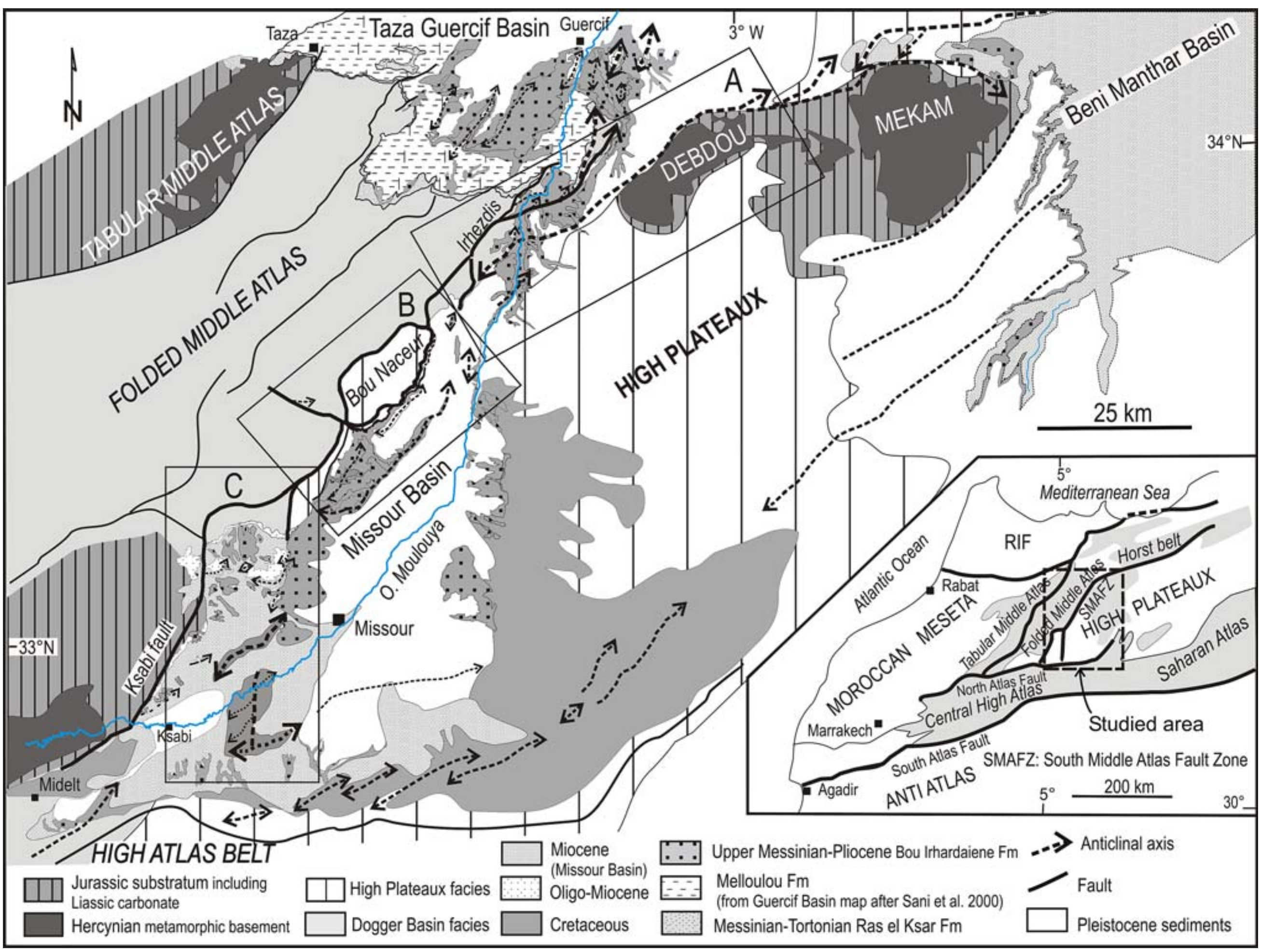

Fig. 1 Simplified geological map of the South Middle Atlas Fault Zone. *Insert*: location of the main structural domains of northern Morocco

The authors describe below the structural geometry and the kinematics of the SMAFZ using field observations and sub-surface data from the Neogene basins of Guercif and Missour (Beauchamp et al. 1996; Gomez et al. 2000; Sani et al. 2000). Geomorphological features observed along the thrust system and in the drainage basins provide information on the processes that govern recent uplift and lateral propagation of active anticlines (Burbank and Anderson 2001; Delcaillau 2004). Geomorphological indices of drainage pattern demonstrate the form and evolution of landforms (Schumm 1986; Wells et al. 1988; Leeder and Jakson 1993; Delcaillau et al. 2001; Schumm et al. 2000).

Geological setting

The Middle Atlas range is located in the south-east of the external Rif tectonic wedge and is divided into two morphostructural units: the Tabular Middle Atlas in the northwest and the fold-and-thrust belt of the Middle Atlas in the southeast (Colo 1964; Martin 1981). To the North, the folded Middle Atlas is partially buried by Neogene and Quaternary deposits that represent the infilling of the Taza-Guercif Basin (TGB). Thrusts and folds of the southern margin of the Middle Atlas affect the Neogene-Quaternary deposits of the Missour Basin (MB) that rest above the carbonate platform of the High Plateaux (Fig. 1). The Tertiary evolution of the Middle Atlas is controlled by the pre-existing Jurassic basin geometry, in particular by the position of normal faults (Mattauer et al. 1977) that controlled the Jurassic palaeogeography (du Dresnay 1975; Beauchamp et al. 1996). The Jurassic palaeogeography was marked essentially by two facies: a basin facies infilling the Jurassic Middle Atlas Trough and a second facies from a extensive carbonate platform that overlaid the High Plateaux (du Dresnay 1979). These two facies were separated by a set of synsedimentary faults during extension (du Dresnay 1975; Beauchamp et al. 1996) or transtension related to the opening of the Central Atlantic Ocean (Mattauer et al. 1977; Fedan et al. 1989; du Dresnay 1988). During the Neogene, most of these normal faults have been inverted in response to the convergence of the African and Eurasian plates (Jacobshagen et al. 1988; Brede et al. 1992; Beauchamp et al. 1996; Sani et al. 2000).

Along the south-eastern boundary of the folded Middle Atlas, the South Middle Atlas Fault Zone (SMAFZ) (Colo 1964; Gomez et al. 1996) is thrust onto coarse deposits of the Neogene intramontaine MB. Towards the North, the SMAFZ, which bends from N 45°E to N 70°E, displays two branches: one that runs into the Neogene infilling of the TGB and disappears northwards; the other aligned along the High Plateaux. To the Southwest, the SMAFZ constitutes a topographic feature that culminates in the Bou Naceur (3,326 m) and decreases north-eastwards into the eastern part of the Neogene TGB (up to 900 m). The SMAFZ is the most dramatic structure between the folded Middle Atlas and the northern uplifted margin of the Neogene MB, which overlaps eastwards onto the Jurassic rocks of the High Plateaux.

The Neogene MB is developed in front of the southern wedge of the Middle Atlas belt while the Taza Guercif basin (TGB) lies above the northern part of the Middle Atlas shear zone in front of the eastern part of the Rifain arc (Bernini et al. 2000). The Neogene sedimentary rocks of the south-eastern part of the TGB are marine deposits, while the MB deposits are fluvial. In the south-eastern part of the TGB the Tortonian to Pliocene deposits 1,500 m thick have basal fluviatile conglomerates which are overlain by shallow marine and thick open marine marls [Melloulou Formation (M Fm)]. These marls are intercalated with turbiditic units, and terminate with gypsiferous marls. These series are unconformably overlain by the Pliocene continental Bou Irhardaiene Formation (BI Fm) (Gelati et al. 2000). This unit is dominated by fluvial deposits near to the frontal thrust of the SMAFZ and by interbedded fine-grained lacustrine carbonates that were deposited distal to the active front thrust. Its base was dated at approximately 6.7 Ma (Krijgsman and Langereis 2000) and locally, it ends with Upper Pliocene lacustrine limestones (Martin 1981; Lefèvre 1985). To the South, the BI Fm outcrops continuously on the northern edge of the High Plateaux where it locally infilled NW-trending palaeotalwegs cut into Jurassic dolomites. On the southern border of the Middle Atlas belt, it overlies unconformably eroded overturned anticlines of Jurassic to Cretaceous carbonates of the High Plateaux; the folds are part of the SMAFZ. In the south-western part of the MB, from distant structurally disturbed region, the coarse fluvial deposits of the BI Fm are difficult to distinguish from a graded clast-supported conglomerate formation. Locally, this formation shows lateral facies changes from fresh-water to brackish-water environments from the margin to the axis of the basin (Duringer et al. 1995). It is of Serravalian–Tortonian age (Benammi and Jeager 1995).

