16 Low Angle Normal-Sense Shear Zones, Folds and Wrench Faults During the Post-Amalgamation Stage of the Arabian-Nubian Shield

Ahmed S. A. A. Abu Sharib

Abstract

The Neoproterozoic East African Orogen (EAO) preserves one of the finest records of a complete Pre-Cambrian Wilson cycle that started with the fragmentation of Rodinia supercontinent (~870–800 Ma) and opening of the Mozambique Ocean, followed by convergence along easterly and/or westerly dipping subduction zones, and was completed by closure of the ocean basin and collision between a collage of continental fragments that comprised East and West Gondwana. A prolonged (~200 Ma) convergence culminated in arcs suturing and terranes accretion followed by arc-continent terminal collision to form a N–S oriented collision zone (EAO) differentiated into the Arabian-Nubian Shield (ANS) to the north and the Mozambique Belt to the south. Terrane accretion resulted in a substantial crustal thickening and differential uplift, of certain parts of the ANS, followed by erosion and deposition of thick cover sequences in a number of, mostly fault-controlled, depositional basins. The latter records a post-accretion complex array of tectonic—"active" and non-tectonic—"passive" related deformations. Active tectonics are attributed to the crustal shortening that accompanied terminal collision and wrenching whilst passive tectonics could be linked to extensional collapse of parts of the orogen and account for the low angle normal and reverse shear zones. Reactivation of pre-existing accretion-related lineaments, and the formation of wrench-related new shears might have created local and overlapping stress fields that resulted in variably oriented structures deviating drastically from the general stress field (s). The differential uplift across the ANS and the use of common criteria to interpret different tectonic regimes (e.g. extension versus wrenching), wherein the deformation events have overlapping, if not matching, dates, make the idea of a regional tectonic model of the ANS inapplicable. Moreover, in many parts of the shield, it is very plausible to interpret some post-accretion deformation events from different tectonic regimes perspective.

Keywords

East African Orogen • Neoproterozoic • Extensional collapse • Wrenching • Differential uplift

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16.1 Introduction

During most orogenic events, the deformation style changes from mainly compressional during the early stages to dominantly extensional and/or wrenching during the closing/terminal stages (e.g. Mercier et al. 1987; Dewey 1988a, b; Dewey et al. 1988). However, in complex orogens, there is evidence of interplay between the three deformation styles. For example, oroclinal loops (e.g. Alpine oroclines) mark the interplay between compressional boundary forces and extension and result in thrust-decorated extensional basins (Dewey 1988b). Moreover, localized shortening and extension during widespread wrenching is very common and results in an array of temporally and spatially related complex structures. Late orogenic extension can be categorized into: tectonic and collapse. Tectonic extension is attributed to: (1) an overall change in the dominant plate boundary forces from compressional to tensional (e.g. the disruption of Pangea: Dewey 1988a), (2) subduction rollback, (3) wrench-related localized extension, and (4) orogen-parallel extension as a consequence of orogen-perpendicular shortening. Extensional collapse occurs when horizontal shortening produces over-thickened crust, wherein the vertical stresses due to load greatly exceed the horizontal stresses. Characteristically, most orogens had undergone substantial uplift, with variable rates, associated with late-to post-orogenic morphotectonic phases of significant extension and magmatism. During orogenesis, it is very common for the two types of extension to interfere and even

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enhance each other. The purpose of this chapter is to shed light on some of the taphrogenic events that took place in the ANS towards the waning stages of the Neoproterozoic evets responsible for the EAO together with the late-to post-orogenic wrenching and shortening.

