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Late Cretaceous to Paleogene Post-obduction extension and subsequent Neogene compression in the Oman Mountains

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ABSTRACT

After the obduction of the Samail ophiolitic nappe onto the Arabian Platform in the Late Cretaceous, north Oman underwent several phases of extension before being affected by compression in the framework of the Arabia-Eurasia convergence. A tectonic survey, based on structural analysis of fault-slip data in the post-nappe units of the Oman Mountains, allowed us to identify major events of the Late Cretaceous and Cenozoic tectonic history of northern Oman. An early ENE-WSW extensional phase is indicated by synsedimentary normal faults in the Upper Cretaceous to lower Eocene formations. This extensional phase, which immediately followed ductile extension and exhumation of high-pressure rocks in the Saih Hatat region of the Oman Mountains, is associated with large-scale normal faulting in the northeast Oman margin and the development of the Abat Basin. A second extensional phase, recorded in lower Oligocene formations and only documented by minor structures, is characterized by NNE (N20°E) and NW (N150°E) oriented extensions. It is interpreted as the far-field effect of the Oligocene-Miocene rifting in the Gulf of Aden. A late E-W to NE-SW directed compressional phase started in the late Oligocene or early Miocene, shortly after the collision in the Zagros Mountains. It is attested by folding and strike-slip and reverse faulting in the Cenozoic series. The direction of compression changed from ENE-WSW in the Early Miocene to almost N-S in the Pliocene.

INTRODUCTION

The tectonic evolution of Oman (Figure 1), commencing in the Late Cretaceous, was marked by four major geodynamic events: (1) obduction of the Samail Ophiolite in northern Oman (Figure 2a); (2)

obduction of the Masirah Ophiolite in eastern Oman associated with the northward drift of the Indian Plate (Figure 2b); (3) rifting and oceanic spreading in the Gulf of Aden along the southern boundary of the Arabian Plate (Figure 2c); and (4) collision of the Arabian Plate with the Eurasian Plate in the Zagros region (Figure 2c; Beydoun, 1970; Glennie et al., 1974; Moseley and Abbots, 1979; Cochran, 1981; Robertson and Searle, 1990; Le Métour et al., 1995a; Loosveld et al., 1996; Immenhauser et al., 2000; Breton et al., 2004).

In this paper we present the analysis of outcrop-scale fractures identified in the Upper Cretaceous and Cenozoic post-nappe succession in the Oman Mountains (Figure 1). Figure 3 presents the facies and depositional environment of this succession, which includes the Aruma, Hadhramaut, Dhofar, and Fars groups and included formations (Nolan et al., 1990; Béchennec et al., 1992; Wyns et al., 1992b; Le Métour et al., 1992b, 1995b). The fractures in this succession were used to reconstruct local stress tensors, and to infer the regional paleostress field since the Late Cretaceous. The post-Late Cretaceous stress history, in turn, allows us to interpret the tectonic evolution of the Oman Mountains in much greater detail than in previous studies. In particular, this study highlights an epidode of extensional deformation that prevailed during the Late Cretaceous and early Cenozoic times, prior to the final collisional phase. The following two sections provide a brief review of the post-Late Cretaceous tectonic setting of the Oman Mountains, and tectono-stratigraphy of the post-nappe sedimentary succession.

TECTONIC SETTING OF THE OMAN MOUNTAINS

In north Oman, the Samail Ophiolite associated with the Sumeini and Hawasina nappes was obducted onto the northeastern margin of the Arabian Platform in the Late Cretaceous (Figure 2a; Coleman, 1981; Nicolas, 1989; Searle and Cox, 1999). The Samail Ophiolite represents relicts of Cretaceous (upper Albian-Cenomanian) oceanic crust of the Neo-Tethys Ocean (Beurrier, 1987; Beurrier et al., 1987). Before the obduction, the margin was dominated by carbonate sedimentation since the Late Permian times (Rabu, 1987; Le Métour, 1987; Le Métour et al., 1995a). The last stable carbonate platform covering Oman is represented by the Natih Formation of late Albian to earliest Turonian age (Hughes-Clarke, 1988; Scott, 1990; Van Buchem et al., 1996; Terken, 1999). Uplift, emergence and erosion of the Arabian Platform in the early Turonian were the first manifestations of the convergence in the continental domain. This broad doming was followed in the early and middle Turonian by rapid subsidence and the development of a foreland basin in front of the thrusted nappes (Patton and O'Connor, 1986; Robertson, 1987a; Béchennec et al., 1995), or alternatively in front of an intracontinental subduction zone (Breton et al., 2004). The pelagic sediments of the Turonian to Santonian Muti (or lower Fiqa) Formation were deposited in the foreland basin (Robertson, 1987b; Rabu et al., 1990; Le Nindre et al., 2003). The Natih Formation is cut by numerous normal faults that are imaged on seismic profiles, and they either die-out in, or are sealed by, the unconformable deposits of the Muti Formation (Boote et al., 1990). These faults are related to the bending of the platform in response to the crustal loading by the nappe stack (Boote et al., 1990; Warburton et al., 1990; Breton et al., 2004). Nappe emplacement in the foreland basin ceased in the latest Santonian-early Campanian times. The deformation was sealed by the middle Campanian beds of the Fiqa (or upper Fiqa) Formation, which rests on the front nappes (Mann and Hanna, 1990). After emplacement of the Samail Ophiolite, shallow-marine sedimentation resumed and carbonates were deposited by successive transgressions during Maastrichtian to late Eocene times (Nolan et al., 1990; Skelton et al., 1990; Le Métour et al., 1995b). Afterwards, the Arabian Platform was largely emergent from late Eocene to early Miocene times.

In eastern Oman, the Masirah Ophiolite represents relicts of Upper Jurassic oceanic crust formed at the latitude of the Somali Basin, between the Indian-Madagascar and Arabian-African plates (Gnos and Perrin, 1996; Gnos et al., 1997). It was emplaced along the eastern Oman margin in the Masirah Island and Ra's Madrakah area during late Maastrichtian-Paleocene times (Figure 2b; Beurrier, 1987; Mountain and Prell, 1990; Shackleton and Ries, 1990; Smewing et al., 1991; Peters and Mercolli, 1997; Schreurs and Immenhauser, 1999; Peters, 2000). Ophiolite emplacement postdated the deposition of the upper Maastrichtian Fayah flysch unit on the oceanic crust (Immenhauser, 1996), and predated the deposition of the unconformable Eocene to lower Oligocene autochtonous deposits above the ophiolite sequence (Le Métour et al., 1992a; Peters et al., 1995). The late Maastrichtian-Paleocene time span of obduction coincides with the start of accretion on the Carlsberg Ridge (Royer et al., 2002). The Masirah oceanic crust (which later became the Masirah Ophiolite) thus formed earlier than the Samail oceanic crust of northern Oman, and was obducted later, during the northward drift of the Indian Plate along the eastern margin of the Arabian-African Plate.

In the Gulf of Aden, rifting started in the Oligocene Epoch and continued until the early Miocene time (Figure 2c; Roger et al., 1989; Watchorn et al., 1998). Rifting induced the formation of a series of grabens along the Gulf of Aden (Beydoun, 1970, 1982; Tamsett, 1984; Platel and Roger, 1989; Abbate et al., 1993; Fantozzi and Sgavetti, 1998). These grabens accumulated calciturbidites of the Chattian to Burdigalian Mughsayl Formation representing typical synrift deposits with slumps, megabreccia, debris flows, and olistolitic material (Roger et al., 1989). Two directions of extension prevailed during the rifting: (1) a N20°E direction, parallel to the direction of opening of the Gulf of Aden; and (2) a N150°E direction, perpendicular to the N75°E mean trend of the Gulf of Aden (Lepvrier et al., 2002; Huchon and Khanbari, 2003; Fournier et al., 2004). The start of oceanic spreading occurred at about 18 Ma (Sahota, 1990; Leroy et al., 2004) and is currently active at a rate of 2.2 cm/year along N25°E at the longitude of Dhofar (Fournier et al., 2001).

In northern Oman, compression resumed after a period of stable carbonate sedimentation and is recorded by a change of sedimentation in the upper Early Miocene to Pliocene deposits of the Fars Group: from open to shallow-marine carbonates, and to evaporitic and continental molasse deposits. The autochtonous sedimentary cover, allochtonous nappes complex and the neoautochtonous sedimentary cover were affected both in the axial zone (Saih Hatat, Jabal Akhdar, Hawasina window, Musandam Peninsula; Figure 1) and the foreland basin of the Oman Mountains (Salakh Arch) by large-scale folding, short-distance thrusting, and uplift (Searle et al., 1983; Michard et al., 1984; Searle, 1985; Poupeau et al., 1998; Mount et al., 1998; Al-Lazki et al., 2002). All these broad structures indicate that only limited horizontal shortening occurred. Cenozoic compressional deformation is evident in the northernmost Oman Mountains and the Musandam Peninsula, where it can be correlated to the Zagros collision belt in Iran (Ricateau and Riché, 1980; Searle et al., 1983; Searle, 1988; Boote et al., 1990; Regard et al., 2005; Kusky et al., 2005). In the Musandam area, the shortening postdates the middle Eocene (Searle et al., 1983; Searle, 1985) and predates the deposition of upper Miocene strata. The upper Miocene units seal the folds and reverse faults on seismic profiles (Ricateau and Riché, 1980). In the central part of the Oman Mountains, compression may have been initiated as early as the late Oligocene, as suggested by the rapid uplift of the Jabal Akhdar between 30 and 25 Ma documented by apatite fission tracks data (Mount et al., 1998). In the eastern part of the Oman Mountains, the start of the compression is dated as late Burdigalian and corresponds to the tectonic inversion of the Abat Basin and Qalhat fault (Wyns et al., 1992b). Thus, the start of the compression in the Oman Mountains immediately followed, or was coeval with the end of, the late Oligocene to early Miocene rifting in the Gulf of Aden. Compressional deformation continued until the Pliocene Epoch and is recorded in the Mio-Pliocene deposits of the Barzaman Formation in the Salakh Arch (Figure 1;

Mercadier and Makel, 1991; Wyns et al., 1992a).

The process responsible for the shortening in the northern Oman Mountains, in the framework of the Arabia-Eurasia convergence, has not been clearly identified and documented. North of the Oman Mountains, the convergence between the Eurasian and Arabian plates is absorbed by the Makran subduction zone since the Eocene Epoch (White and Ross, 1979; McCall and Kidd, 1982; Vernant et al., 2004). The oceanic crust in the Gulf of Oman, which is a remnant of the Neo-Tethys Ocean, is being subducted northwards beneath the Makran accretionary wedge. Further to the northwest in the Zagros Mountains, the convergence is absorbed by the Arabia-Eurasia continental collision, which started in the Oligocene Epoch (Figure 2c; Ross et al., 1986; Allen et al., 2004; Agard et al., 2005). Boote et al. (1990) proposed that the Musandam Peninsula acted as a rigid indentor of the Arabian Plate, focusing compression and transmitting it back into northern Oman. Alternatively, Hanna (1990) interpreted the Cenozoic deformation in the central part of the northern Oman Mountains as the result of gravitational collapse. This latter explanation cannot account for most of the compressional structures observed in the Cenozoic units.

Besides these major compressional geodynamic events, extension occurred in the Oman Mountains after the obduction of the Samail Ophiolite and prior to the re-establishment of compressional conditions in the late Oligocene time (Mann et al., 1990). This extensional stage followed exhumation of the high-pressure, low-temperature rocks in the Saih Hatat dome accommodated by ductile extension (Lippard, 1983; Goffé et al., 1988; Michard et al., 1994; Searle et al., 1994, 2004; Chemenda et al., 1996; Jolivet et al., 1998; Miller et al., 1998; Searle and Cox, 1999; Gray et al., 2004). In the Central Oman Mountains, the extensional tectonics were recognized from the observation of normal faults putting into contact the post-nappes sedimentary deposits and the autochtonous series or the ophiolites; for example, in the Batinah Coast Plain and the Rusayl Embayment (Figure 1; Mann et al., 1990). Extension is also expressed offshore by normal faults affecting the Arabian continental margin of the Gulf of Oman (Mann et al., 1990). This extension is associated with basin development and controls the deposition of the Upper Cretaceous-lower Cenozoic sedimentary series (Nolan et al., 1990).