Structural geometry of the South Middle Atlas Fault Zone (Figs. 1, 2)

From the geometry of the structures observed in the SMAFZ, three main segments are proposed. These segments are represented in the structural scheme of Figs. 1 and 2a, from the south-eastern part of the Taza Guercif basin to the northern border of the Central High Atlas belt. Segment A is composed of the J. Maarouf-Tafrata–J.Tanout–J. Irhesdis belt has two morphological expressions. The first (F1) is expressed by the northern edge of High Plateaux that exceeds 1,600 m. This scarp runs in a N 50°E direction and bends northwards trending in a 70°E direction to the Neogene Beni Manthar Basin (BMB). The second (F2) corresponds to a N 30°E elongated topographic high involving outcropping Triassic and Jurassic sediments that outcrop in the core of anticlinal arrays in the southern part of the Neogene Taza Guercif basin (TGB). Segment B is composed of the J.Bou Naceur thrust belt that trends N 40°E and forms the central part of the SMAFZ. The J. Tamdafelt-Arhal–J. Tsiouant fold system makes the segment C that shows *en échelon* arrangements of folds developed in a N–S direction. In this direction synclines are infilled by Neogene sequences of the MB while anticlines merge exhibiting Jurassic and Cretaceous rocks. This system represents the eastern branch of the southward prolongation of the Main Fault and trends almost parallel to a western branch, the Ksabi Fault (KF).

Segment A (J. Irhezdis–J. Maarouf-Tafrata–J. Tanout belt)

On cross-sections A1–A3 (Fig. 3), from north to south, the structures appear as two main lateral and upwards diverging fault splays F1 and F2 that deform the

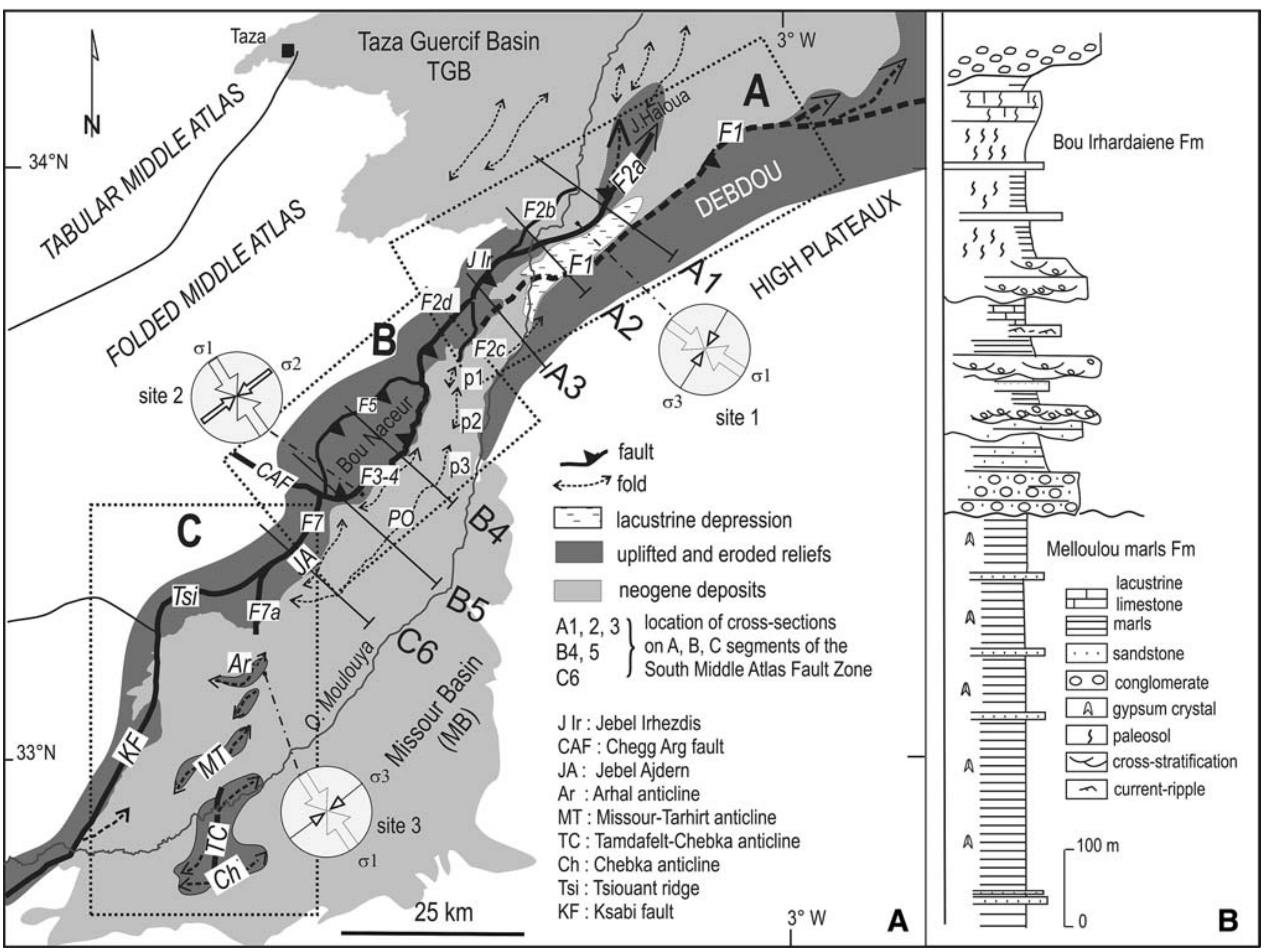

Fig. 2 **a** Simplified structural map of the South Middle Atlas Zone Fault (SMAZF). Location of the studied area segments A, B and C are indicated. **b** Composite stratigraphical column of the Neogene Taza-Guercif basin (adapted from Gelati et al. 2000)

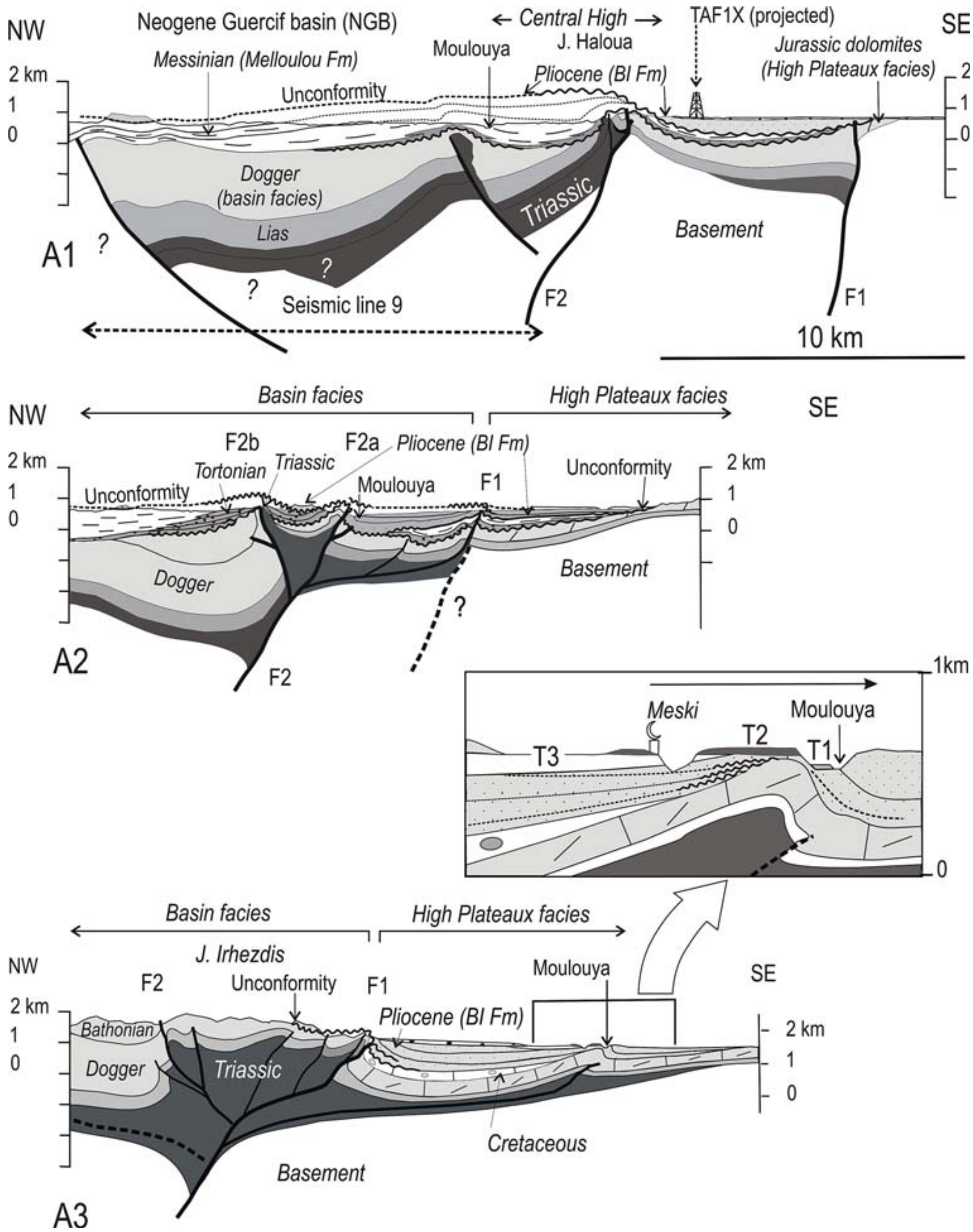

Fig. 3 Cross-sections through the SMAFZ (A1, A2, A3 from segment A)

overlying sedimentary cover. Southwards, they rejoin at depth to terminate probably either in a low-angle décollement zone or in a reactivated Jurassic normal fault. These two fault-systems F1 and F2 are discussed below.