16.2 Geologic Setting

The Arabian-Nubian Shield (ANS) is a greenschist to amphibolite facies-dominated collisional belt that, together with the granulite-facies-dominated Mozambique Belt (MB) (Fig. 16.1), form the N–S trending East African Orogen (EAO) (Stern 1994; Fig. 16.1). The latter formed following the closure of the Mozambique Ocean basin separating the continental fragments comprising East and West Gondwana ~870–800 Ma (Li et al. 2007) and culminated in the collision between these continental fragments (Fig. 16.1). Formation of the EAO started during the late Cryogenian (~850–750 Ma) and ended during the Ediacaran (~600–550 Ma) (Li and Powell 1993; Meert 2002 and references therein; Collins and Pisarevsky 2005; Li et al. 2007; Pisarvesky et al. 2008; Eyal et al. 2014; Abd El-Rahman et al. 2016; Elisha et al. 2017; Abu Sharib et al. 2019) making it, despite the intermittent periods of quiescence of convergence, the longest documented orogeny in Earth history. The ANS is made up of a number of Neoproterozoic arc terranes juxtaposed along ~NE–SW-and N–S-trending mega shear zones (Fig. 16.2) (Bentor 1985; Stern 1994, 2002; Stein and Goldstein 1996; Meert 2002; Stoecer and Frost 2006; Johnson et al. 2011; Fritz et al. 2013; Robinson et al. 2017). The former trend marks the accretion of the juvenile arcs (Western arc terranes of Johnson et al. 2011), whereas the latter trend marks the collision of the arc terranes (Eastern and Western of Johnson et al. 2011) against the Sahara metacraton to the west and the Arabian craton to the east (Fig. 16.2) (e.g. Stern 1994; Meert 2002; Johnson et al. 2011, and references therein). The prominence of ophiolitic rocks and fragments bounding some of the arc terranes, the lower grade of metamorphism, and the voluminous amounts of post-orogenic granitoids (Tables 16.1 and 16.2) are characteristic features that distinguish the ANS from the Mozambique Belt.

16.3 Post-Amalgamation Events

In the literature on the EAO, the term post-amalgamation refers to all the deformation events (including extension, wrenching and shortening), magmatic activities and depositional processes that post-dated terrane accretion. In a strict sense, apart from geochronological data that might help in distinguishing pre- and post-amalgamation deformation events, structures related to post-amalgamation events crosscut and overprint the accretion-related structures. However, in the absence of a clear crosscutting relationship, it is difficult to distinguish between post-amalgamation and accretion-related shortening since both events produced the same type of structures mainly folds and thrusts, with similar orientations.

Hence, there is a consensus among researchers interested in ANS geology to use the post-amalgamation depositional basins as a reference point. The latter are variably sized Neoproterozoic terrestrial, shallow marine and mixed terrestrial/shallow marine mostly structurally controlled depositional basins that are well developed in the north-eastern part of the ANS. The Hammamat (Egypt) and the Ablah, Murdama, Hibshi, Jibalah, Bani Ghayy and Fatima (Saudi Arabia) basins are the best-studied basins from the Nubian and Arabian shields, respectively. A common feature of most basins is the basal regional unconformity surface separating them from the underlying newly accreted arc terranes (Abdeen et al. 1992; Rice et al. 1993; Johnson 2003; Johnson et al. 2011). Moreover, whilst some basins are totally localized within a specific terrane, others formed across adjacent terranes or sub-terranes. For example, the Murdama group basins overlie, the Siham and Suwaj subterranes, of the Afif complex terrane (e.g. Johnson 2003), whilst the Bani Ghayy basins lie across the boundary between Afif and Asir terranes.

All compressional deformation events that affected these basins will be assigned to the "post-amalgamation" shortening category. However, it should be kept in mind, as will be seen in the next sections, that these post-amalgamation events and processes are, to a great extent, interlinked in space and time in a rather complex manner. For example, wrenching was accompanied with localized zones of shortening and extension. The latter produced a number of pull-apart basins that have been potential depocenters for molasse and/or marine sediments, as well as sites for magmatic activities. On the contrary, late orogenic extension has been interpreted to facilitate wrenching (see below), and of course, played a significant role in the emplacement of the widespread extension-related intrusions.

16.3.1 Taphrogenic Event

16.3.1.1 Low Angle Normal Shear Zones (LANSZ)

Normal faults and low angle normal-sense shear zones (detachments) are widespread, but typically are better developed in the Nubian sector of the ANS.