TECTONO-STRATIGRAPHIC SETTING OF THE POST-NAPPE SEDIMENTARY UNITS

Upper Cretaceous and Cenozoic post-nappe units are exposed along the periphery of the Oman Mountains (Figure 1). These sedimentary units unconformably overlie, or are in fault contact with, the nappes or their autochtonous substratum. In the central Oman Mountains, the post-nappe sedimentary cover is exposed on the northern and southern flanks of the Hawasina and Jabal Akhdar tectonic windows, in the Batinah Coastal Plain and the Suneinah Foreland Basin, respectively (Figure 1). Further to the east, several isolated basins occur in the area of Muscat to the west of the Saih Hatat culmination, including the Rusayl Embayment, the Fanjah Graben, and the Bandar Jissah Basin. The largest exposures of post-nappe series are found in the eastern Oman Mountains between Quryat and Sur, in the Jabal Bani Jabir (Figure 1). The Jabal Bani Jabir rises up to 2,000 m and represents an uplifted platform of Upper Cretaceous and Cenozoic rocks, bounded by the Ja'alan Fault to the southwest and the Qalhat Fault to the east (Figure 4). During the deposition of the Paleogene series, these faults were active as normal faults, and during the Late Cenozoic they were reactivated as reverse faults**.** The Jabal Bani Jabir is deeply incised by numerous wadis, providing good exposures. Other outcrops are present to the north of the Batain Plain near Ras al Hadd, and on the flanks of Jabal Ja'alan.

The basal units of the neo-autochtonous series consist of continental terrigeneous alluvial fan deposits with coarse conglomerate and sandstone of the late Campanian to Maastrichtian Qahlah Formation (Aruma Group; Figure 3) (Nolan et al., 1990; Béchennec et al., 1992). The clasts of the conglomerates come from progressively deeper crustal levels, including ophiolitic, carbonate, and finally metamorphic rock fragments from the Saih Hatat dome (Mann et al., 1990). The vertical sequence of these clasts attests to the progressive uplift and erosion of the northern Oman Mountains during the late Campanian-early Maastrichtian times. The Qahlah Formation is overlain by the carbonate platform sediments of the late Maastrichtian rudist-bearing Simsima Formation (Glennie et al., 1974; Béchennec et al., 1992). These shelf deposits correspond to an open-marine facies and pass eastwards to a slope facies of debris-flow and turbiditic deposits of the Hasad and Fayah formations, respectively (Figure 5; Roger et al., 1991; Immenhauser et al., 2000). The deeper marine conditions resulted from the collapse of the basin margin through normal faults.

Shallow-marine sedimentation prevailed as soon as the early Danian with the deposition of the carbonate series of the Hadhramaut Group during three transgressive-regressive cycles. The first cycle is represented by the restricted Murka platform of Danian age (Figures 3 to 5). The second cycle is dominated by the carbonate platform of the Thanetian-Ypresian Jafnayn Formation (Figure 5; Wyns et al., 1992b). The Jafnayn Formation is up to 500 m thick and is coeval to the Umm Er Radhuma Formation in Interior Oman. In the Bandar Jissah Basin, the base of the Jafnayn Formation is represented by continental conglomerates resting directly on the ophiolites. The Jafnayn Formation is overlain by the restricted marine deposits of the 150-m-thick Rusayl Formation. The third cycle is characterized by the deposition of the Lutetian-Bartonian Seeb Formation (Nolan et al., 1990), which consists in shelf carbonate deposits, up to 600 m thick in the Jabal Bani Jabir. The Seeb Formation is a local equivalent of the Damman Formation in Interior Oman.

In the southeastern Oman Mountains, between Sur and Muscat, the Paleocene-Eocene period is marked by extensional tectonics that created the Abat Basin in the northeastern continental margin of Oman opened towards the Gulf of Oman. The platform sediments of the Jafnayn Formation pass eastward to deeper basinal facies with hemipelagic mudstones and intercalated turbidites of the Abat Formation (up to 700 m thick; Figure 5). Similarly, during the deposition of the Lutetian to Bartonian platform carbonates of the Seeb Formation, deeper pelagic and turbiditic deposits of the Musawa Formation (up to 1,100 m thick) filled the Abat Basin.

The Dhofar Group is well developed in the Abat Basin with the 1,000-m-thick debris flow and turbiditic deposits of the Priabonian to Chattian Tahwah Formation (Wyns et al., 1992b). On the Muscat-Tiwi Platform and in the area southeast of Sur, the Dhofar Group is represented by the carbonate shelf facies of the Priabonian Shama Formation (less than 100 m thick).

Following the deposition of the Dhofar Group, the early Miocene to Pliocene Fars Group was deposited in regressive marine to continental settings. The fan-delta facies deposits of the Burdigalian Sur Formation overlie the Tahwah Formation (Figure 3). In the area of Sur, the formation displays important lateral facies variations and progressive unconformities, attesting of synsedimentary compressional deformation in relation with the inversion of the Qalhat Fault (Wyns et al., 1992b). The conglomeratic fan delta sequence of the Salmiaya Formation was deposited above the Sur Formation, in turn overlain by the continental molasse deposits of the Barzaman Formation of middle Miocene to Pliocene age (Maizels, 1987; Béchennec et al., 1992).

POST-NAPPES DEFORMATION IN THE CENTRAL AND EASTERN OMAN MOUNTAINS

In the areas of Muscat (Rusayl Embayment, Fanjah Graben, Bandar Jissah Basin), Jabal Bani Jabir, and near Ibri and Dank (Figure 1), about 500 striated fault planes and tectonic joints were examined in 30 localities (Table 1). Based on the collection and inversion of fault-slip data, the orientation of the principal stress axes was determined using computer-aided methods developed by Angelier (1984). In some localities the observed fault-slip data sets were too complex to be interpreted by a single stress tensor. They are the result of superimposed distinct tectonic events. For such data sets it was necessary to separate homogeneous subsets into groups A or B (Sites 15, 16, 29, 30, 31, 33, 36, 38, 42, 43, 45, and 47 in Table 1). Sorting was done in three ways:

1. (1) at sites where all fault planes are of the same type (e.g. dip-slip normal faults), they were sorted according to strike (e.g. Site 42A and 42B);
2. (2) at sites where two different types of fractures are observed (e.g. normal and strike-slip faults), the two subsets were distinguished in case the fractures are not compatible (e.g. Site 43A and 43B);
3. (3) in some exposures, conjugate normal faults have been reactivated as oblique-slip faults (Sites 16A, 31A, and 39) making the chronology of events obvious.

In localities with scarce or non-existing fault-slip data, stress inversion is not possible. In these cases the principal axes of deformation was deduced from the geometric pattern of tectonic joints (Hancock, 1985). **[Comment 14: questionable]** To allow a comparison between the stress axes deduced from fault-slip inversion and the deformation axes deduced from joint geometry, we assumed that the principal stress axes $_1$, $_2$, and $_3$ are parallel to the shortening, intermediate and extension axes, respectively.

Late Cretaceous to Early Eocene ENE-WSW Extension (Tectonic Stage 1)

An average ENE-directed extension is documented in the central and eastern Oman Mountains in the basal levels of the post-nappe units (Upper Cretaceous Qahlah and Hasad formations). In the area of Muscat, several outcrops of the Qahlah Formation are exposed in the Rusayl Embayment near Ghallah and Al Khawd, and in the Fanjah Graben (Figure 6). South of Ghallah (Sites 9 and 42), the strata of the Qahlah Formation strikes east and dips 25° to the south. The strata is cut by conjugate synsedimentary NW-trending normal faults that display dip-slip striations indicating a NE-SW extension (N48°E at Site 42A). West of this site, near the Oman Cement Factory, a complete section of the supra-ophiolite series from the Qahlah to Rusayl formations is exposed. A set of NNW to N-trending synsedimentary faults are observed in the reddish, coarse-grained conglomerates of lowermost Qahlah Formation, which dip about 40° southwest (Site 28). A NE-SW (N50°E) extension is computed after back-tilting at this site. At Site 29A near Sunub, ENE (N70°E) extension was accommodated by synsedimentary faults during the deposition of the Thanetian to Ypresian Jafnayn Formation.

West of Muscat city, between Al Qurum and Mutrah, the highway cuts through small hills of calcareous and multi-coloured marly units of the Jafnayn Formation with detrital beds. At Site 40 the strata of the Jafnayn Formation strikes northwest and dips 25° to the west, and is in contact with the ophiolite along a N-trending fault. Numerous smaller normal faults, filled with fibrous gypsum, run parallel to the border fault. Gypsum-filled tensional gashes are also common at this site. Changes in bed thickness across the fault planes and the progressive upward reduction of throws indicates that these faults are synsedimentary. The stress tensor calculated at this site provides a direction of extension ($_3$) oriented east-northeast (N72°E).

The Upper Cretaceous Hasad Formation crops out in Jabal Ja'alan and is affected to the north by the NW-trending Ja'alan Fault (Figure 6). The Hasad Formation consists of limestone with associated coarse tectonic breccias and is cut by synsedimentary NW-trending normal faults. These faults are subparallel to the Ja'alan Fault and indicate a NE-trending extension (N49°E at Site 13A and N51°E at Site 33A). Further north, Jabal Bani Jabir is dissected at map scale by a system of NW-trending normal faults that progressively downthrow the sedimentary series toward the shore. The Abat Basin is related to the activity of these faults, including the Ja'alan and Qalhat faults (Figure 5). In the area of Abat and Qalhat, NW-trending normal faults have been measured in the Murka Formation (Sites 15A and 21; see Site 15A in Figure 7a). They document a NE-trending extension (N45°E in Sites 15A). A similar set of NW-striking conjugate normal faults is observed in the Jafnayn Formation near Tiwi (Site 23; Figure 7b) and Umq (Site 24; Figure 7c). The related directions of $_3$ are N53°E and N46°E, respectively.

The investigation of the lower part of the post-nappe series identifies the extensional tectonic activity, hereafter referred to as "Tectonic Stage 1", which prevailed in the Late Cretaceous during the deposition of the Qahlah and Hasad formations. Tectonic Stage 1 persisted until early Eocene (Ypresian) during the deposition of the Jafnayn Formation. The timing of the tectonic activity is attested by the synsedimentary character of faults in the Qahlah, Hasad, and Jafnayn formations (Carbon, 1996). Extension was accommodated by NW to N-trending normal faults indicating an ENE extension (from N45°E to N72°E). Northwest to N-trending synsedimentary faults are not observed in younger formations.

Record of Two Post-Eocene Extensions (Tectonic Stages 2A and 2B)

N20°E Extension (Tectonic Stage 2A)

Fractures relevant to a NNE-SSW tensional stress field have been found throughout all the sedimentary succession from the Upper Cretaceous to the Oligocene formations. In the Fanjah Graben, minor faults have been measured in the Qahlah Formation in a quarry which dominates the highway (Site 31; Figure 8). The Qahlah Formation, which overlies the ophiolite, dips 20° toward the south and exhibits tilted blocks bounded by normal faults (Figure 7d). Two sets of normal faults can be distinguished: (1) faults parallel to the major border fault of the Fanjah Graben and trending about N100°E (Site 31B); and (2) NNW-trending faults (Site 31A). The N100°E conjugate dip-slip normal faults document a NNE-SSW-oriented extension. The NNW- trending faults are oblique normal faults and also indicate a NNE-SSW-oriented extension. Similar NNW-trending oblique normal faults that document a NNE-SSW direction of extension, have been observed in the Murka Formation in the vicinity of Tiwi and Abat in the eastern Oman Mountains (Sites 16A and 39 in Figure 8). These observations imply two extensional stages: (1) an older, ENE-WSW-oriented extensional stage that caused the NNW faulting (Tectonic Stage 1); and (2) a younger, NNE-SSW-oriented extensional phase that caused the ~N100°E normal faulting and the reactivation of the NNW-trending faults as oblique normal faults (Tectonic Stage 2A).