(1) Fault F1 has been identified on a seismic profile beneath Quaternary alluvial fans which drape over the eroded footscarp of the northern edge of the High Plateaux. This structure links at depth to a Jurassic normal fault (sections A1, A2) that was inverted during the Neogene (Sani et al. 2000). Towards the northeast, this inverted fault bordering the Hercynian basement at Debdou in the west branches to form an E–W trending subvertical transfer fault zone visible on seismic section profile 10 (Sani et al. 2000) that runs south of the 'Horsts belt'. This lineament remained active during the Late Miocene to Pliocene, and is documented by its eastward extension where Neogene continental coarse deposits were folded into northeast–southwest striking open synclines and asymmetrical anticlines. These anticlines appear to coincide with the underlying faults affecting a system of Jurassic half-grabens. Their geometry was recently interpreted as a Neogene dextral transcurrent fault zone between the 'Horst belt' and the thrust-faults system of the SMAFZ (Charroud 2002).

Towards the southwest the scarp decreases morphologically and is progressively overlapped by conglomerates of the Bou Irhardaene Formation (BI Fm). This buried fault F1 is expressed upwards by an eastwards-verging asymmetric anticline developed in conglomerates of the BI Fm and lacustrine carbonate (cross-section A2). This structure bends towards a N70°E direction along which it constitutes the near-vertical upturned southern limb of a fold affecting the BI Fm sequences. Further south (cross-section A3) in this fold the underlying reverse fault (F1) has cut through the Cretaceous carbonate strata and subsequent sequences of BI Fm. A prominent unconformity at the base of the BI Fm truncating westwards-overturned Cretaceous beds is very obvious. Above its truncational unconformity, overlapping sequences of the BI Fm are themselves truncated and overstepped by upper sequences that directly onlapped the SE-tilted Jurassic beds belonging to the Jurassic Middle Atlas basin. The pattern of onlap, flexuring and truncation in the vicinity of the structure F1 records the fold growth during a Pliocene compressional event.

(2) Fault F2 represents a complex fault system that shows, in map plan (Fig. 2a), lateral connecting fault splays developed on both sides of a central inflexion zone that superposes the Bajocian limestones of J Arhezdis onto the Bathonian sandstones (cross-section A3). This fault extends to the north where it has a sigmoidal trace ending in two diverging splay faults F2a and F2b, while the other runs towards the south where it is represented by two branches, F2c and F2d.

On the northern side, cross-sections A1 and A2 show a syncline that is bounded by two main faulted folds F2a and F2b diverging in opposite directions. Along its length, F2b constitutes an eastwards-dipping reverse fault that cuts through the Melloulou Unit Neogene deposits that unconformably overlie Jurassic limestones and Triassic shales and evaporites exposed in the core of a truncated anticline. Further north this structure progressively disappears beneath the Neogene deposits of the TGB. The Fault F2a is bent in a N 70°E direction along which Neogene structures are morphologically expressed by a steeply dipping reverse fault and by oblique folds with horizontal axis trending N 40°E to N 60°E. Some of these are disrupted by steeply dipping faults that are associated with en-échelon folds. The system of structures associated with fault F2a deforms the conglomerate succession of BI Fm that is strongly tilted north-westerly at 60°. This deformed conglomerate succession rests unconformably either on the Messinian deposits of M Fm or on the Jurassic limestones and Triassic shales and evaporates. Near the tectonic contact some upright beds are cut off by steep minor faults and are displaced horizontally. Offsets indicate a right-lateral component on N 60°E to N 90° E-trending minor faults. Stress tensors determination from minor fault analysis (site 1, Fig. 2a) indicate local transpressive stress fields which are characterised by a direction of maximum stress σ_1, orientated subhorizontally and trending N 120° E, and a direction of minimum stress σ_3 horizontal and trending N 30°E. This is coherent with the shortening direction derived from imprinted pebbles pits, sheared pebbles and folds axis. To the north (cross-section A1), this fault bends abruptly in a N 30°E direction and merges into the core of an anticline (J Haloua). This anticline has been partly eroded and the erosional surface, which has reached Triassic and Jurassic underlying strata, is overlain by Messinian marine deposits of M Fm. These sequences have been folded together with the underlying Mesozoic strata and they themselves are truncated by upper sequences of conglomerates of the BI Fm. Finally, the fault disappearing laterally is substituted by a NNE–SSW striking Tertiary complex anticline which is developed on the right side of Moulouya river. Its major structural element is defined as a Central High which coincides with the underlying earlier inversion structures affecting a system of Jurassic half-grabens (Sani et al. 2000).

On the southern side of the central part of the fault F2 several structures can be seen along its length at several positions where the southern branch fault plane F2c undergoes change in strike. From north to south, the fault F2c bends sharply to a roughly N 10° E direction which limits the fault F1 westwards. As shown by the sigmoidal upright to southwards-converging folds along the fault-western bounding block, these folds indicate a left-lateral component of the displacement. To the south, the fault F2c bends again to a SW direction and thrusts conglomerates of the BI Fm which rest unconformably on eroded overturned Cenomanian strata. Further to the south, the fault F2c again bends towards a N–S direction where it is buried by alluvial fan deposits. It is locally expressed by a set of three N–S narrow anticlines (p1, p2, p3, Fig. 2a) that gently deform conglomerates of the BI Fm. These folds which are arranged *en échelon* attest to a sinistral motion. They are connected to the southeastwards-verging El Organe anticline (P0, Fig. 2a) which emerges in Quaternary deposits in front of the J. Bou Naceur thrust system (B4, Fig. 4). The second branch fault (F2d), which is further north, constitutes another steeply S-dipping fault running NE–SW. It thrusts Bajocian marls of Basin facies over Bathonian sandstones. This fault also changes abruptly in strike and connects southwestwards to the J. Bou Naceur front

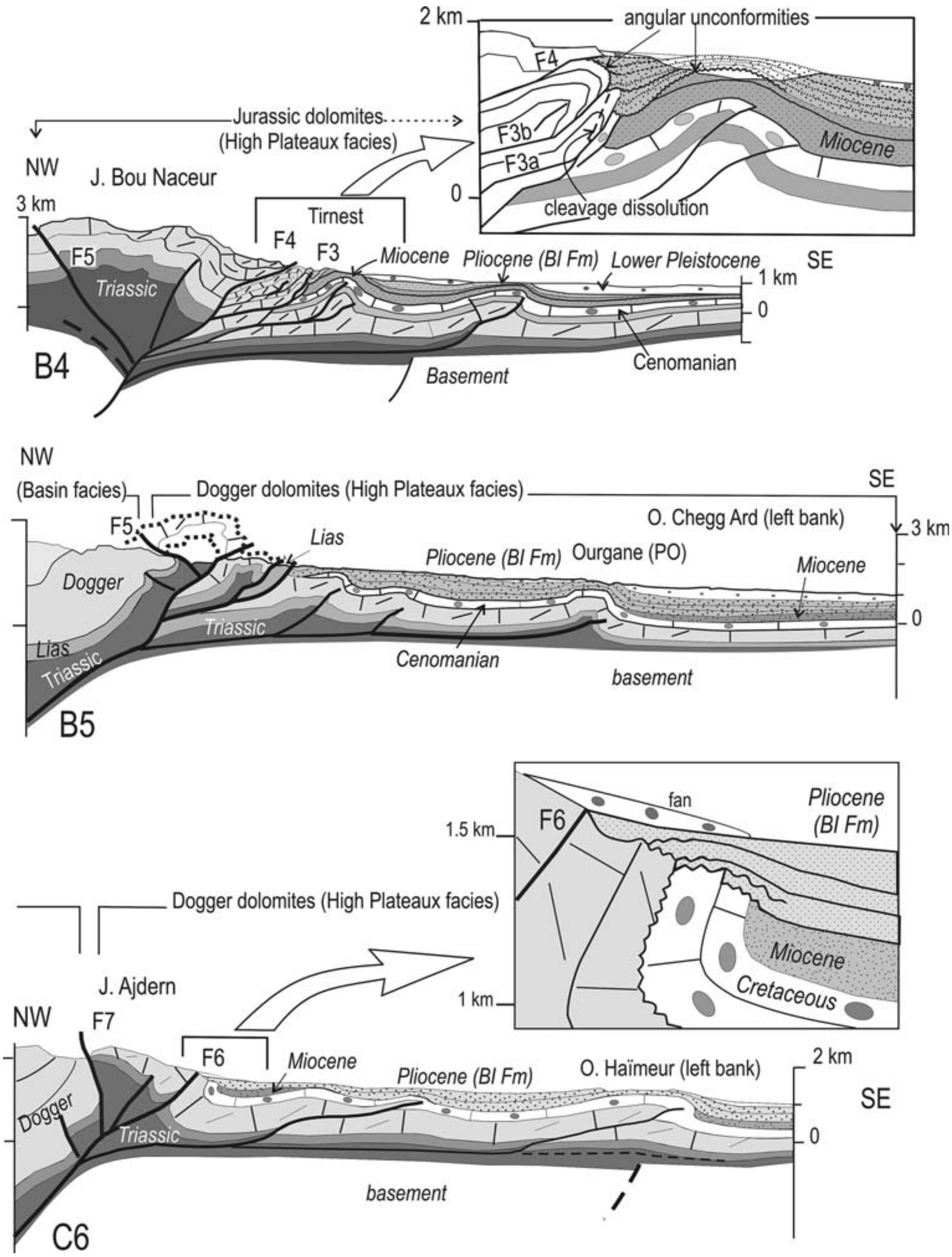

Fig. 4 Cross-sections through the SMAFZ (B4 and B5 from segment B and C6 from northern part of segment C)

thrust via a sinistral N–S trending tear fault. This front thrust continued to be active during the Pliocene and is documented in the B4 cross-section insert, where Cretaceous and the overlying BI Fm coarse deposits were faulted and folded by the J. Bou Naceur thrust system.