LANSZ in Northern ANS

Low angle normal shear zones have been recorded from the Eastern Desert and Sinai terranes. In the Central and Southern Eastern Desert of Egypt, the NW-trending Meatiq

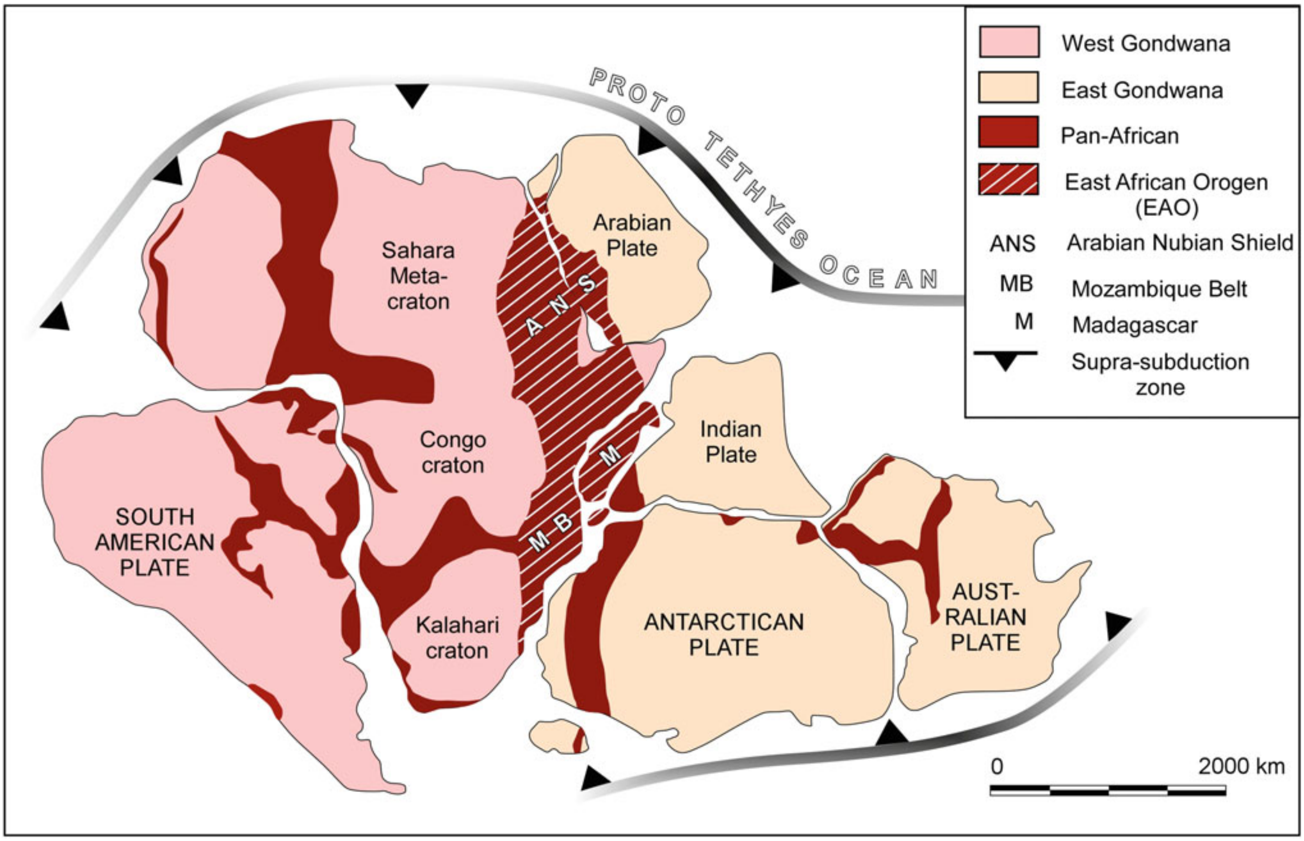

Fig. 16.1 A general map showing the distribution of the Pan-African belts in the assembled East and West Gondwana continents