The NNE-SSW-oriented extension is also documented in more recent formations. A set of WNW-trending conjugate normal faults have been measured in the Abat Formation (Sites 36A and 38A;

Figure 8) and in the Jafnayn Formation in the vicinity of the Ja'alan Fault (Site 32). They indicate a direction of extension that is oriented NNE-SSW (N22°E in Site 36A). The overlying Rusayl Formation is also affected by this extension (Sites 30A and 43A). E-W to NW-trending conjugate normal faults provide a NNE-SSW direction of extension (N24°E in Site 30A and N13°E in Site 43A). At Site 43A near Al Khawd, the strata of the Rusayl Formation dip about 60° toward the northeast and the normal faults have been tilted together with the strata (Figure 7e). This indicates that normal faulting preceded folding and tilting of the strata. Similar sets of normal faults have been found in the Oligocene Shama (Site 20) and Tahwah formations (Site 35), but the fault planes do not exhibit preserved striation. A NNE-SSW direction of extension can only be inferred from these data.

N150°E Extension (Tectonic Stage 2B)

A distinct NNW-SSE direction of extension is also evident in the post-nappe cover (Figure 9). This extension is recorded by ENE-trending normal faults throughout the sedimentary pile, from the lowermost Qahlah and Hasad formations up to the Eocene Seeb Formation. Near Ghallah in the Rusayl Embayment, the Qahlah conglomerates and sandstones are affected by ENE-trending conjugate normal faults that indicate a N152°E direction of extension (Site 42B). In the nearby Jafnayn Formation, NE-oriented normal faults document a N141°E direction of extension (Sites 29B and 8). In the vicinity of Muscat, the Jafnayn Formation, which crops out in Al Qurum, also displays ENE-trending conjugate normal faults giving a N163°E direction of extension (Site 47A). Further east along the road to Qantab (Bandar Jissah Basin), the Jafnayn Formation lies unconformably above the ophiolite through a basal conglomerate (Site 45A; Le Métour et al., 1986). The sedimentary contact is nearly horizontal. NE-trending normal faults have been measured in this formation, providing a NW-SE direction of extension (N127°E).

In Jabal Ja'alan, the same extension is documented in the Hasad Formation by the existence of NE-SW non-striated faults (Site 33B). At the northeastern corner of the Arabian Peninsula, in the eastern part of the Batain Plain, the Seeb Formation is exposed along the seashore. It consists in a subhorizontal calcareous and siliceous succession giving rise to prominant cliffs. It is cut by numerous and regularly spaced ENE to NE-trending normal faults with throws of the order of 50 cm to 1–2 meters. Although no striation has been preserved on these fault planes, a NNW-SSE to NW-SE direction of extension can be inferred.

In summary, two directions of extension have been identified in the neoautochtonous series of the Oman Mountains, with a N20°E (from N13°E to N38°E) and a N150°E (from N127°E to N163°E) mean trend. These phases of extension, which are recorded in the upper Eocene and Oligocene formations, postdate the Late Cretaceous to early Eocene ENE-WNW extensional event (Tectonic Stage 1). This is further confirmed by the reactivation of normal faults from the ENE-WNW extensional phase during the N20°E extensional phase. The two N20°E and N150°E directions of extension have never been observed in the same locality and no relative chronology between the two phases could be determined. That is why they are referred to as "Tectonic Stages 2A and 2B", respectively.

We have identified three distinct episodes of normal faulting in northern Oman between the Late Cretaceous and the Oligocene times, with three different directions of extension. Our results significantly differ from those of Carbon (1996), who concluded that a multidirectional (radial) extensional event occurred during the same period. Carbon (1996) combined different types of faults with different trends in the same stereodiagrams to arrive at an interpretation that is here considered incorrect.

Early Miocene Inversion and Compression (Tectonic Stage 3)

In numerous localities of the Oman Mountains, strike-slip and reverse faults are observed in the post-nappe units (Figure 10; Carbon, 1996). They document a strike-slip or compressional stress regime, with an E-W to NE-SW mean direction of compression ($_1$), perpendicular to fold axes.

In the area of Muscat, three sites display conjugate sets of strike-slip faults in the Jafnayn Formation (Sites 41, 45B, and 47B). The right-lateral faults trend NE-SW and the left-lateral faults trend about E-W. Stress inversion gives $_{Hmax} = {}_1$ trending ENE-WSW (between N54°E and N85°E). Along the highway to Qantab, the compression is spectacularly expressed by the basal truncation of the Jafnayn beds that are thrusted over the ophiolite (Figure 7f). Two kilometres away (at Site 45), the Jafnayn Formation lies unconformably above the ophiolite through a stratigraphic contact. Further west in the Rusayl Embayment, strike-slip faults are observed in the Rusayl Formation (Sites 30B and 43B). In the vicinity of Al Khawd (Site 43B), compatible strike-slip and reverse faults document a NE-SW (N41°E) compression perpendicular to the trend of the folded beds. At this locality, normal faults pertaining to the NNE-SSW extensional stress field (Tectonic Stage 2A) have been tilted with the beds (Figure 7e).

The compression therefore postdates the extensional phase.

In the eastern Oman Mountains, the Murka Formation is affected by low-angle reverse faults associated with compatible strike-slip faults (Sites 15B and 16B; Figure 10), which indicate an ENE-directed compression (N82°E and N81°E, respectively). In the overlying Abat and Jafnayn formations (Sites 22, 36B, and 38B), E-W to NE-SW compression is also expressed by reverse and strike-slip conjugate faults.

In the area of Dank and Ibri at the southwestern front of the Oman Mountains, the lower Eocene Umm Er Radhuma Formation displays ENE-trending conjugate sets of reverse faults giving a N60°E and N32°E direction of compression (Sites 3 and 4; Figure 10). The compression is perpendicular to the axis of pluri-kilometric folds trending NW-SE. There, reverse faulting preceded folding since the faults have been tilted with the sedimentary beds (Table 1).

At a regional scale, compression was responsible for the inversion of sedimentary basins that formed during the Late Cretaceous and early Cenozoic extensional phase. The bounding master faults of the Fanjah Graben and of the Rusayl Embayment, in the area of Al Khawd, were reactivated as strike-slip faults with a reverse component (Carbon, 1996). In the region of Sur, the Qalhat Fault was inverted during the early Miocene, as evidenced by the synsedimentary angular unconformities in the lower Miocene Sur Formation in the vicinity of the fault (Wyns et al., 1992b). The compression thus started during the early Miocene in this area. Further west, the uplift of the Jabal Akhdar between 30 and 25 Ma, as documented by apatite fission tracks data, even suggests a late Oligocene age for the beginning of the compression (Mount et al., 1998).

At the southern front of the Oman Mountains, the compressional deformation is recorded in the Mio-Pliocene Barzaman Formation by folds and reverse faults associated with the formation of the "whaleback" anticlines of the Salakh Arch (Mercadier and Makel, 1991; Wyns et al., 1992a). There, the direction of compression is oriented almost N-S, perpendicular to the anticline axes (Carbon, 1996).

The compressional phase is revealed by the strike-slip and compressional paleostress tensors. The tensors display a similar direction of compression and apparently reflect a single transpressional deformation regime. However, considering all the local stress tensors computed for the Oman Mountains, the direction of compression varies from E-W to NE-SW (from N94°E at Site 38B to N32°E at Site 4), and even to N-S taking into account the Pliocene directions of compression determined in the Salakh Arch (Carbon; 1996). The different directions of compression could reflect two successive phases of compression, a first phase oriented E-W to NE-SW of Early Miocene age and a second phase oriented N-S to NNE-SSW of Pliocene age. Alternatively, Carbon (1996) suggested that the $_1$ trajectories at the regional scale could be sigmoidal, with local inflections across the main faults.

SYNTHESIS OF FAULTING EPISODES AND GEODYNAMIC INTERPRETATION

Figures 11 and 12 provide a synthetic overview of the deformation in the central and eastern Oman Mountains since the Late Cretaceous. On the basis of field observations in the dated post-nappe formations, three main phases of deformation have been recognized; from the oldest to the youngest:

1. Tectonic Stage 1 was a Late Cretaceous to early Eocene extension phase that trended ENE-WSW.
2. Tectonic Stages 2A and 2B consisted of two extensional phases that were oriented N20°E and N150°E, and of probable Oligocene age.
3. Tectonic Stage 3 was a compressional phase which started in the Late Oligocene-early Miocene and continued until the Pliocene. Two distinct compressional episodes may be distinguished: an Early Miocene one with a direction of compression oriented E-W to NE-SW and a Pliocene one with a N-S to NNE-SSW direction of compression.

The first stage of ENE-WSW directed extension was established as early as the Maastrichtian, as evidenced by syn-sedimentary faulting in the Qahlah and Hasad formations. It immediately followed the Turonian to early Campanian emplacement of the Samail ophiolitic nappe and the exhumation of the Saih Hatat metamorphic units. It persisted until the deposition of the lower Eocene Jafnayn Formation, which was also affected by NNW-SSE trending synsedimentary normal faults. This extensional phase is attested by normal faulting in the northeastern Oman margin and the development of the Abat Basin, accommodated by the Ja'alan and Qalhat normal faults. It also was responsible for the formation of the Fanjah Graben.

Exhumation of high-pressure and low-temperature metamorphic units visible in the Saih Hatat window involved shallow-dipping NE-directed extensional shear zones (Figure 12; Searle et al., 1994, 2004; Jolivet et al., 1998; Breton et al., 2004). The extensional nature of the shear zones is attested by the pressure gap recorded across each of them with a downward increase of pressure. Across each shear zone several kilobars are missing showing that a significant crustal thickness has been removed during the formation of the shear zone (Goffé et al., 1988; Searle et al., 1994). Deformation within the shear zones evolved with time from ductile to brittle, implying that the temperature decreased during exhumation. At the top of the Saih Hatat metamorphic units, in the vicinity of Muscat, the Wadi Kabir Fault reworked the basal contact of the ophiolitic nappe as normal shear zone and afterward as a brittle normal fault offsetting the lower Eocene Jafnayn Formation (Searle et al., 2004; Figure 12). There is thus a progressive transition in time from ductile "extensional" shear zones related to exhumation, to brittle faulting along the Wadi Kabir Fault coeval with normal faulting in the Maastrichtian to Early Eocene basins. The relative homoaxiality between the direction of the Late Cretaceous extension in the sedimentary basins and the direction of shear along the main shear zones responsible for exhumation (Figure 12) further suggest a strain continuum between exhumation and extension stage 1. Tectonic stage 1 thus appears as an episode of crustal thinning closely related (in time and kinematics) to the dynamics of exhumation of HP-LT units in the Saih Hatat window.

Following the first extensional stage, two N20°E and N150°E directed extensional phases were recorded in the lower Cenozoic series, including in the upper Eocene and lower Oligocene formations. No chronology was observed in the field between these extensional phases. In northern Oman, the two extensional phases are generally expressed by outcrop-scale fractures and are not associated with major structures, such as large normal faults, grabens, or sedimentary basins. At the southern end of the Arabian Plate, the same N20°E and N150°E directions of extension were identified along the northern and southern margins of the Gulf of Aden in Oman (Lepvrier et al., 2002; Fournier et al., 2004), Yemen (Huchon and Khanbari, 2003), and Socotra Island (Fournier et al., submitted). They are associated with the Oligocene-Miocene rifting of the Gulf of Aden. Nowhere has it been possible to establish unambiguously a relative chronology between the two extensional phases (Fournier et al., 2004). These extensional phases have also been recognized in eastern Oman in the Huqf area (Montenat et al., 2003; Fournier et al., 2005; Bertotti et al., 2005) and Masirah Island (Marquer et al., 1995). In eastern Saudi Arabia, a NNE-directed extension phase of Late Cretaceous to Eocene age has been documented in the central Arabian graben system (Hancock et al., 1984). Thus, a major part of the future Arabian Plate was under tension during the Early Cenozoic. This tension likely resulted from the gravitational force exerted on the Arabian-African Plate by the Neo-Tethys slab subducting under the Eurasian Plate (Manighetti et al., 1997; Meijer and Wortel, 1999; Jolivet and Faccenna, 2000). The diffuse extension observed in the Arabian Platform ultimately localized along the Red Sea and Gulf of Aden rifts in the Oligocene Epoch (Platel and Roger, 1989; Ghebreab, 1998; Watchorn et al., 1998), during the peak of activity of the Afar mantle plume (Ebinger and Sleep, 1998), and progressively induced the separation of the Arabian Plate from the African Plate. Bellahsen et al. (2003) have shown with laboratory experiments that the interaction between far-field extensional forces and a weakness zone related to the Afar plume could produce a pattern of extension resembling the Red Sea-Gulf of Aden rift system.