Segment B (The J. Bou Naceur thrust belt) (Fig. 2 and cross-sections B4 and B5 Fig. 4)

This segment is characterised by a diverging thrust fault system which superposes Jurassic dolomites belonging to the so-called High Plateaux facies onto Cretaceous and Neogene deposits of the MB to the east, and onto calcareous and marls (basin facies) of the Jurassic Middle Atlas Trough to the West. It consists of a crest separating north-west and south-east dipping fold limbs. This structural system is cut across by thrusts or conjugate reverse faults (F3, F4, F5) which are compatible with a NNW-trending maximum horizontal compressive stress (site 2, Fig. 2a). They are associated with a series of upright to overturned folds. These folds are related to either a blind SE dipping reverse fault (F5) or NW dipping ramps or flats (F3 and F4). Towards the west, the south-westward termination of the imbricate faults, well exposed in the Chegg Arg valley, shows from east to west: (1) two NW-dipping main thrust faults (F3, F4) progressively curving roughly in an E–W direction to merge with Chegg Arg fault (CAF) trending N 120°E, and (2) a blind SE-dipping reverse fault (F5) which is indicative of a break-backward faulting that is pinned against CAF. The CAF plane becomes very steep towards the west. Along its steep-dipping fault which has been partly exhumed by river incision, drag folds can be observed and they support dextral component of the fault. CAF separates the J. Bou Naceur imbricate faulted structures from the J. Ajdern faulted Anticline (JA). This faulted anticline is an upright to overturned anticline (cross-section C6). The flanks of this anticline are, respectively, cut by two faults (F6 and F7) which run roughly parallel in a NE-trending direction. Its overturned south limb, well exposed in Haïmer valley, shows vertical strata of Cretaceous limestones that rest unconformably on Jurassic dolomites of the High Plateaux (C6 insert, Fig. 4). The flank, which has been partly truncated by an erosional surface, is directly overlapped by a coarse deposit of the BI Fm that are gently tilted (15°) southeastwards. The northern limb of JA is thrusted by a SE-dipping steep reverse fault (F7) which is locally outlined by Triassic shales. This fault progressively branches into two directions: one bends southwards to become vertical on a N–S direction, whereas the second runs roughly E–W through the northern limb of the Tsiouant anticline (Tsi) and bends southwards to join the KF that has been defined as a sinistral fault (Beauchamp et al. 1996; Morel et al. 1993). Towards the south, in a N–S direction, the fault (F7a) dies out in the Neogene age coarse deposits. Further to the south, the fault itself, which is buried by Neogene sediments, is locally expressed by the J. Tamdafelt-Arhal–J. Tsiouant fold system (Ar, Figs. 2a, 5a).

Segment C (The J. Tsiouant-Arhal–J. Tamdafelt fold system) (Fig. 5a)

South of J. Ajdern, the fault plane F7a clearly shows horizontal slickensides which deform coarse deposits of Mio-Pliocene age and indicate a sinistral deplacement. This fault is replaced, just north of J. Arhal, by a very narrow anticline-fault structure (Ar) which deforms conglomerates and a lacustrine deposit of BI Fm. For this segment, (site 3, Fig. 2a), data derived from minor fault analysis connected to this fault allows calculation of transpressive stress fields with a subhorizontal $\sigma_1$orientated N 150° which indicates a sinistral transpressive movement along the N-S fault system.

Southwards, between the J. Arhal (Ar) and the J. Chebka (Ch) anticlines, the segment is characterised by *en échelon* left-stepping minor asymmetrical anticlines with axial direction striking N 40°E. They are associated with major anticlines: the J. Missour-Tarhirt (MT) and J. Tamdafelt-Chebka ridges (TC) that involve mainly the Cretaceous substratum. The axis of MT is sigmoidal and its geometry was interpreted as a Jurassic N-dipping normal fault inverted during the Cenozoic (Beauchamp et al. 1996). Southwards, TC ridge consists of two exhumed anticlines with a sigmoidal axis. Their axial directions strike from N 20°E in their southwest end to N 60°E in their eastern end. Further, these axes are offset by about 500 m by a sinistral vertical fault trending N–S. This fold system dies out southwards under the thrust fault system of the High Atlas belt directed to the North. Together these fold systems deform the Plio-Pleistocene cover.

Three active structural alignments (A, B, C) are identified on the boundary of Middle Atlas-High Plateaux in Miocene and Plio-Pleistocene. From the cross-sections, presented above, two generations of structures were discerned in each alignment: the oldest structural elements include inherited Jurassic age normal faults which constituted the eastern and north-eastern margin of the Jurassic Middle Atlas Trough. They also include the latest structures of the Neogene that are: (1) a NE-trending thrust-fault system that carried the dolomites of High Plateaux upwards. With increased contraction, the exhumed dolomites of the J. Bou Naceur block become a pop-up structure (segment B), where the dolomite strata were thrown into asymmetric folds above a reverse fault, dipping westwards, which were thrust over Upper Cretaceous, Miocene and Pliocene sediments. Here the fold-propagation that deform the Plio-Quaternary cover of the MB from the front of the Main thrust toward the foreland is possibly related to a décollement within the Triassic disharmonic layers; (2) two sets of folds (segments A and C) developed, respectively, on the North-East and on the South-West terminations of the pop-up structure (segment B), on a N–S and on a ENE–WNW direction, respectively. Both appear to have acted as transfer-faults. The first, segment A, is characterised by a set of asymmetrical anticlines that formed by the inversion of Jurassic normal faults inverted during the Neogene (Gomez et al. 1996; Sani et al. 2000). These structures are both consistent with a contemporaneous movement along a ENE to E–W-trending right-lateral, sub-vertical strike-slip fault (F1) which is inferred to run through the southern edge of the 'Horst belt' and adjacent area of the Mekam-High Plateaux. They serve as accommodation folds between

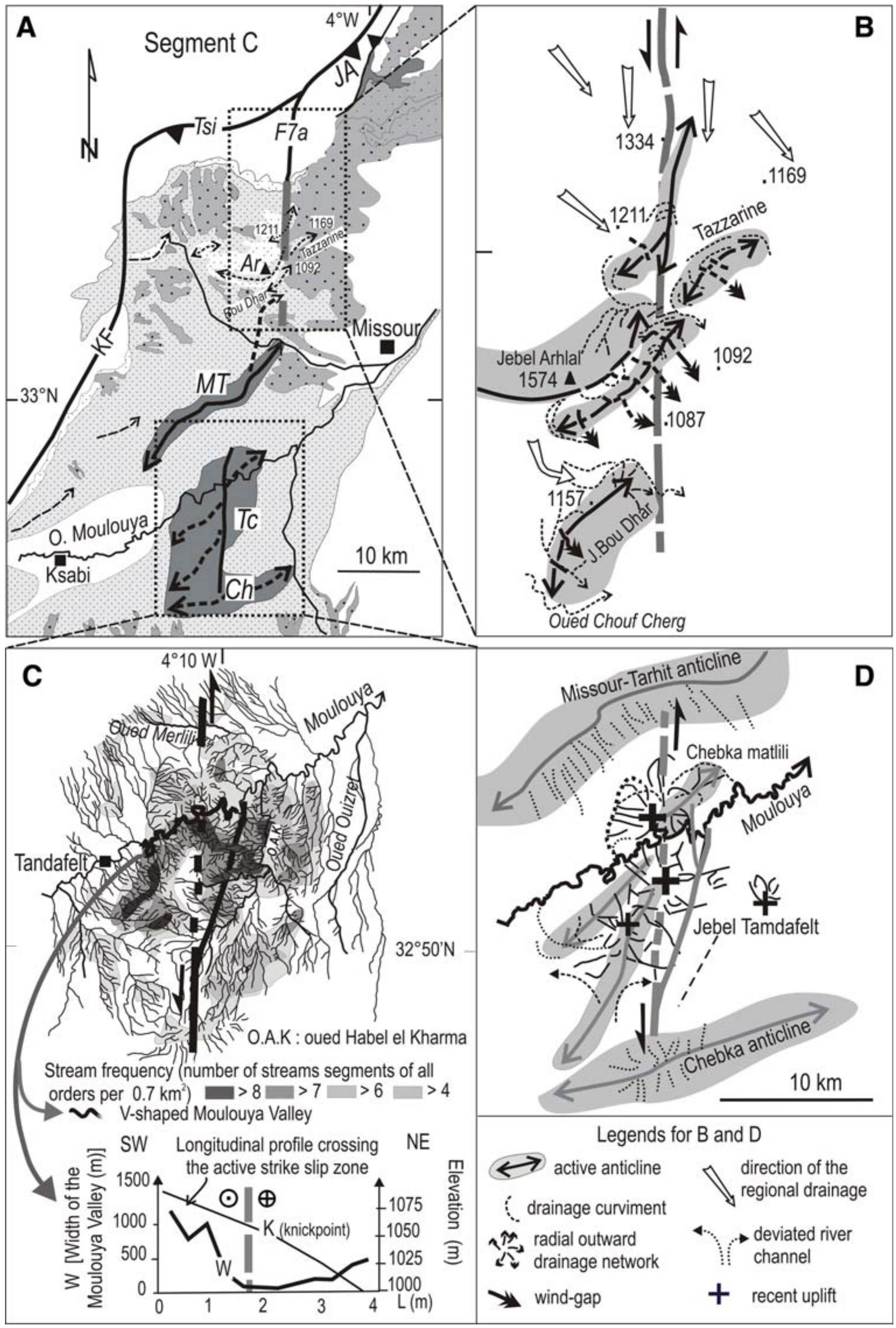

Fig. 5 **a** Geological and structural map of the SMAFZ (segment C) and of the western part of the Missour basin (same captions as Fig. 1). **b** Morphotectonic activity of the J. Bou Dhar. **c** Stream frequency and longitudinal profile segment of the Moulouya river crossing the J. Tamdafelt zone. **d** Drainage network anomalies extracted from topographical maps and Landsat TM images

the 'Horst belt' and reverse-faults systems of the segment B. The second, segment C, was active during both the Miocene and Plio-Pleistocene time. It is revealed at the surface by *en échelon* left-stepping minor anticlines and minor faults. This narrow zone of folds is manifested in a sinistral transpressive system and conforms to a N 150° E-trending shortening direction.