and Hafafit gneissic domes, respectively, are bounded to the north and south by NNW- and SSE-dipping normal shear zones, with NNW-and SSE-directed sense of shear, respectively (Rice et al. 1992; Wallbrecher et al. 1993; Fritz et al. 1996, 2000; Fowler and Osman 2009; Andersen et al. 2010). In both cases, the shear zones separate a footwall block comprising amphibolite facies ortho- and para-gneisses from an allochthonous greenschist facies succession of island arc rocks, ophiolitic melange and Hammamat sediments in the hanging-wall. The gneissic domes have been interpreted to represent metamorphic core complexes associated with crustal extension (Sturchio et al. 1983a, b; Fritz et al. 1996, 2002; Neumayr et al. 1996a, 1998; Loizenbauer et al. 2001). According to Neumayr et al. (1998), the N-and S-directed low angle normal faults in the Meatiq area played a significant role in the exhumation and updoming of the Meatiq core complex and were associated with a phase of low grade metamorphism, their M3, that has been dated at 580 Ma. To the west of the Meatiq dome, Fowler and El Kalioubi (2004) interpreted the NW-trending Neoproterozoic Um Esh-Um Seleimat nappe (an eugeoclinal succession comprising intensively foliated molasse-type sedimentary rocks and ophiolitic melange) as an extensional, top-to-the NW and low angle shear zone. Towards the extreme north-eastern tip of the ANS in the Sinai Peninsula, a widespread sub-horizontal, 1.5 km thick and NW-dipping normal shear zone with top-to the NW sense of shear has been recorded in Wadi Kid area (Blasband et al. 1997, 2000). The shear zone has been linked to a high geothermal gradient as evidenced by regional metamorphism at LP and HT (Blasband et al. 1997, 2000; Brooijmans et al. 2003) and has been interpreted to have developed during the exhumation of a metamorphic core complex similar to that in the Eastern Desert. However, as in the case of the Eastern Desert, compressional rather than extensional origin has been suggested for the low angle shear zones (Shimron 1984, 1987; Fowler et al. 2010). Despite the common belief and the growing body of evidence that the low angles shear zones are linked to core complex formation, the nature of the extension that resulted in exhumation of the core complex is rather controversial (see below).

LANSZ in Southern ANS

Towards the southernmost part of the ANS, extensional shear zones have been recorded from the Bulbul Belt, in southern Ethiopia (Tsige and Abdel Salam 2005). The ~100 km long, 1–5 km wide N-trending and Chulul shear zone (southern extension of the Bulbul shear zone) have