Finally, fault-slip data demonstrate the existence of one or two late compressional events in the Oman Mountains. Compression started in the late Oligocene or early Miocene, shortly after the collision in the Zagros Mountains. The direction of compression documented by associated strike-slip and reverse faults is E-W to NE-SW. The same direction has been recognized in Masirah Island and in southern Oman along the northern margin of the Gulf of Aden where it is expressed by conjugate sets of strike-slip faults documenting a strike-slip regional stress field with ${}_{\mathrm{Hmax}} = {}_{1}$ trending E-W to NE-SW (Fournier et al., 2004). At the scale of the Arabian Plate, the stress regime seems to change from transpressional to the north in the Oman Mountains, to purely strike-slip to the south in the Gulf of Aden area. This could reflect a decrease of the intensity of the compression away from Zagros collision zone. However, the E-W to NE-SW directions of compression recorded in the Arabian Plate are not parallel to the direction of convergence between the Arabian and Eurasian plates, which is nearly N-S (Vernant et al, 2004; Regard et al., 2005). The origin of the E-W to NE-SW compression is therefore not entirely clear and could also result from the interaction between the Arabian and Indian plates. The deformation recorded in the Mio-Pliocene series at the southern front of the Oman Mountains indicates a rotation of the direction of compression from ENE-WSW to almost N-S.

CONCLUSION

Based on kinematic analysis of fault sets in the post-nappe strata and reconstruction of paleostress tensors, this study provides a model for the tectonic evolution of northern Oman following the obduction of the Samail Ophiolite. During the Late Cretaceous and early Cenozoic times, northern Oman experienced extensional tectonics, which progressively led to the establishment and development of sedimentary basins. Stretching culminated in the early Eocene with the formation and deepening of the Abat Basin on the northeastern Oman margin. Extension, documented through numerous observations of synsedimentary faulting, was dominantly oriented in an ENE to NE direction. A second extensional stage, characterized by two N20°E and N150°E directions of extension, chronologically undistinguishable in the field, is recorded up to the Oligocene formations. These extensions have already been identified on the margins of the Gulf of Aden and correspond to the rifting of the Gulf of Aden. Compressional tectonics was initiated in northern Oman possibly as early as the late Oligocene coeval with the starting of the Arabia-Eurasia collision in the Zagros Mountains. Compatible reverse and strike-slip faults indicate a direction of compression between NE-SW and E-W, i.e. oblique to the Arabia-Eurasia direction of convergence. The origin of this oblique compression is not clearly established. The direction of compression evolved from E-W to NE-SW in the Early Miocene to almost N-S in the Pliocene.

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Figure captions

Figure 1: Geological and structural map of the Oman Mountains after the 1:1,000,000 geological map of the Sultanate of Oman (Béchennec et al., 1993). Insert shows the geodynamic setting of the Arabian Plate. AOC, Aden-Owen-Carlsberg triple junction, configuration after Fournier et al. (2001); Mas, Masirah Island; OFZ, Owen fractue zone; Soc, Socotra Island.

Figure 2: Late Cretaceous to Miocene geodynamic events in Oman. Paleogeographic reconstructions modified after Stampfli and Borel (2002) and Dercourt et al. (1993). (a) Late Cretaceous (Coniacian-Santonian) obduction of the Samail ophiolitic nappe onto the northeast margin of the Arabian Platform. (b) Obduction of the Masirah Ophiolite in eastern Oman at the Maastrichtian-Paleocene transition during the northward drift of the Indian Plate. (c) Oligocene to early Miocene rifting in the Gulf of Aden, formation of the Arabian Plate, and inception of the Arabia-Eurasia collision in the Zagros Mountains.

Figure 3: Stratigraphic synthesis of the post-nappe sedimentary succession exposed in the central and eastern Oman Mountains from the Muscat to Sur, with indications on the main facies rocks and related domains of sedimentation.

Figure 4: Perspective view from the southeast (N135°E) of northeastern coast of Oman between Sur and Muscat (SRTM digital elevation model; Farr and Kobrick, 2000). The elevated reliefs (greater than 2,000 m) of the Jabal Bani Jabir in the foreground, correspond to the Upper Cretaceous to Eocene series uplifted during the inversion of the northeast Oman margin in the late Cenozoic Era. The Jabal Bani

Jabir is bounded by two initially normal Ja'alan and Qalhat faults, reactivated as reverse faults during the late Cenozoic Era. The star indicates the location of the photograph showing the superimposed carbonate platforms of the lower Cenozoic Murka, Abat, and Seeb formations in the Jabal Bani Jabir.

Figure 5: Sedimentological evolution of the northeast Oman margin from Maastrichtian to Eocene.

Figure 6: ENE-WSW extensional stress field recorded in the Upper Cretaceous to lower Eocene formations in the areas of Muscat and Sur (see the inserted location map). Synsedimentary normal faults observed in the Maastrichtian Qahlah and Hasad formations and in the Thanetian-Ypresian Jafnayn Formation document a Late Cretaceous to early Eocene ENE-WSW extensional phase. Stereonets show fault slip data in equal-area lower hemisphere projection and arrows indicate the trend of the horizontal principal stresses computed (solid arrows) or inferred (open arrows) from fracture analysis. Stars in stereonets correspond to the principal stress axes: $_1$ (five branches), $_2$ (four branches), and $_3$ (three branches). Dashed line is for the bedding plane. Geological maps after the 1:250.000 geological maps of Muscat (Le Métour et al., 1992b), Seeb (Béchennec et al., 1992), and Sur (Wyns et al., 1992b).

Figure 7: Field photographs illustrating the style of deformation in the Upper Cretaceous to Eocene series of the Oman Mountains. (a) Major normal fault scarps in the Paleocene Murka platform in the area of Abat (Site 15A in Figure 6). (b) Conjugate normal faults in the Thanetian to Ypresian Jafnayn Formation near Tiwi (Site 23 in Figure 6). (c) Normal fault scarps in the Thanetian to Ypresian Jafnayn Formation near Umq (Site 24 in Figue 6). (d) Normal faults affecting the Maastrichtian Qahlah Formation in the Fanjah Graben (Site 31, location in Figure 8). (e) Tilted normal faults affecting the upper Ypresian Rusayl Formation in the area of Al Khawd (Site 43A in Figure 8, corrected from the tilt of the strata). (f) Basal truncature of the beds of the Jafnayn Formation lying above the ophiolite through a basal 30°- dipping tectonic contact, near Qantab.

Figure 8: NNE-SSW (N20°E) extensional stress field recorded in the Upper Cretaceous to Oligocene formations in the areas of Muscat and Sur. In three sites (16A, 31A, and 39), conjugate NNW-SSE trending normal faults from the first extensional stage have been reactivated as oblique slip faults. Same legend as Figure 6.

Figure 9: NNW-SSE (N150°E) extensional stress field recorded in the Upper Cretaceous to Oligocene formations in the areas of Muscat and Sur. Same legend as Figure 6.

Figure 10: E-W to NE-SW (N90°E to N30°E) strike-slip or compressional stress field recorded in the Paleocene to Eocene formations in the areas of Muscat and Sur. Same legend as Figure 6.

Figure 11: Synthesis of Late Cretaceous and Cenozoic brittle deformation in northern Oman. Three stages of deformation are identified: a Late Cretaceous to early Eocene WSW-ENE extension (Tectonic Stage 1), two N20°E (Tectonic Stage 2A) and N150°E (Tectonic Stage 2B) extensions of probable Oligocene age, and an E-W to NE-SW compression (Tectonic Stage 3) of early Miocene to Pliocene age.

Figure 12: Kinematics and evolution of deformation in the central and eastern Oman Mountains since the Late Cretaceous. Map of ductile deformation in the Saih Hatat tectonic window (modified after Jolivet et al., 1998).

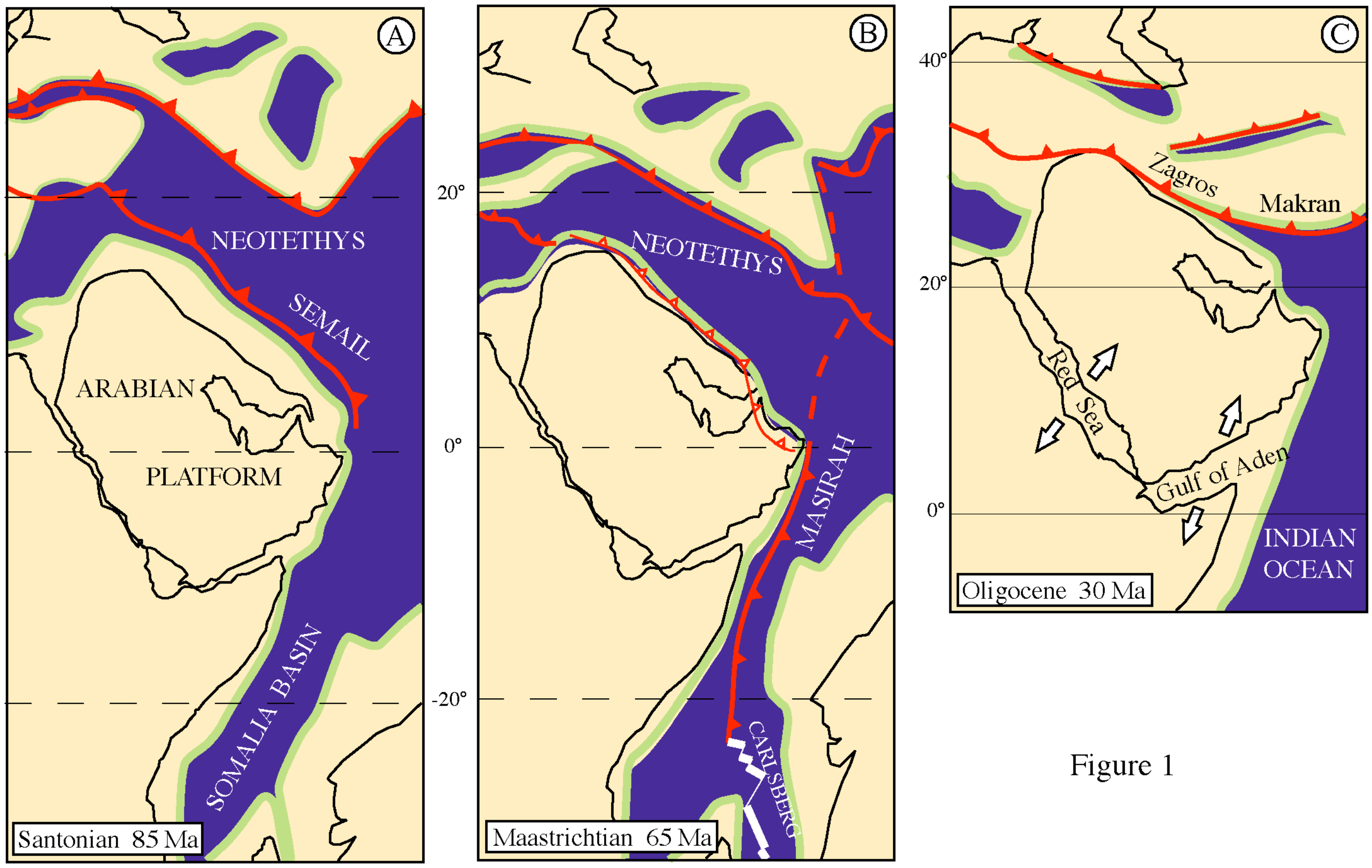

A
NEOTETHYS
SEMAIL
ARABIAN
PLATFORM
SOMALIA BASIN
Santonian 85 Ma
B
20°
0°
-20°
NEOTETHYS
MASIRAH
CARLSBERG
Maastrichtian 65 Ma
C
40°
20°
0°
Zagros
Makran
Red Sea
Gulf of Aden
INDIAN
OCEAN
Oligocene 30 Ma