The Pliocene and Pleistocene record of tectonic activity

The BI Fm is exposed along both the uplifted western margin of the MB and the flanks of raised anticlines that constitute segment A and segment C structures. These structures corresponding to a coarse continental deposit which was mostly sourced by erosion of the nearby active wedge of SMAZF and the lift of the High Plateaux. The geometries of deposits, with proximal coarse facies and lateral changes, attest to a tectonic activity during sedimentation. The BI Fm deposits end with lacustrine deposits, the age of which is attributed to the Upper Pliocene (Martin 1981). A radical geomorphomological change begins at the end of the Pliocene with the incision of the Moulouya river and its tributaries that were responsible for successive alluvial fans mostly concentrated between the front wedge of Middle Atlas and the modern Moulouya river. Their geometry pattern attests to the tectonic activity that continued into the Pleistocene.

Pliocene sedimentary record of tectonic activity

Evidence for the uplift of both the northern margin of the MB and the south-eastern margin of the TGB is indicated by the depositional setting of the BI Fm. A major unconformity is expressed by a large-scale subaerial erosion, both at the south-eastern part of TGB and at the north of the MB. This unconformity is characterised in both areas by the truncation of the underlying folded Messinian marine marls (Melloulou Fm; cross-sections A1 and A2, Fig. 3) and the underlying folded and overturned Jurassic strata of the front thrust zone (cross-section A3), respectively. It postdated an early compressional event before the deposition of the BI Fm.

The BI Fm consists of several sequences of massive conglomerates interbedded with sandstones and siltstones that thicken basinwards. These deposits are expressed by fan-delta conglomerates that were deposited along narrow shelfal zones bordering the Missour bassin to the north and the TGB to the south. They interfinger with fluvial and lacustrine strata basinward and also upwards. These conglomerates were derived from hinterland relief which developed during older phases of deformation.

During sedimentation of Pliocene deposits (BI Fm) continuing deformation was recorded. Nearby the segment A structures, the conglomerates of BI Fm rest on an angular unconformity on either the Jurassic age marly calcareous deposits that correspond to the SE-dipping flank of the J. Ighrehis anticline (cross-section A3) or the marine marls of the M Fm that form the anticline termination of the J Haloua (cross-sections A1, A2) and finally on the dolomite of the High Plateaux to the south. Along segment A, from southwest to the northeast, part of the conglomerates are deformed by a NW-dipping reverse fault (F2, cross-sections A3) that limits the thick Jurassic cover southeastwards. To the northeast this fault is not observed at the surface but it is expressed with a southeastwardly inclined anticline that deforms the conglomerates. Part of these deposits is overlapped on the Jurassic marly calcareous sediments of the J. Irhezdis anticline and is folded into a syncline. This unconformity is related to the previous development of the asymmetrical pop-up structure at J. Irhezdis.

The deformation is also exemplified by the front thrust of the J. Bou Naceur pop-up structure where the successive conglomeratic sequences of the BI Fm progressively onlap northwards (cross-section B4 inset, Fig. 4). While the lower parts of the BI Fm rest unconformably on folded coarse Miocene deposits, they are thrust by a reverse fault F3a nearby the front thrust. This fault does not cut the medium sequences that have onlapped the strongly deformed dolomite of the eroded thrust sheet showing pressure cleavage. These sequences of coarse deposits are cut by the stacking of another sheet (F3b) that is onlapped by the upper part of the BI Fm that are finally cut by third unit (F4). The fact that they are successively thrusted by the stacking of a new sheet indicates that the deformation was still continuing. They have recorded the local uplift of the J. Bou Naceur pop-up structure caused by an out of sequence thrusting process. To the South, the BI Fm shows a basinward lateral transition from massive conglomerates to reddish sandstone and minor conglomerates that are locally flexured and their thickness variations associated with local internal unconformities argue for a Pliocene activity.

The geometry of the BI Fm and the Jurassic underlying rocks suggests a folding followed firstly by an erosional episode and then by a rotative onlap of the coarse conglomerate deposits caused both by the uplift and the re-folding of the pop-up structure during the Pliocene. In some places, these conglomerates lie on successive angular unconformities over: (1) an overturned eroded anticline (cross-section A2, Fig. 3 and cross-section C6 inset, Fig. 4) where they have been folded together with the underlying Mesozoic strata; and (2) they sealed successive thrust sheets (cross-section B4 inset, Fig. 4) where several syntectonic angular unconformities related to an overall composite progressive unconformity can be observed. These internal unconformities indicate the contemporaneous occurrence of tectonic pulses of uplift with sedimentation. Thus, from the front thrust to the basin, but even in the flanks of synsedimentary folds of segments A and C, lateral transitions from syntectonic angular unconformity to progressive unconformity can be observed in the conglomerates. These assembled composite progressive unconformities emphasise the synsedimentary character of the Pliocene deformation.

Pleistocene record of tectonic activity

The northwestern margin of the Neogene MB has been overlapped by alluvial fans which are located at the foot of the thrust-fault segments of the SMAFZ (Fig. 6). Morphometric analysis of twenty-five selected fans have been used to determine modern tectonic activity during the Quaternary by studying the arrangement of ancient alluvial fans, variability of modern fans and topographical effects of active structures.

Ancient alluvial fans

Large fossil alluvial fans, with truncated apices, have been identified using Landsat imagery (http://www.zulu.ssc.nasa.gov/mrsid/). Their topographic profile shows irregularities and morphological scarps within the alluvial fan deposits. These scarps are mostly rectilinear and vary in size from 2 to 10 km in length (Fig. 6 inset). In the Chegg Ard valley segmented radial-fan profiles and incision of the fan-heads are developed (Fig. 7a). The Chegg Ard alluvial fan system is composed of four stepped surfaces, from the youngest (Qf5) to the oldest (Qf1). The apices of Qf1 and Qf2 overlap the thrust front. In this dry river, the fan system is characterised by five entrenchments. The oldest segmented fans are located in the middle of the

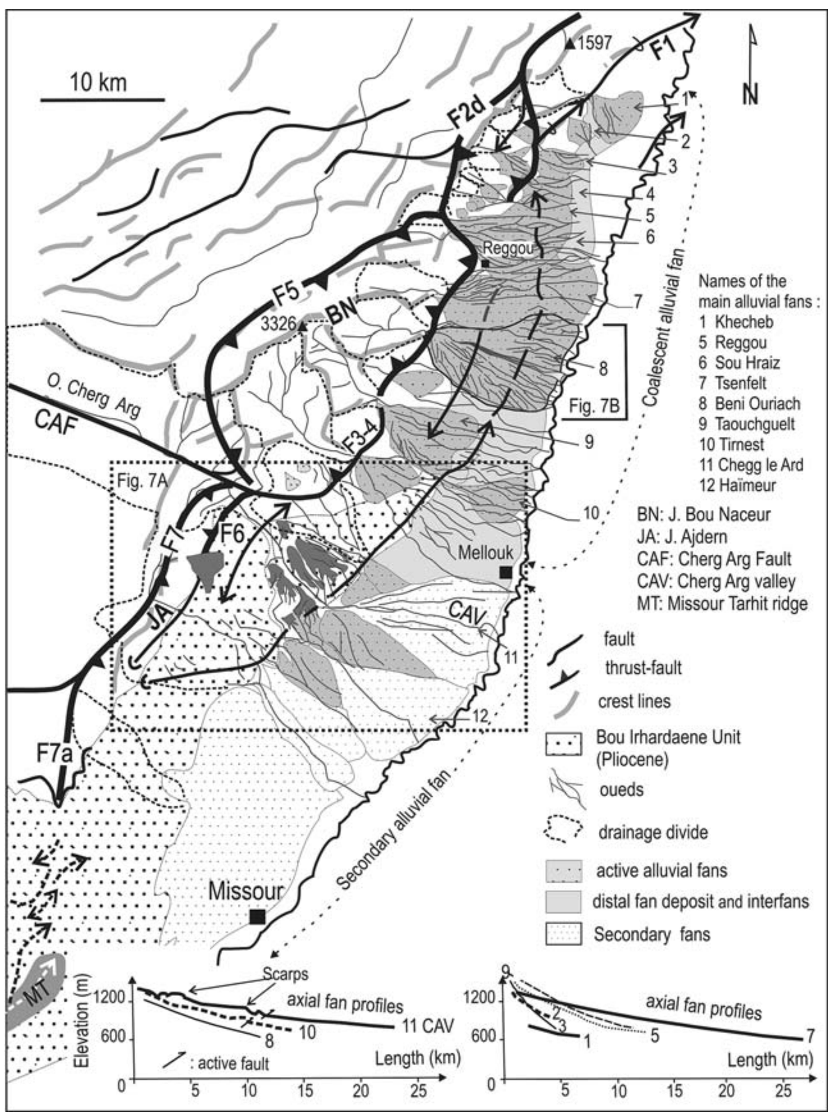

Fig. 6 Map of the alluvial fans and physiographic features of the mountain front and the Missour basin. *Insert*: longitudinal profiles of the main fans