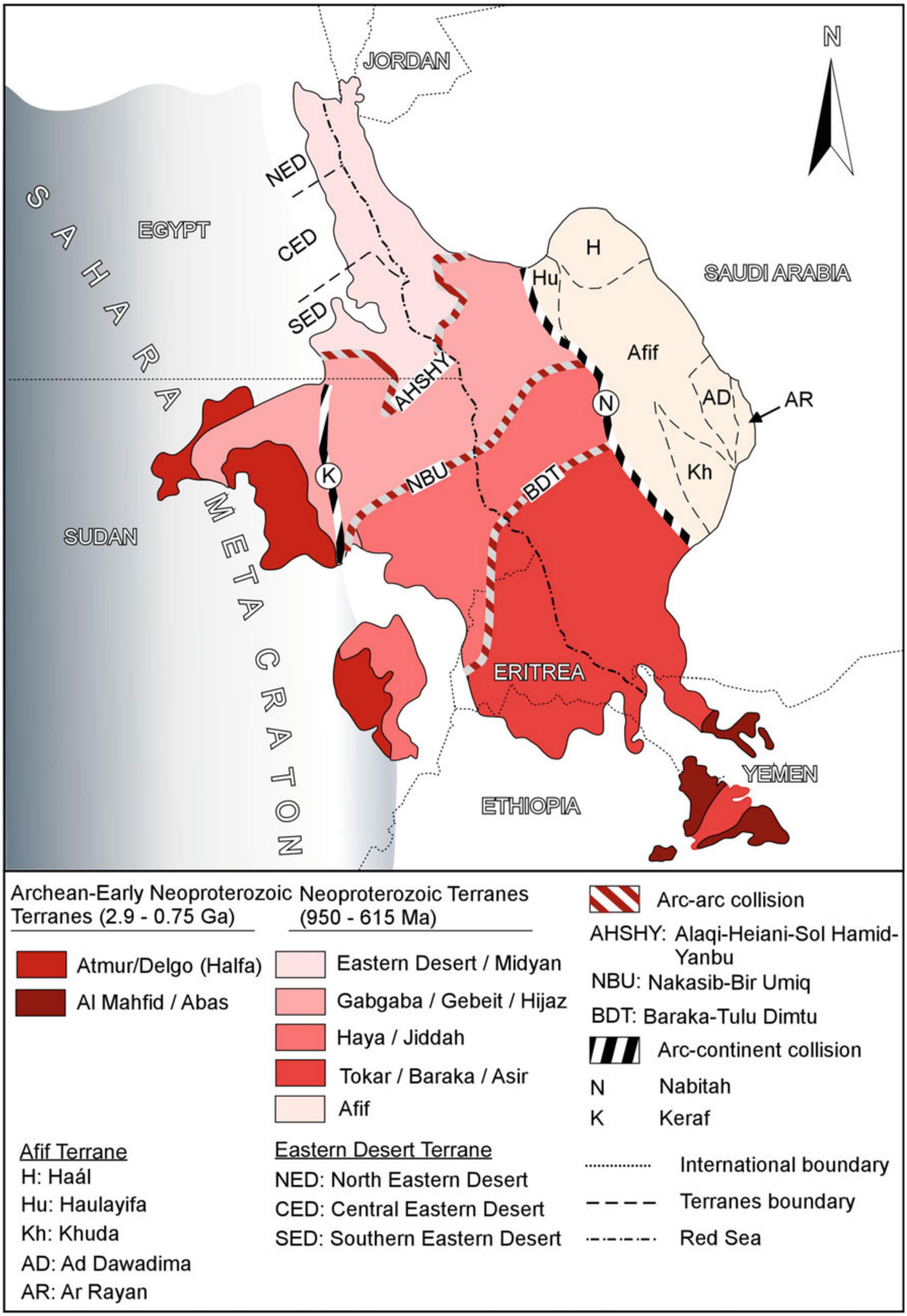

Fig. 16.2 A general map showing the different accreted terranes (arcs) the make up the Arabian-Nubian Shield (ANS) prior to the opening of the Red Sea Rift

Table 16.1 Geochronological data of some selected extensional-related dykes from the different terranes of the ANS

			Locality	Age in Ma	Lithology	References
Nubian shield	Terrane	Eastern Desert	Feiran area, Sinai (Egypt)	591 ± 9 Ma		Stern and Manton (1987)
			NE Sinai (Egypt)	591 ± 12 Ma		Stern and Manton (1987)
			N Sinai (Egypt)	600–540 Ma		Kessel et al. (1998)
			Eastern Desert (Egypt)	540–595 Ma		Stern and Hedge (1985)
Arabian Shield		Midyan	Ajaj shear zone (Saudi Arabia)	573 ± 6 Ma		Kennedy et al. (2011)
			Jordan	574 ± 11 Ma 564 ± 10 Ma		Jarrar et al. (1992, 2003)
			Jordan	575 ± 6 Ma 545 ± 13 Ma		Jarrar (2001)
			Wadi Araba Jordan	550 ± 13 Ma		Jarrar et al. (1991)
		Higaz	Jibalah Group Saui Arabia	577 ± 5 Ma		Kusky and Matsah (2003)