Figure 1

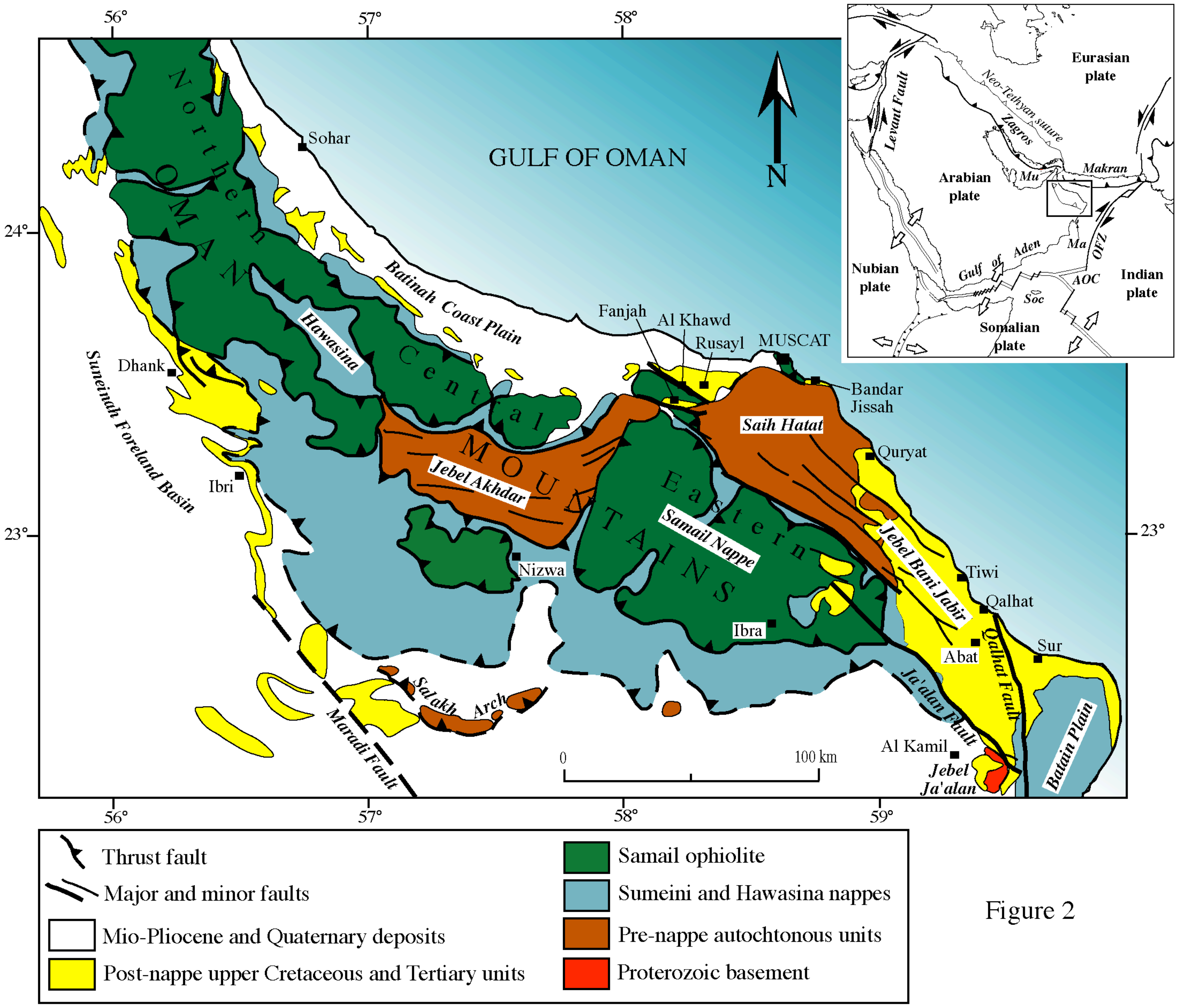

56°
57°
58°
59°
24°
23°
GULF OF OMAN
N
Sohar
Northern OMAN
Batinah Coast Plain
Hawasina
Central
Dhank
Suneinah Foreland Basin
Ibri
MOUNTAINS
Jebel Akhdar
Nizwa
Eastern
Samail Nappe
Fanjah
Al Khawd
Rusayl
MUSCAT
Bandar Jissah
Saih Hatat
Quryat
Jebel Bani Jabir
Tiwi
Qalhat
Sur
Abat
Ibra
Qalhat Fault
Ja'alan Fault
Al Kamil
Jebel Ja'alan
Batain Plain
Salakh Arch
Maradi Fault
0
100 km
Eurasian plate
Neo-Tethyan suture
Levant Fault
Zagros
Arabian plate
Mu
Makran
Nubian plate
Gulf of Aden
Ma
OFZ
AOC
Indian plate
Soc
Somalian plate
Thrust fault
Major and minor faults
Mio-Pliocene and Quaternary deposits
Post-nappe upper Cretaceous and Tertiary units
Samail ophiolite
Sumeini and Hawasina nappes
Pre-nappe autochtonous units
Proterozoic basement

Figure 2

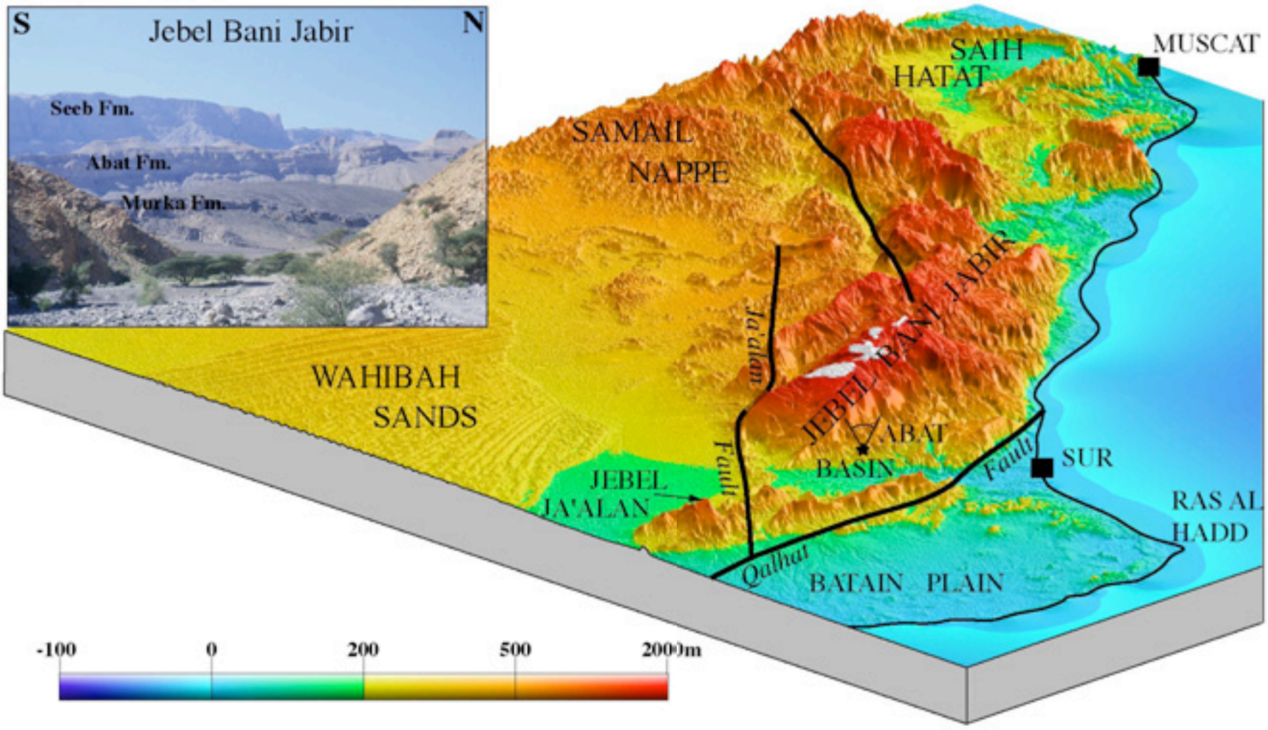

S
Jebel Bani Jabir
N
Seeb Fm.
Abat Fm.
Murka Fm.
SAIH
HATAT
MUSCAT
SAMAIL
NAPPE
WAHIBAH
SANDS
Ja'alan
Fault
JEBEL BANI JABIR
ABAT
BASIN
Fault
SUR
JEBEL
JA'ALAN
Qalhat
BATAIN PLAIN
RAS AL
HADD
-100
0
200
500
2000m

Figure 3

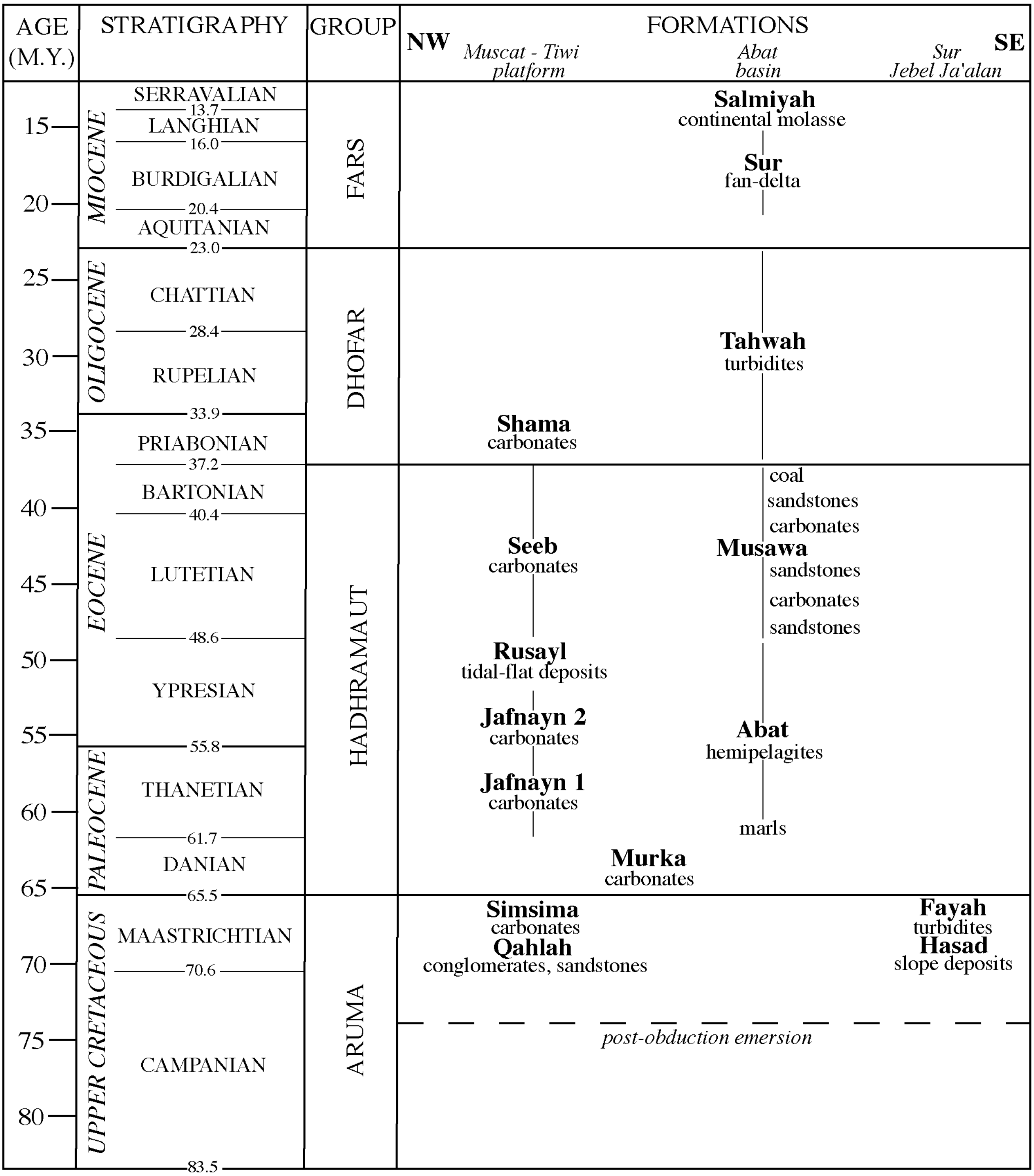

AGE (M.Y.)
STRATIGRAPHY
GROUP
FORMATIONS
NW
Muscat - Tiwi platform
Abat basin
Sur Jebel Ja'alan
SE
15
20
25
30
35
40
45
50
55
60
65
70
75
80
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
UPPER CRETACEOUS
SERRAVALIAN
13.7
LANGHIAN
16.0
BURDIGALIAN
20.4
AQUITANIAN
23.0
CHATTIAN
28.4
RUPELIAN
33.9
PRIABONIAN
37.2
BARTONIAN
40.4
LUTETIAN
48.6
YPRESIAN
55.8
THANETIAN
61.7
DANIAN
65.5
MAASTRICHTIAN
70.6
CAMPANIAN
83.5
FARS
DHOFAR
HADHRAMAUT
ARUMA
Salmiyah
continental molasse
Sur
fan-delta
Tahwah
turbidites
Shama
carbonates
coal
sandstones
carbonates
Musawa
sandstones
carbonates
sandstones
Seeb
carbonates
Rusayl
tidal-flat deposits
Jafnayn 2
carbonates
Jafnayn 1
carbonates
Abat
hemipelagites
marls
Murka
carbonates
Simsima
carbonates
Qahlah
conglomerates, sandstones
Fayah
turbidites
Hasad
slope deposits
post-obduction emersion