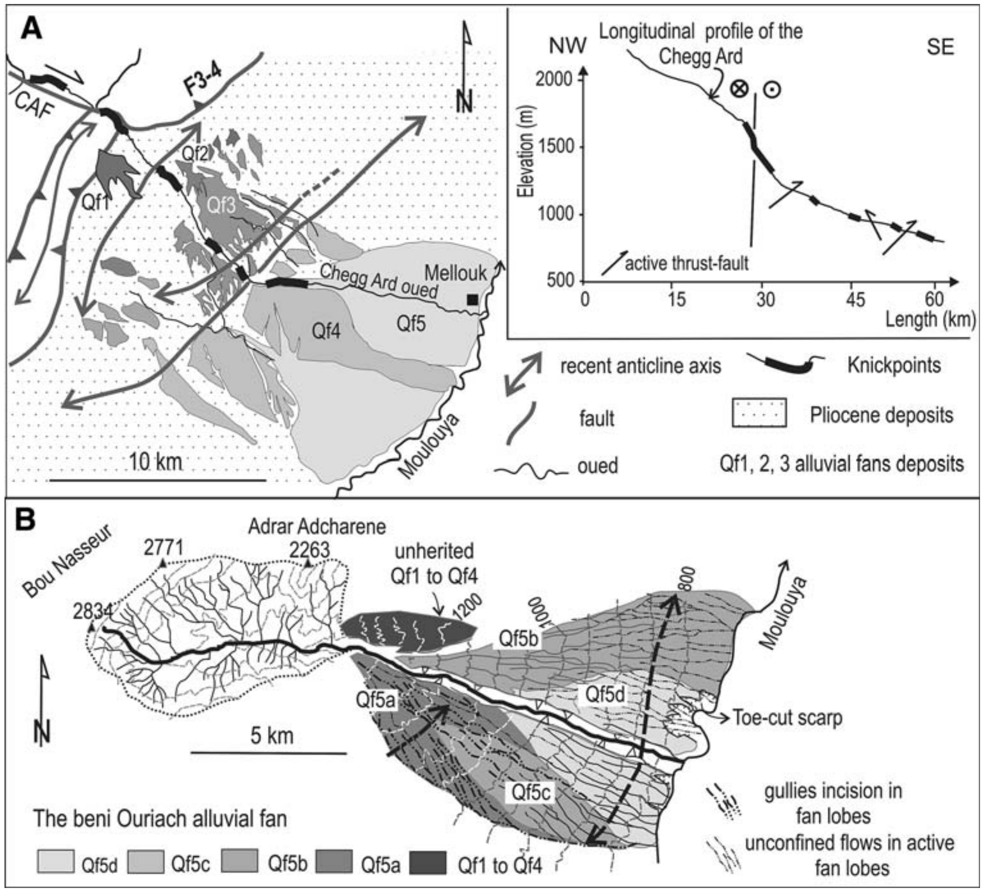

Fig. 7 Relationship between alluvial fans and drainage basins systems. **a** The Chegg Ard alluvial fan system (No. 11, Fig. 6). *Insert*: longitudinal profile of the Chegg Ard oued channel. **b** Relationship between drainage basins and the beni Ouriach alluvial fans (No. 8, Fig. 6)

northwestern valley while the youngest are situated close to Moulouya river in the southeast. The steepening of the oldest fans (Qf1, 2, 3) with a concomitant down-fan shift in the depositional area attests to uplift tectonics and the growth of anticlinal ridges.

Variability of modern alluvial fans

Two fan-system deposits, on the western border of the MB, are observed from the NE to the SW (Fig. 6). In the NE part large coalescent alluvial fans form a bajada and in the SW part, secondary fans resulting from localised drainage of abandoned areas of primary fans.

Large coalescent alluvial fan system Four morphometric parameters indicate strong variability of constructional landforms: (1) increased size of surface of fans (4–30 km^2) and drainage basins; (2) fan radii ranging from 2–5 km in the NE border to 9–13 km in the central and SW border. Large-radial fans with a low angle (< 60°) indicate a high sediment supply/subsidence ratio on the basin margin (Viseras and Fernandez 1994); (3) the width of the fans varies from 1.5 to 8 km; and (4) their slope decreases from 4° to 2°, but locally, the fan apex gradient can reach 10°. The steep slope of the fans (2, 3, 5 and 9, Fig. 6) is related to their small drainage basins and suggests SE tilting. The delimitation of functional and abandoned fan sectors includes drainage network and longitudinal profiles of oueds.

The Beni Ouriach alluvial fan has a steep gradient from the fanhead (~9°) to the distal part (2–3°) (Fig. 7b). This fan consists of five surfaces at different heights: the highest is referred to as Qf1; the other segmented fans (Qf2–Qf5) indicate the recent morphosedimentary evolution of stacked fan lobes. Further to the southwest, the trunk stream, which cuts deeply into the fan deposits and the entrenchment of the Beni Ouriach fan system, are the result of uplift movement. In the distal part of the Holocene Qf5 set, active toe-cutting follows the avulsion of the Moulouya axial channel.

Secondary fan system From Mellouk, fans are resulted from the accumulation of large debris transferred from actively dissected drainage basins inside primary fans located further upslope (Fig. 6). These fans are actively prograding onto floodplains. The reworking of the proximal parts of successive fan accumulations is linked to the uplift of the source area.

Large accumulation of debris results from active drainage basin dissection followed by a propagation of uplift from range front to the MB.

Summing up, the uplift of the source area induces linear erosion by streams which cause alluvial fan deposition and fan rebuilding. Uplift and Jurassic lithology (High Plateaux and basin facies) influence stream incision and control morphological development of the fans. Dissected and the entrenched lobes of fans indicate two steps in their evolution: first, uplifting of the areas of clastic deposition; second, folding propagation in the piedmont plain from NW to SE.

Geomorphological evidence of topographic effects of active thrust and strike-slip fault zone

The digitised topography and river channels crossing active structures reflect the interaction between erosion and active tectonic processes. Observations have been made on the 11 channel profiles that cut across the SMAFZ. The Chegg Ard drainage basin is steep (Fig. 7a). It has a concave-up profile with a low concavity ratio of the stream long profiles which are consistent with the relatively youthful and uplifted watersheds. The analysed stream long profiles show several knickpoints that correspond closely to active structures (Fig. 7a insert) and changes in rock-types observed locally. Four slope breaks, which coincide with an active strike-slip fault (CAF), main thrusts and frontal anticlines, indicate tectonic uplift.

Along segment C, (Figs. 2, 5), anomalies associated with drainage pattern, channel incision, thalweg longitudinal profiles and course deflection have been identified. Along the Jebel Arhlal (Ar, Fig. 5b) streams outline *en-échelon* anticlines developed above a blind N–S sinistral strike-slip fault. Geomorphological features diverted drainage valleys. Anomalies consist in antecedent rivers, such as some rivers, perpendicular to the drainage divide through the anticline axis (Bou Dhar and Tazzarine anticlines). These rivers have maintained their original course during the growth of anticlines. Some thalwegs show air gaps along the anticlinal axis suggesting a stream system predating uplift of the ridges. The exhumed anticlines, such as the Ar and Tazzarine, show radial and annular drainage patterns superimposed around the anticlinal terminations. In the northern part, most fluvial reaches are aligned N–S along the strike-slip fault (F7a, Fig. 5a).

The Tamdafelt-Chebka ridge (Fig. 5c, d) exhibits different drainage patterns which can be divided into three parts: (1) a regular system of parallel and trellis streams that dissect the flanks of rising anticlinal and monoclinal structures; (2) an arcuate course of streams and annular curviments in relation to the propagating ends of anticlinal ridges, and (3) a pronounced radial drainage system and inflection patterns suggesting recent uplift of ridges producing active push-up structures (Fig. 5d). Several rivers trend north–south cutting deep V-shaped valleys. They are guided or deflected by north–south active strike-slip faults. Stream frequency ($Fu = \Sigma Nu/Au$), defined by the sum of the number of all rivers in one square unit area ($Au = 0.7\ km^{-2}$), depends on bedrock characteristics and uplift. The TC, which is dominated by high-stream frequency (> 6 rivers/0.7 km^2) and is shown in Fig. 5c, is in contrast to the adjacent watersheds of low-stream frequency. The anomalous drainage pattern (trellis- and radial-drainage networks), developed on elongated blocks, suggests the uplift of ridges located in the north–south active strike-slip fault zone.