been interpreted to be a low angle oblique slip normal-sense shear with a top-to-southeast sense of shear as indicated by SE-plunging stretching lineation that overprints an earlier E-dipping mylonitic fabric (Tsige and Abdel Salam 2005). The footwall of the shear zone comprises amphibolite facies gneisses and migmatites of the Melka Guba domain, the southern extension of the Alghe terrane, whereas the hanging-wall is occupied by greenschist facies association of island arc, ophiolite and plutonic rocks constituting the Chulul domain, the southern extension of the Bulbul terrane. According to the authors, extension along the Chulul shear zone took place after a prolonged period of convergence that culminated in the collision between the Melka Guba and Chulul domains with the development of the pervasive E-dipping mylonitic foliation. In southern Ethiopia, the Bulbul belt is one of four low grade N-trending belts (others being Moyale, Megado and Kenticha) sandwiched between high grade gneisses and migmatites and dominated by volcano-sedimentary successions, wherein the mafic-ultramafic rocks have been interpreted to be ophiolites marking Neoproterozoic suture zones (Tsige and Abdel Salam 2005, and the references therein). However, the Wilson cycle model proposed for the belts has been challenged by Warden and Horkel (1984), Ghebreab (1992) and Worku and Yifa (1992) who suggested an ensialic model wherein the mafic-ultramafic rocks intruded into the high grade gneisses and migmatites in an intracratonic rift basin that did not evolve into a passive plate margin.

In eastern Eretria, Ghebreab and Talbot (2000) recorded late Pan-African sub-horizontal ductile to semi-ductile extensional shear zones with top-to-the northeast tectonic transport in the amphibolite facies gneisses and schists of the Ghedem domain that is separated from the structurally overlying volcano-sedimentary rocks of the Bizen domain by a 2–3 km wide moderately to gently west-dipping transition zone. The shear zones are attributed to a phase of gravitational collapse that took place late during the second phase of Pan-African deformation (PAD2; Ghebreab and Talbot 2000). According to the authors, the sub-horizontal shear zones together with the flat-lying fabric (PAD2) were exploited during the Cenozoic NE–SW extension of the Red Sea in that they influenced the localization of the detachments and controlled the location of potential subsequent normal faults. The Oligocene dolerite sills were intruded along these reactivated structures. It is noteworthy that many low angle normal-sense shear zones overprint earlier mylonitic fabrics having senses of shear opposite to those shown by the normal shear zones. The latter observation implies reactivation of earlier reverse-sense shear zones as normal-sense shear zones as the stress regime changes from compression to extension.

16.3.2 Wrenching

A common feature of many orogenies is the late orogenic wrenching. Typically, it follows terrane accretion and continent–continent collision and decorates the latter with an extensive array of strike-slip faults associated with transpressional and/or transtensional strain. For example, in the Tibetan plateau, Himalaya, the N–S shortening between Eurasia and India micro-plates during the mid-Eocene (∼45 Ma) ended up with continent–continent collision that was followed during the Miocene by a significant wrenching that produced widespread conjugate strike-slip faulting (Dewey 1988b). Similarly, the EAO witnessed a significant period of late orogenic wrenching along with what is known as the Najd Fault System (NFS) that affects mainly the northern and north-eastern parts of the orogen

Table 16.2 Geochronological data of some selected post-orogenic granitoids from the different terranes of the ANS

			Locality	Age in Ma	Lithology	References
Nubian shield	Terrane	Eastern Desert	Gebel Gattar	576 ± 6 Ma, 594 ± 3	Younger granite	Youssef (2005), Moussa et al. (2008)
			Um Had	596.3 ± 1.7, 595	Granite	Andersen et al. (2009), Abu Sharib et al. (2019)
			Arieki	593 ± 3.1	Granite	Andresen et al. (2009)
			Central Eastern Desert	550–540	Granite	Lundmark et al. (2011)
			CED and SED (Egypt)	620–530	K-rich granites	Schmidt et al. (1979), Habib et al. (1985), Greiling et al. (1994)
			Sinai (AL Suite)	608–580	Alkaline and peralkaline granite and monzodiorite	Be'eri-Shlevin et al. (2009)
			Sinai	579–594	monzogranite, syeno—granite and alkali granite	Ali et al. (2009)
		Haya	Sabaloka Central Sudan	506 ± 4 591 ± 5	High-K, calc-alkaline granodiorite shoshonitic granite	Abdel Salam and Stern (1985)
			Ethiopia	606 ± 1 613 ± 1, 612 ± 6	Granodiorite granite	Miller et al. (2003), Avigad et al. (2007)
Arabian shield		Afif	Abanat suite	570–585	peralkaline to peraluminous granites	Cole and Hedge (1986)
		Ar Rayn	alkali granite suite	607 ± 6 and 583 ± 8	alkali granite	Doebrich et al. (2007)
		Midyan	Araba complex (Jordan)	600–560		Jarrar et al. (2003)