Figure 4

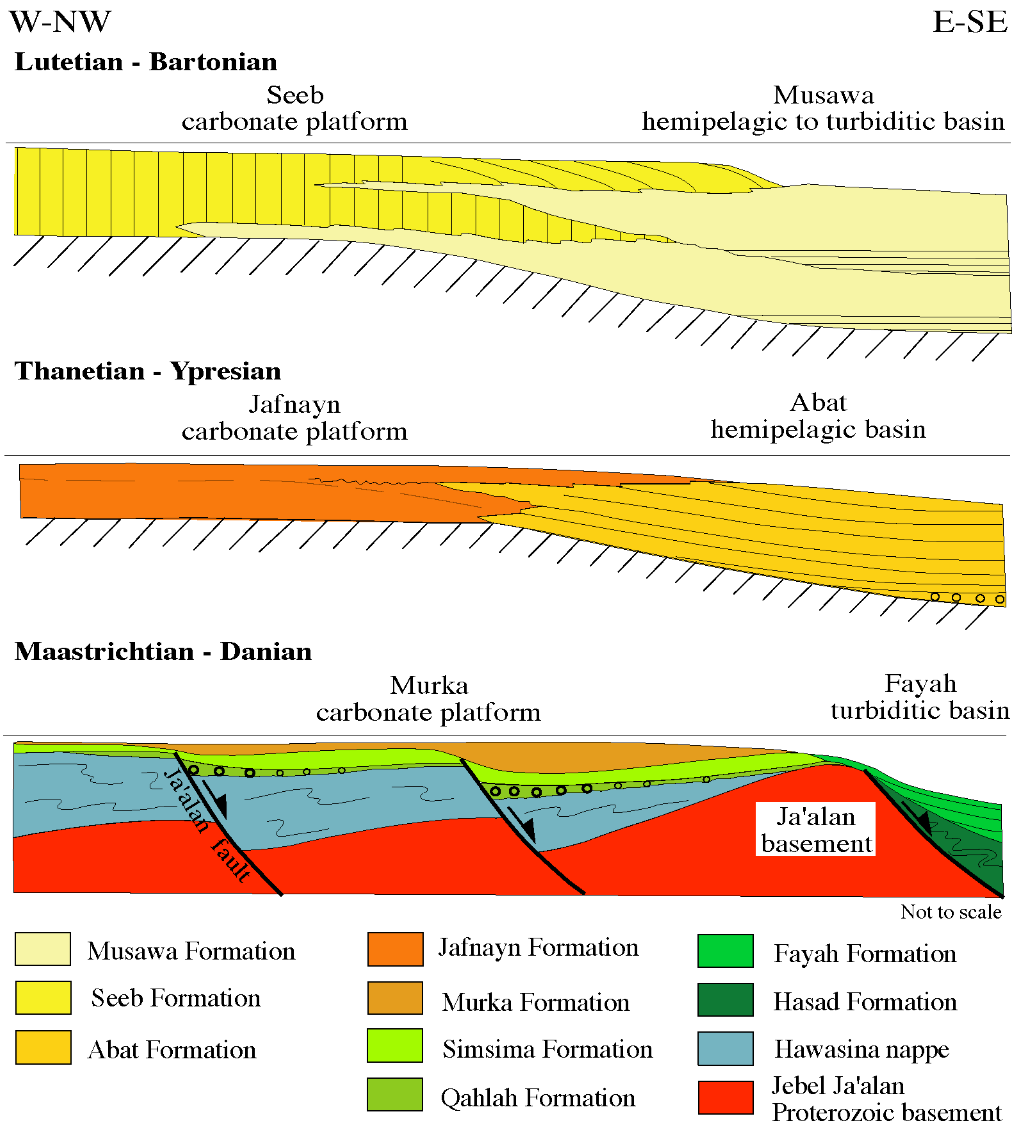

W-NW
E-SE
Lutetian - Bartonian
Seeb
carbonate platform
Musawa
hemipelagic to turbiditic basin
Thanetian - Ypresian
Jafnayn
carbonate platform
Abat
hemipelagic basin
Maastrichtian - Danian
Murka
carbonate platform
Fayah
turbiditic basin
Ja'alan fault
Ja'alan
basement
Not to scale
Musawa Formation
Seeb Formation
Abat Formation
Jafnayn Formation
Murka Formation
Simsima Formation
Qahlah Formation
Fayah Formation
Hasad Formation
Hawasina nappe
Jebel Ja'alan
Proterozoic basement

Figure 5

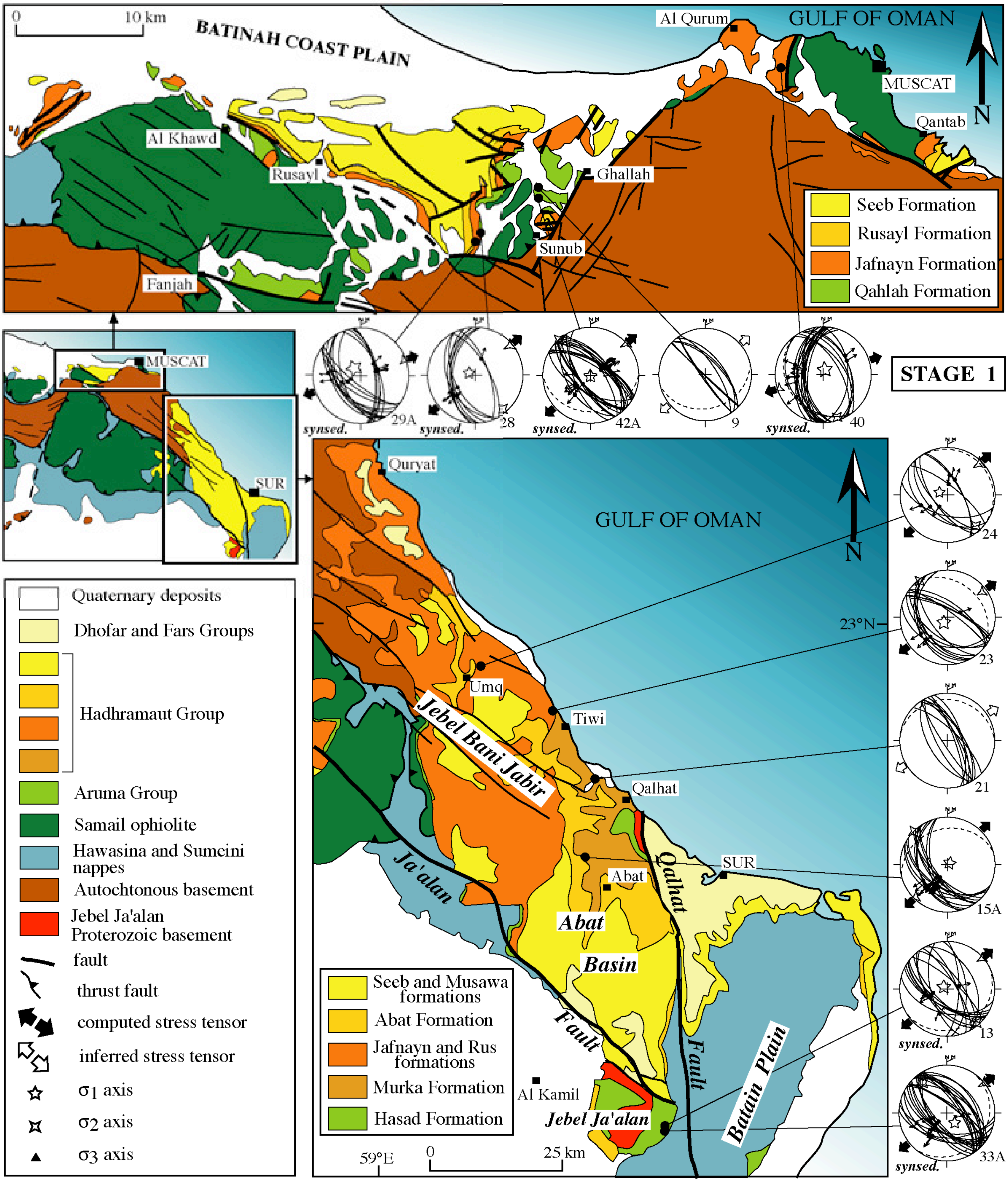

0
10 km
BATINAH COAST PLAIN
Al Qurum
GULF OF OMAN
MUSCAT
N
Qantab
Al Khawd
Rusayl
Ghallah
Sunub
Fanjah
Seeb Formation
Rusayl Formation
Jafnayn Formation
Qahlah Formation
MUSCAT
SUR
29A
synsed.
28
synsed.
42A
synsed.
9
40
synsed.
STAGE 1
Quryat
GULF OF OMAN
N
23°N
Umq
Tiwi
Jebel Bani Jabir
Qalhat
SUR
Abat
Abat
Basin
Ja'alan
Fault
Qalhat
Fault
Batain Plain
Al Kamil
Jebel Ja'alan
59°E
0
25 km
Seeb and Musawa formations
Abat Formation
Jafnayn and Rus formations
Murka Formation
Hasad Formation
24
23
21
15A
13
synsed.
33A
synsed.
Quaternary deposits
Dhofar and Fars Groups
Hadhramaut Group
Aruma Group
Samail ophiolite
Hawasina and Sumeini nappes
Autochtonous basement
Jebel Ja'alan Proterozoic basement
fault
thrust fault
computed stress tensor
inferred stress tensor
σ1 axis
σ2 axis
σ3 axis