Discussion

From these observations, it appears that thrusts at the present exposure level on the South-eastern border of the Middle Atlas belt result from the rejuvenation of Jurassic age normal faults that took place during the Upper Miocene-Pliocene and the Pleistocene. Details of inversion structures along the SMAZF are distinct and consistent.

From the analysis of Fig. 8a and b, it is clear that the recent thrust ramps and fold pattern are obliquely placed in comparison to the eastern bounding fault of the Jurassic Middle Atlas basin. In the southern part, along segment B, thrusts and folds are developed apart from the Jurassic basin margin fault and passed from calcareous-marly alternations (basin facies) to the dolomite platform of High Plateaux, while in the north-eastern part (segment A), thrusting and folding are developed only in the thicker Jurassic series of basin facies and their overlying Neogene deposits in the Taza Guercif Basin. Whereas on both sides from an inflexion zone located between segments A and B (Fig. 8b), a radical change in thrust geometry can be observed. In the southern part, deformation is characterised by a complex pop-up structure related to thrusts faults, imbrication and folding of dolomite associated with backthrusting and foreland propagating faults. By comparison, in the northern part, deformation is concentrated only in the Mesozoic subsided block of the Middle Atlas Trough that corresponded to a complex asymmetrical structural depression dipping north-eastwards in Jurassic times (Fig. 8a) where

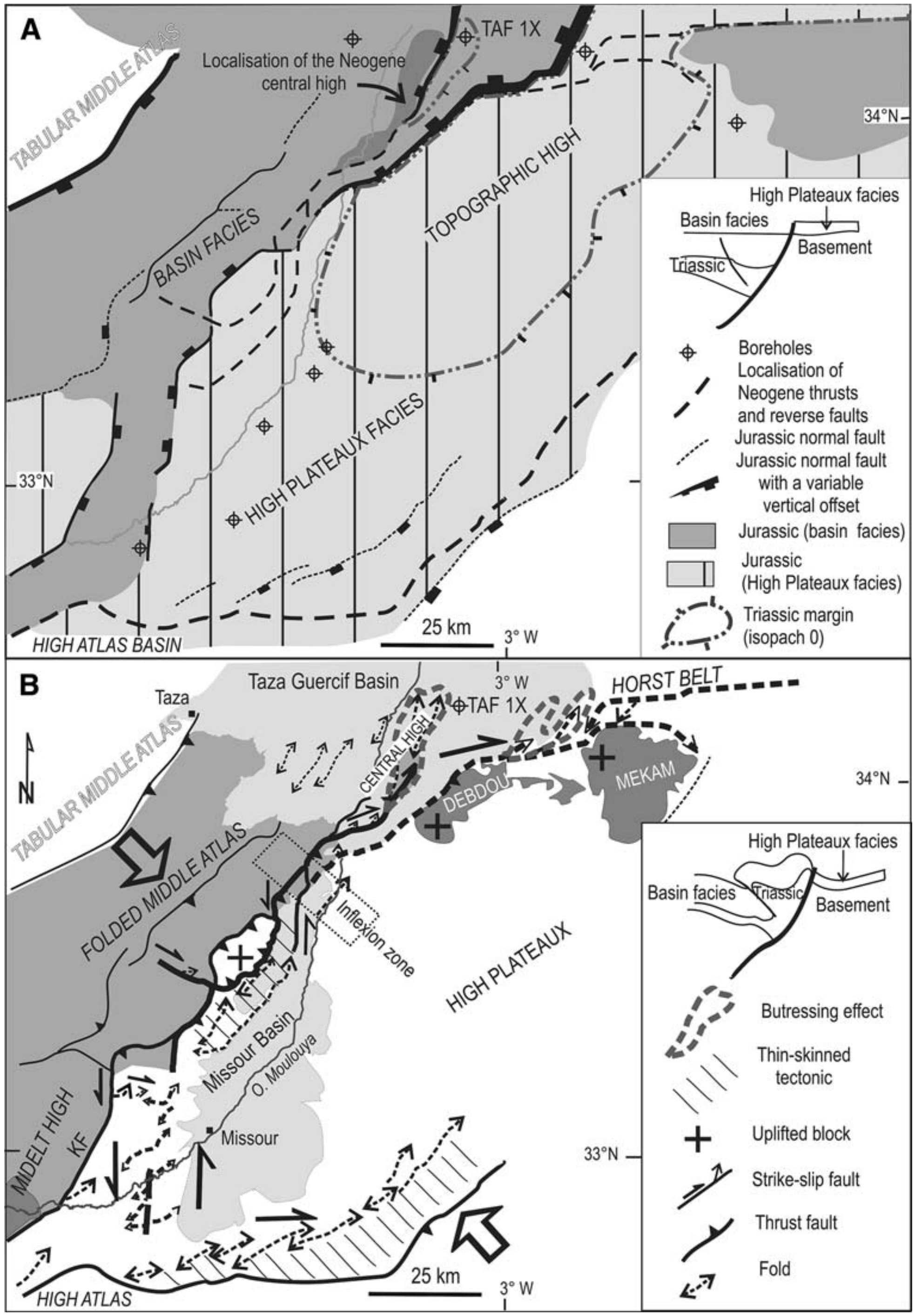

Fig. 8 **a** Reconstruction of the basin/platform configurations in the Eastern Morocco during the Middle Jurassic, showing the stratigraphical relationships between a subsiding rhomb-shaped basin and its south-western adjacent tilted platform. **b** Reactivation of older structures during the Plio-Pleistocene. This reactivation is linked with the geometries of the Jurassic fault systems that control the detachment levels, fault trajectories and apparent fault sequences with the development of backward- and upward-thrust faults produced by the buttress effect of a footwall block

Dogger basin facies attained a maximum thickness north of Guercif (5,000 m). Thinning of these Dogger sediments has been observed in south-westwards where they overlap a Liassic carbonate platform and filled-up small subsident 'ombilics' (El Hammichi et al. 2002). The deformation is marked by folding and reverse faults often injected by Triassic evaporites that have affected both Jurassic sediments and their overlying Neogene deposits. These structures form a Central High that can reach up to 1,000 m. Further to the North, it is bounded to the east by a west-dipping fault adjacent to a tilted-basement block identified by seismic profiles and boreholes (Sani et al. 2000). Indeed, this basement block is directly overlapped by thick Liassic carbonate which is capped by thick sequences of Dogger and Late Jurassic marls. The TAF 1X borehole basement was reached at a depth of 3,800 m. Thus, this elevated block trends northwards obliquely to the northern High Plateaux scarp where the basement (Debdou) is at 1,600 m. The High Plateaux block, where an Upper Triassic sequence with argillaceous and sandy beds is absent, is separated from the basin facies Jurassic series by a blind fault (F1). This formed a permanent Mesozoic high that dipped southwestwards.

On its south-west margin beneath the carbonate platform, the presence of Upper Triassic deposits have been identified by boreholes and seismic profiles (Beauchamp et al. 1996), and they thicken both southwards in the High Atlas and northwards in the Middle Atlas (Fig. 8a). It appears that anticlinal stacking of dolomite sheets, associated with piggy-back deformation sequences, developed in front of the Bou Naceur wedge to have a direct relationship with the presence of a thrust detachment in the Triassic evaporites.

In summary, the Neogene inversion has inherited: (1) a Mesozoic asymmetric geometry of three adjacent blocks composed of a Jurassic topographical high (High Plateaux) that dips south-westwards, a fault-bounded Jurassic trough (Middle Atlas basin) that dips north-eastwards and is infilled by thick sequences of marls, and a tilted basement block where Triassic deposits are absent, within the Jurassic trough. These three blocks are separated by westward-dipping Jurassic normal faults system that controlled subsidence with an north-eastward deepening low; and (2) the presence of Upper Triassic deposits which have controlled the basal detachment of the Jurassic cover.

Consequently, in northern areas, folding developed because of thrust detachment in the Triassic evaporites is blocked by rigid basement (Debdou) in the footwall of the pre-existing normal fault. The narrow folding belts that constitute the Central High can be considered as diagnostic of buttressing by early normal faults that dip back to the orogenic hinterland (Gillcrist et al. 1987). In the southern areas, thick-skinned compressional deformation is recorded by stacking of dolomite thrust sheets (High Plateaux facies), which produced a structural high elevation up to 3,400 m. Such a geometry, which associated a structural high and backthrusting, may have been depended on the buttressing effect of an hypothetic Triassic or Jurassic normal fault or footwall shortcutting fault. Nevertheless, the structures result from the underlying Triassic evaporites that have favoured décollement and a thin-skinned deformation. Elsewhere, a forward migration of the fluviatile terrace deposits belonging to the Moulouya river, with stepping and incision (T3 to T1) that is associated with the growing of a ramp-anticline (inset A3, Fig. 3), indicates that the deformation was still continuing during the Pleistocene. Locally, further to the north, the buttressing effect has probably favoured the deep incision of the Moulouya river (220 m) through the BI Fm representing alluvial fan deposits. In contrast, in front of the Bou Naceur wedge, the development of thin-skinned tectonics is recorded by uplifted imbricate fans that have been moved SE-wards, and by the inner conglomerates (BI Fm) that are incised and reworked forward in large recent alluvial fans. The shape of these alluvial fans indicates a high sediment supply linked to a low subsidence rate in the MB.

The interpretation of these data suggest that the SMAZF is a complex inversion structure. It was initiated during the Upper Cretaceous to Early Miocene (Vially et al. 1994; Zizi 1996) and continued to develop through the Plio-Pleistocene (this paper). Tortonian conglomerates, overlapping transverse palaeovalleys that cut through the Central High, have been laterally folded and exhumed by rapid uplift and partly reworked by the BI Fm. This Pliocene continental formation outcrops on the flanks of anticlinal structures where progressive syntectonic unconformities with basinward coarse-deposit progradation record the contemporaneous onset of the final growth of the anticlines.

As a consequence the distribution of all the structures analysed appears to highlight a rough NW–SE oriented shortening which is perpendicular to the folded Middle Atlas, but oblique to the N–S trend of the Midelt High to the south-west and the E–W trend of the Horst belt to the north (Fig. 8b). Considering the regional kinematic implications from these structures in the geodynamical evolution of the western Mediterranean region, they are related to the convergence of the European and African plates. A variety of tectonics models have been proposed to define the plate boundary between Africa and Iberia (e.g. Torres-Roldan 1986; Platt and Vissers 1989; Sanz de Galdeano 1990; Docherty and Banda 1995; Calvert et al. 2000; Gutscher et al. 2002). This boundary remains in a state of uncertainty. Nevertheless, in the Pliocene and Pleistocene plate motions reasserted control of the deformation in the Maghrebian region with primarily NW–SE shortening and strike-slip faulting (Fig. 9a). This complex local neotectonic setting involved a north-westerly migration of a central block, namely the High Plateaux that was considered as an indenter (Piqué et al. 1998), limited by two main transfer zones: the Middle and High Atlas belts to the west and the Tunisian Atlas to the east.

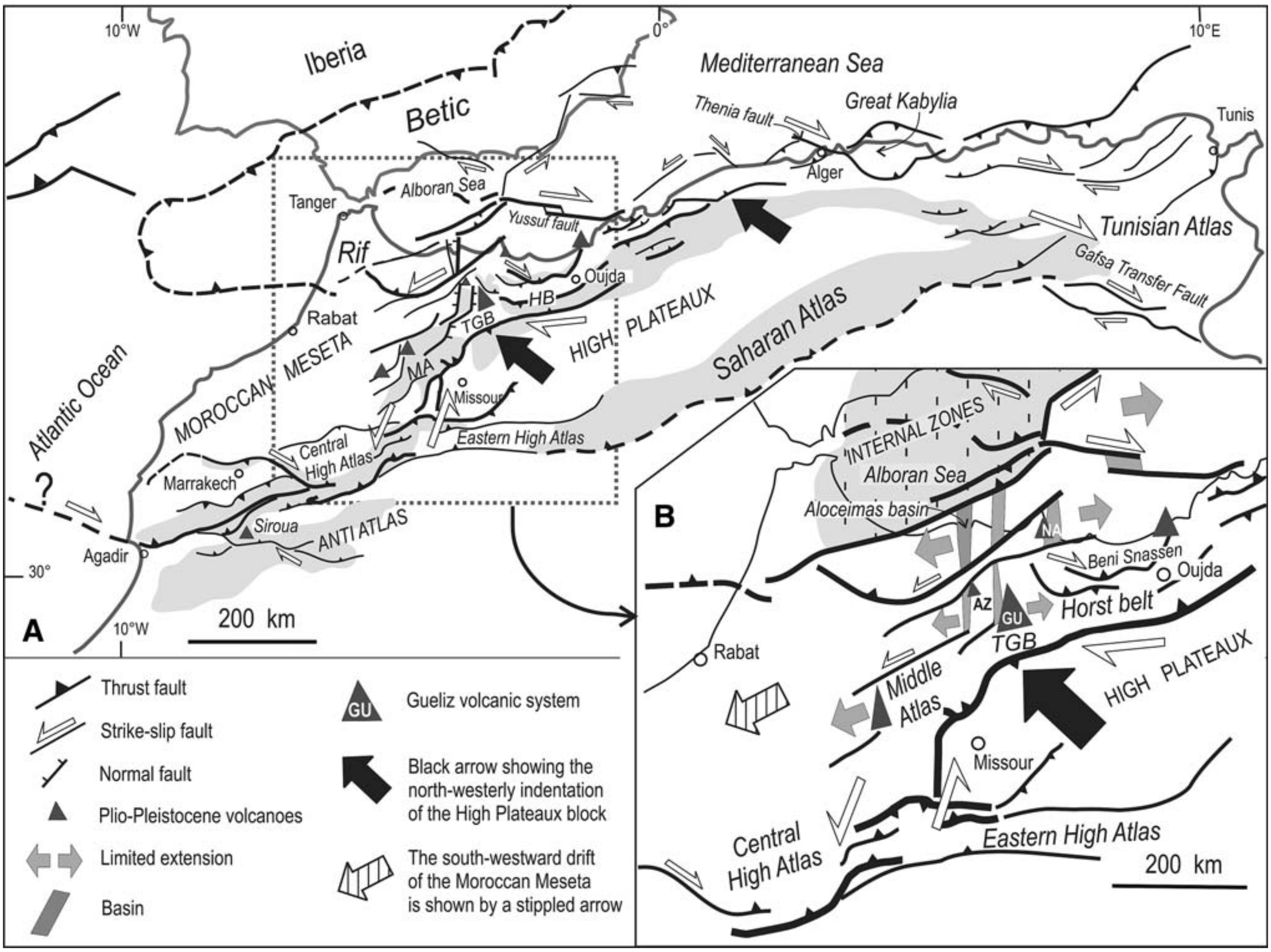

Fig. 9 **a** Structural map illustrating the spatial relationships of the High plateaux indenter between the main structural domains of the North Africa during the Plio-Pleistocene (adapted from Barrier et al. 2005). **b** Tectonic interpretation from the data analysed in this study and from the offshore geology (Meghraoui et al. 1996)

In this convergent setting, the Internal zones of the arcuate Betic and Rif mountain belts are uplifted and fragmented (Martinez-Diaz and Hernandez-Enrile 2004). Fragmentation occurred along dextral N 110 ± 20°E trending strike-slip faults such as the Yussuf fault (Meghraoui et al. 1996) and the Thenia fault that bounds the compressed and uplifted Great Kabylia block (Boudiaf et al. 1999; Yelles-Chaouche et al. 2006; Domzig et al. 2006) and other faults belonging to the Gafsa transfer zone (Ouattani et al. 1995). This fragmentation is also observed along sinistral faults (Fig. 9b) that are predominant in the western Magrebian region where they are distributed over a broad zone more than 100 km wide stretching from the Alboran sea to the High Atlas. Zones of local extension have occurred roughly along N–S trending normal faults. They delimit long and narrow grabens that subsided rapidly such as the Plio-Pleistocene Aloceimas basin (Saadi et al. 1984; Ait Brahim and Chotin 1989). This extension is accompanied by limited potassic volcanism that occurred in the north-eastern part of the Morocco during the Pliocene and that was superseded by alkaline basaltic magmatism in the Pleistocene (El Bakkali et al. 1998). This alkaline volcanism that extends from Oujda to Siroua (Fig. 9a) is predominantly distributed on the northern border of the Neogene Taza Guercif basin (TGB), Guilliz volcanic system (GU), and further to the north, Ain Zohra (AZ) and Nador volcanic systems (NA). Furthermore, in the Middle Atlas localisation of volcanoes and dikes are linked to limited extension controlled by sinistral strike-slip motion (Harmand and Moukadiri 1986).

Situated along the western arcuate flank of the High Plateaux indenter, the Middle Atlas and the Horst mountains belts have partly accommodated the Cenozoic shortening by inversion of Jurassic basins such as the Middle Atlas and the Beni Snassen basins (Fig. 9b). In the Pliocene and Pleistocene the NW-trending convergence reasserted thrusting and strike-slip faulting characterized by limited extension situated mostly to the north and to the north-west of the meeting boundary of the East Moroccan Meseta and the West High Plateaux block.

Conclusion

The structural relationship between the position of frontal-thrust system of J. Bou Naceur (segment B) and the distribution of two lateral ramp systems (segments A and C) is certainly a response to north-westerly directed motion of the High Plateaux block. This motion corresponds closely to the kinematics of the African plate and especially to its NW-trending convergence with the Iberian plate that has occurred since the Pliocene.

The thrust fault system of the SMAFZ may partly accommodate north-westwards directed motion of the High Plateaux indenter (Figs. 8b, 9b). Also, worth noting are the geometries of the positive inversion structures and the buttressing effect that are clearly dependent on the geometry and sedimentology of the original basin-controlling fault system and on the presence of a décollement surface. In the Atlas domain the last episode of inversion occurred during the Upper Messinian and continued through the Plio-cene-Pleistocene. During this period the inverted basin of the Middle Atlas and its south-frontal rising thrust acted as a source area of coarse continental deposits that spread out to form the BI Fm. This rise has resulted in an unconformity at the base of this stratigraphical interval and synsedimentary movements of the SMAFZ are recorded within these conglomerates by the development of progressive unconformities. Since the Early Pleistocene, the Moulouya river and its transverse distributaries have strongly incised both topographic highs and the BI Fm. Uplift causing migration and perturbation of the Moulouya river and its tributaries and erosion seem to be the dominant process which is still continuing at present.

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