Figure 6

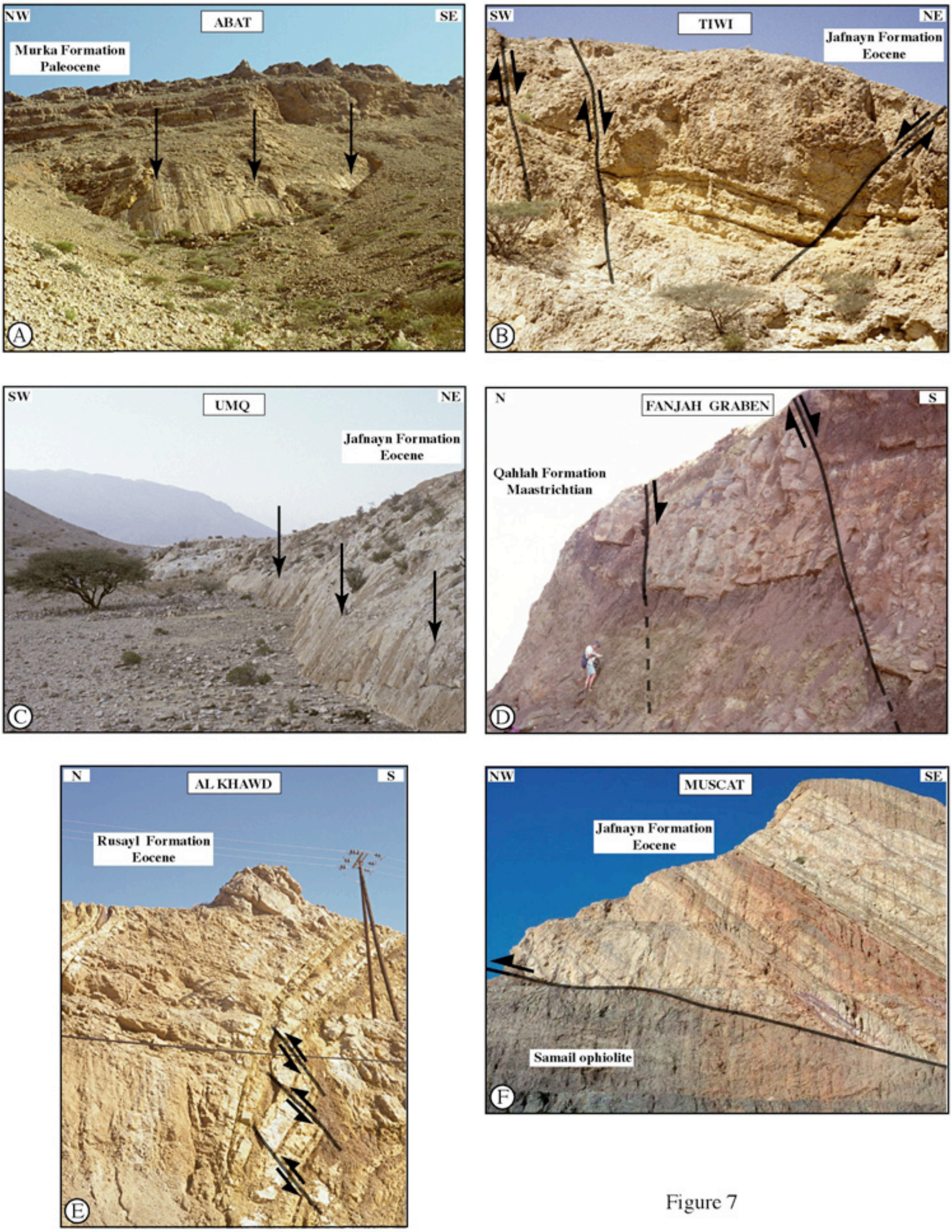
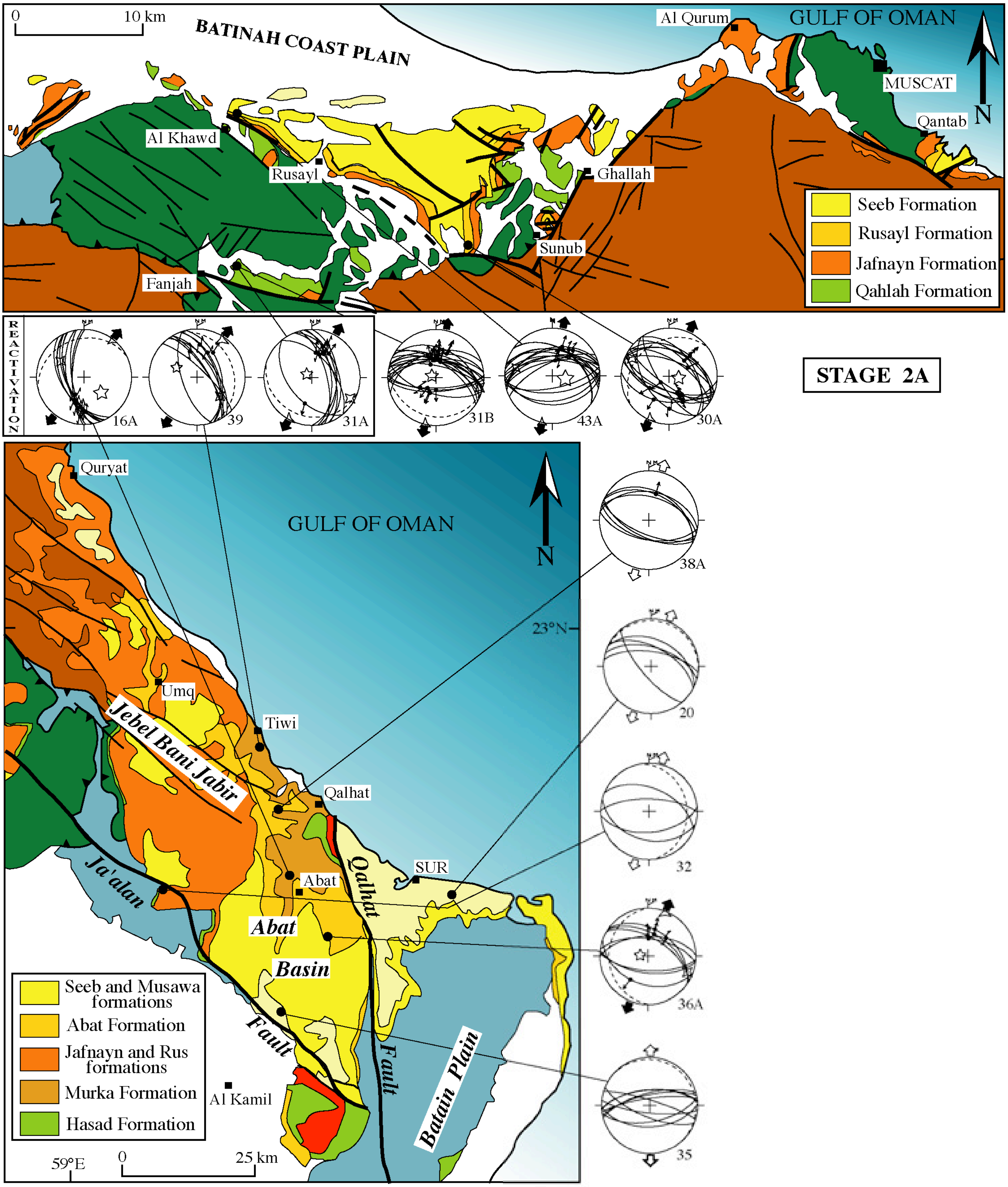

NW
ABAT
SE
Murka Formation
Paleocene
A
SW
TIWI
NE
Jafnayn Formation
Eocene
B
SW
UMQ
NE
Jafnayn Formation
Eocene
C
N
FANJAH GRABEN
S
Qahlah Formation
Maastrichtian
D
N
AL KHAWD
S
Rusayl Formation
Eocene
E
NW
MUSCAT
SE
Jafnayn Formation
Eocene
Samail ophiolite
F

Figure 7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BATINAH COAST PLAIN
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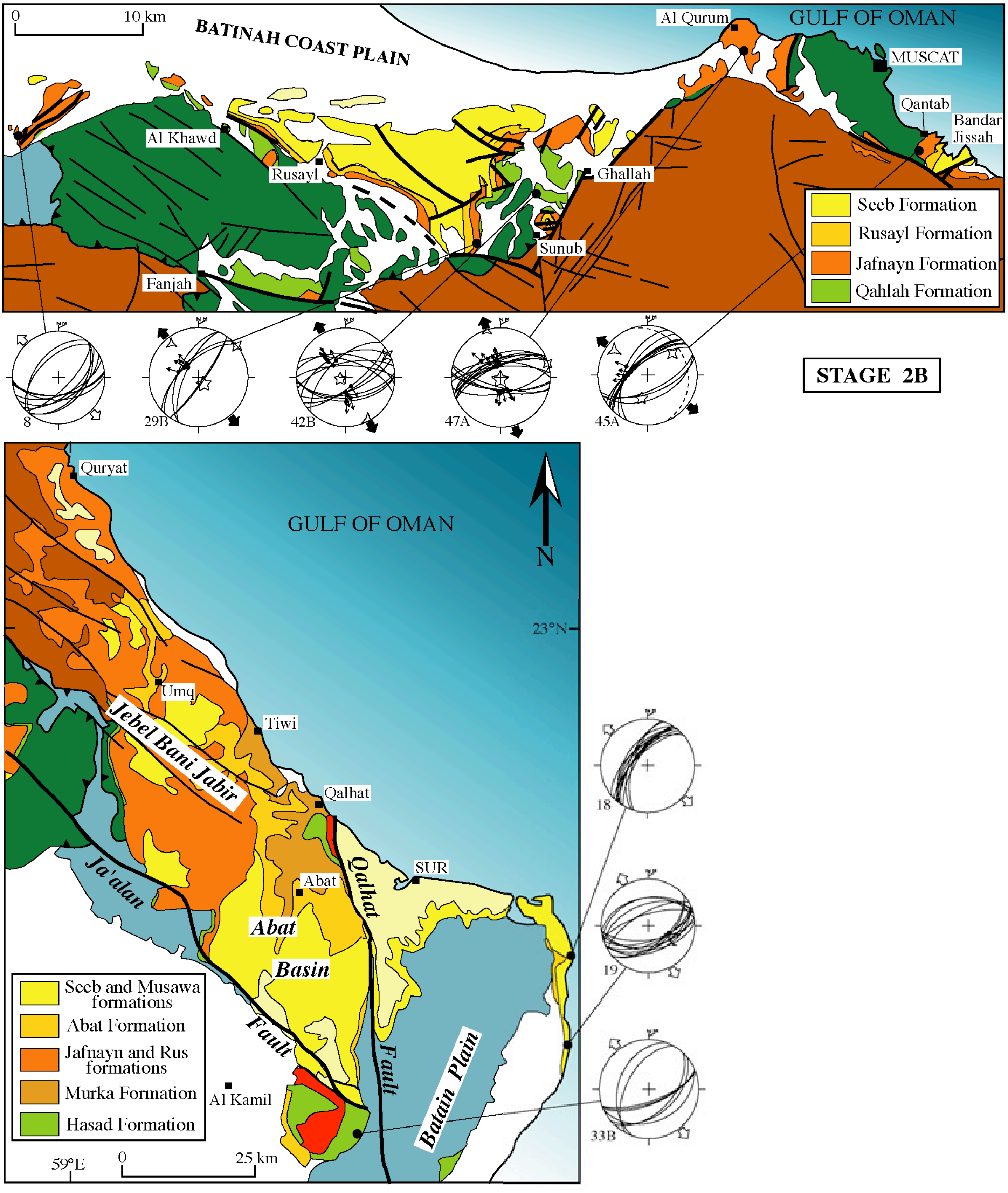
Al Khawd
Rusayl
Ghallah
Sunub
Fanjah
Seeb Formation
Rusayl Formation
Jafnayn Formation
Qahlah Formation
REACTIVATION
16A
39
31A
31B
43A
30A
STAGE 2A
Quryat
GULF OF OMAN
N
38A
23°N
20
Umq
Tiwi
Jebel Bani Jabir
Qalhat
32
SUR
Abat
Qalhat
Ja'alan
Abat
Basin
36A
Fault
Fault
Batain Plain
35
Seeb and Musawa formations
Abat Formation
Jafnayn and Rus formations
Murka Formation
Hasad Formation
Al Kamil
59°E
0
25 km

Figure 8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BATINAH COAST PLAIN
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GULF OF OMAN
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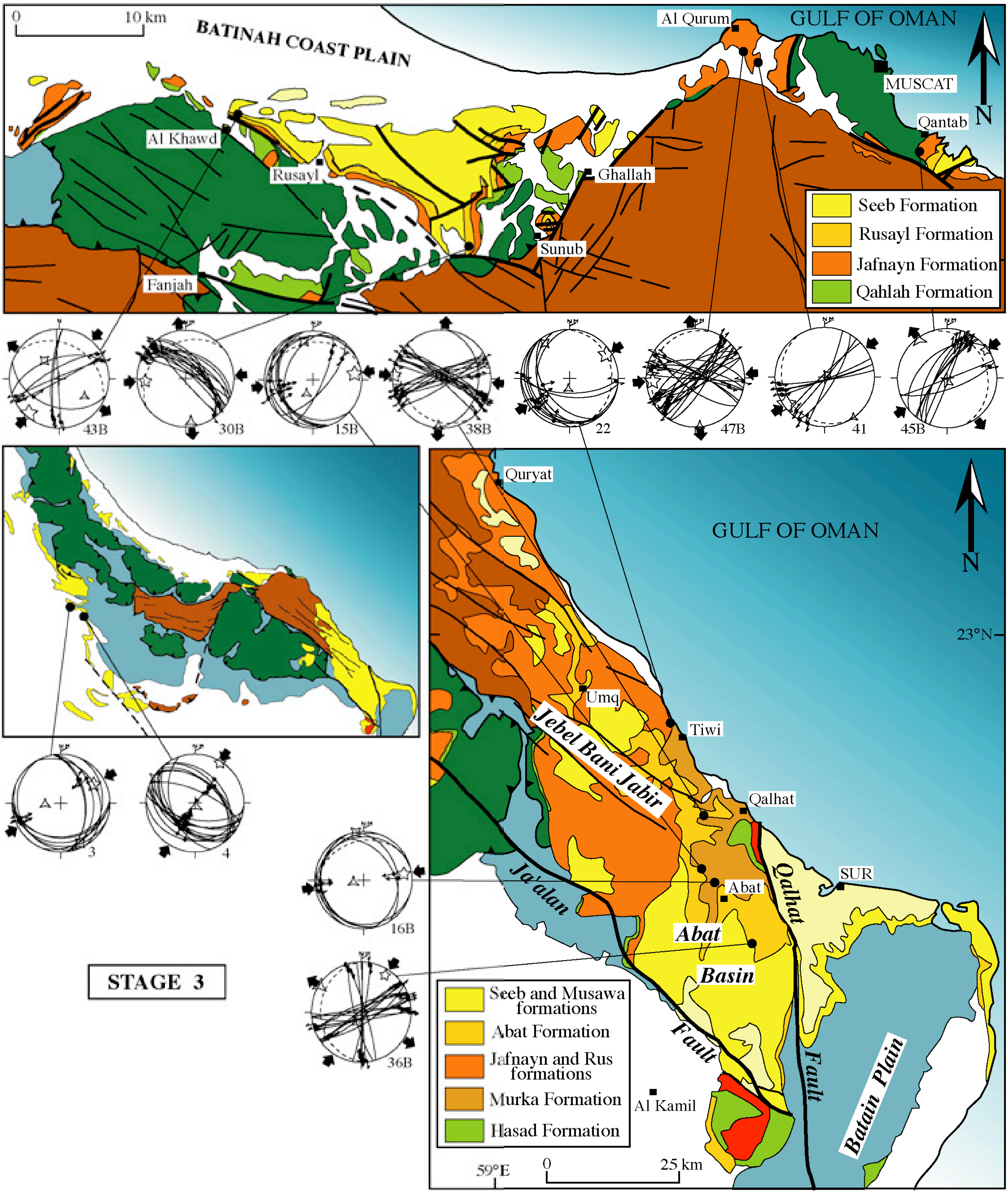
Bandar Jissah
Al Khawd
Rusayl
Ghallah
Sunub
Fanjah
Seeb Formation
Rusayl Formation
Jafnayn Formation
Qahlah Formation
8
29B
42B
47A
45A
STAGE 2B
Quryat
GULF OF OMAN
N
23°N
Umq
Tiwi
Jebel Bani Jabir
Qalhat
SUR
Abat
Abat
Basin
Qalhat
Fault
Ja'alan
Fault
Batain Plain
Al Kamil
Seeb and Musawa formations
Abat Formation
Jafnayn and Rus formations
Murka Formation
Hasad Formation
59°E
0
25 km
18
19
33B

Figure 9


0
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BATINAH COAST PLAIN
Al Qurum
GULF OF OMAN
N
MUSCAT
Qantab
Al Khawd
Rusayl
Ghallah
Sunub
Fanjah
Seeb Formation
Rusayl Formation
Jafnayn Formation
Qahlah Formation
43B
30B
15B
38B
22
47B
41
45B
Quryat
GULF OF OMAN
N
23°N
Umq
Tiwi
Jebel Bani Jabir
Qalhat
SUR
Abat
Ja'alan
Qalhat
Abat
Basin
Fault
Fault
Batain Plain
Al Kamil
3
4
16B
36B
STAGE 3
Seeb and Musawa formations
Abat Formation
Jafnayn and Rus formations
Murka Formation
Hasad Formation
59°E
0
25 km

Figure 10

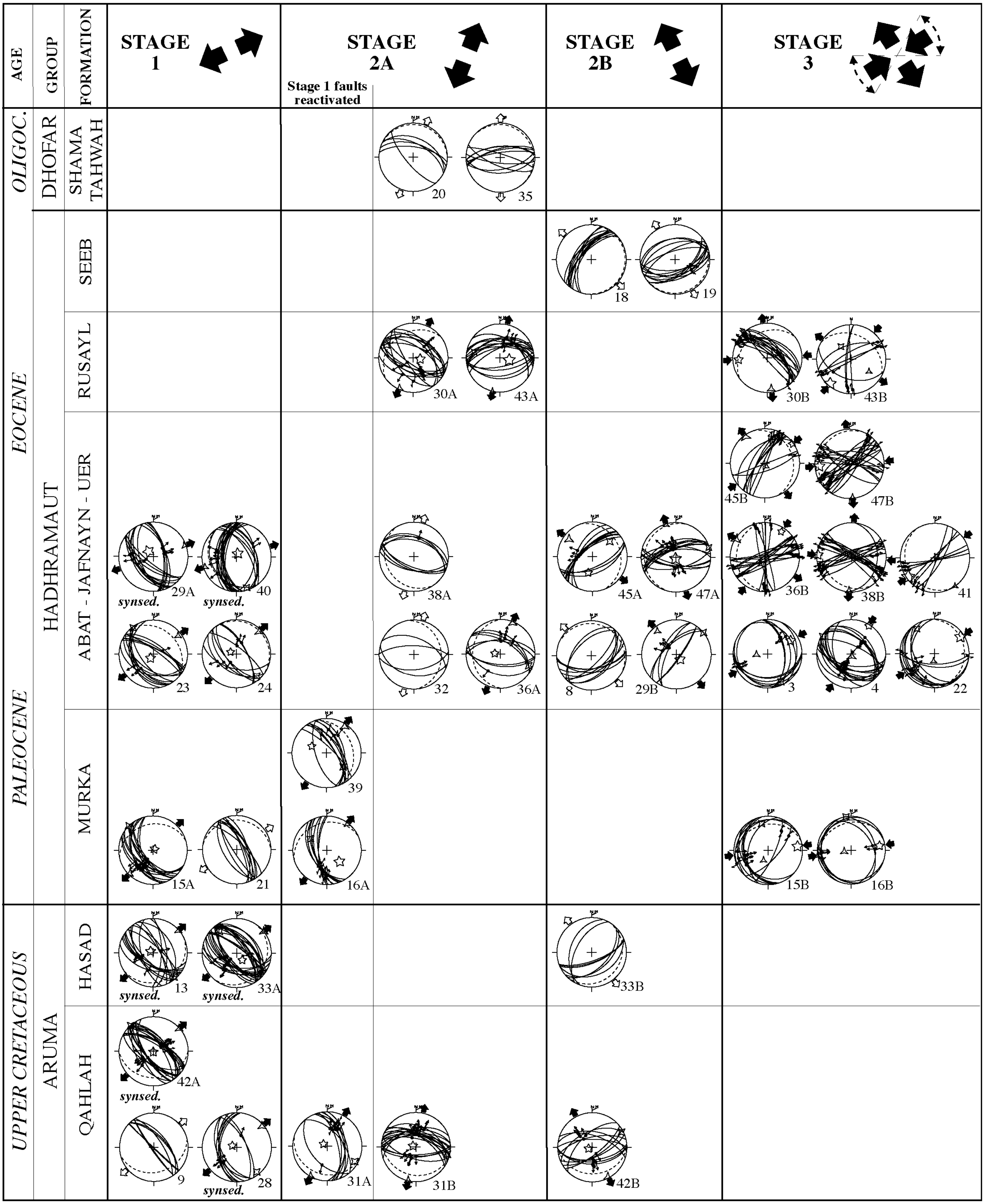
AGE
GROUP
FORMATION
STAGE 1
STAGE 2A
Stage 1 faults reactivated
STAGE 2B
STAGE 3
OLIGOC.
EOCENE
PALEOCENE
UPPER CRETACEOUS
DHOFAR
HADHRAMAUT
ARUMA
SHAMA TAHWAH
SEEB
RUSAYL
ABAT - JAFNAYN - UER
MURKA
HASAD
QAHLAH
20
35
18
19
30A
43A
30B
43B
45B
47B
29A
40
synsed.
38A
45A
47A
36B
38B
41
23
24
32
36A
8
29B
3
4
22
39
15A
21
16A
15B
16B
13
33A
33B
42A
9
28
31A
31B
42B

Figure 11

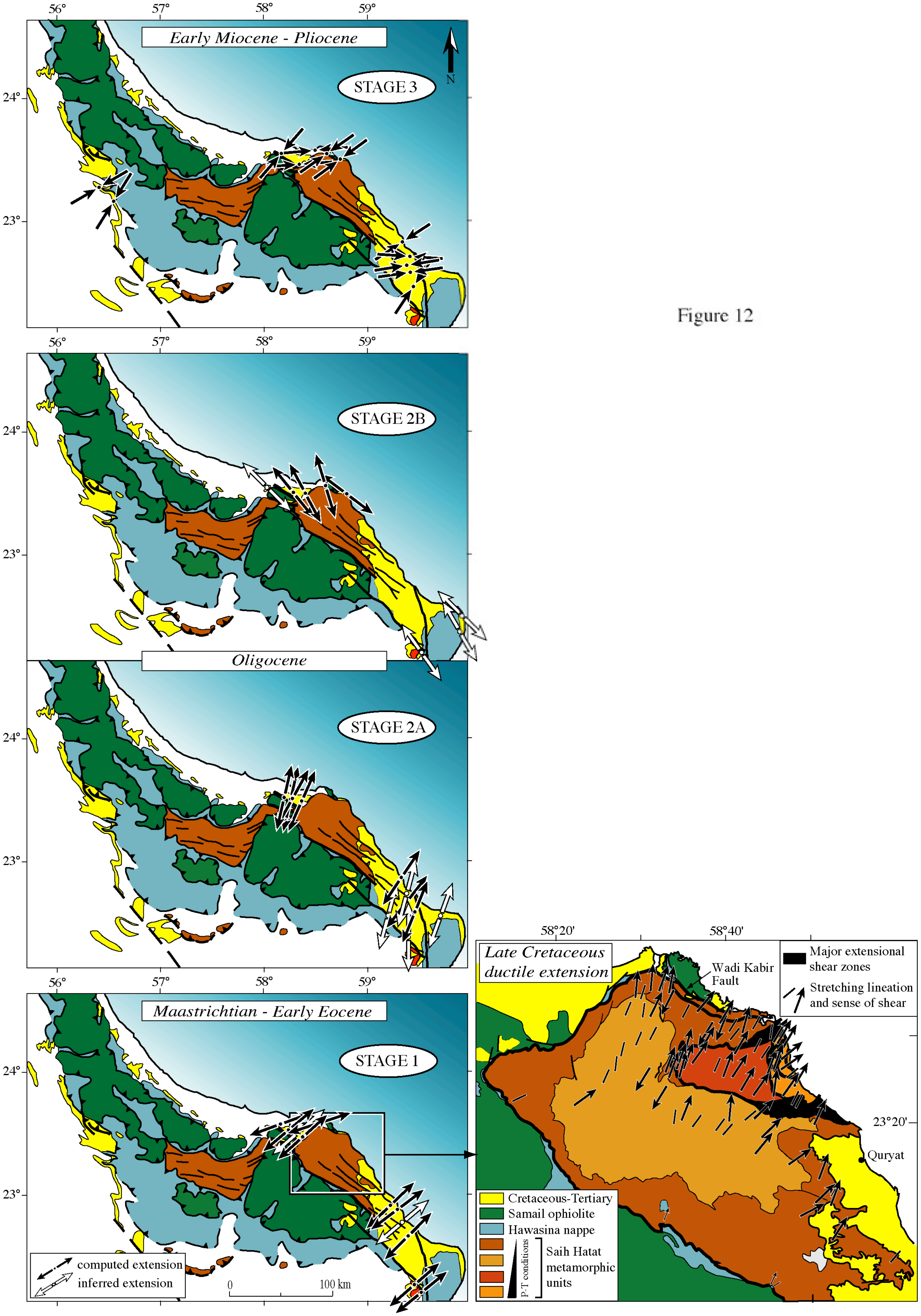
56°
57°
58°
59°
24°
23°
Early Miocene - Pliocene
STAGE 3
N
STAGE 2B
Oligocene
STAGE 2A
Maastrichtian - Early Eocene
STAGE 1
computed extension
inferred extension
0
100 km
58°20'
58°40'
23°20'
Late Cretaceous ductile extension
Wadi Kabir Fault
Major extensional shear zones
Stretching lineation and sense of shear
Quryat
Cretaceous-Tertiary
Samail ophiolite
Hawasina nappe
P-T conditions
Saih Hatat metamorphic units

Figure 12