cutting across the ANS in a NW–SE direction. The NFS is a brittle to ductile NW–SE striking crustal scale shear zone (1100 km long and up to 400 km wide) dominated by left-lateral strike-slip faults having a total net displacement of some 240–300 km (Fig. 16.3) (Brown and Jackson 1960; Delfour 1970; Brown 1972; Brown and Coleman 1972; Moore 1979; Schmidt et al. 1979; Davies 1984; Stern 1985; Johnson et al. 2011). Subordinate conjugate NE-trending right-lateral shears are documented (Moore 1979; Davies 1980; Johnson et al. 2011, and the references therein). The NW- and NE-trending faults are arranged in a parallel, en echelon and sinusoidal curved geometry (Moore 1979). Braided fault zone is very common when curved faults join or intersect together (Moore 1979). The inferences that the NFS extends south-eastward across the covered basement rocks of the Arabian plate into south Yemen, eastern Arabia, India and Iran (Brown 1972; Moore and Al-Shanti 1979; Stern and Johnson 2010; Al-Husseini 2000), southwards in the southern ANS and Mozambique Belt in Kenya and Madagascar (Raharimahefa and Kusky 2010), and north-eastward into Jordan El-Rabaa et al. 2001) with a total length of more than 2000 km (Moore 1979) make the NFS one of the greatest transcurrent fault zone on Earth (e.g. Johnson et al. 2011). Examples of NFS in the Arabian part of the shield include the sinistral NW-trending Qazaz-Ar Rika and the Halaban-Zarghat, and the dextral NE-trending Ad Damm shear zones (Johnson et al. 2011). Examples from the Eastern Desert terrane of the Nubian shield include the NW-trending Kharit-Hodein, Nugrus and Atalla shear zones, and the NE to ENE-trending Qena-Safaga and Mubarak-Barramiya conjugate shear belts (Hamimi et al. 2019). Based on superposition and overprinting criteria, the NFS affects and displaces the late Cryogenian-Ediacaran sutures that formed during terrane accretion, and hence, it is attributed to a late Ediacaran post-accretion event. As is the case in all strike-slip fault systems (e.g. Sylvester 1988), the NFS was accompanied with an array of secondary structures such as normal faults, thrusts, folds and oblique-and strike-slip faults. Along the course of the NFS, diverse zones of transpression, transtension and pure strike-slip faulting were produced (e.g. Fritz et al. 1996; Abd El-Wahed 2010; Abd El-Wahed et al. 2016; Stern 2017). The extensional domains controlled sediment accumulation within some post-accretion depositional basins and the sites of extrusion of some volcanics and dyke swarms (Fig. 16.4) (see below).

Time of Activity of the Najd Fault System (NFS)

Generally speaking, the NFS is a late Proterozoic crustal scale transcurrent fault that has been active during the interval 620–540 Ma (Fleck et al. 1976; Stern 1985). Criteria used to constrain this age range include (1) depositional age of sediments accumulated within syn-Najd basins and (2) crystallization age of syn- and post-shear igneous rocks. Compared to syn-shear plutons, which are slightly to intensively deformed and elongated parallel to strands of the Najd Fault System, post-shear plutons are non-deformed, circular in map-shape and discordant to the main fabric of the country rock. Strands of the NFS have been constrained between the pre-shear 567 ± 86 Ma Abu Aris granite, in central Arabia, and the post-shear 563 ± 71 Ma Tukhfah granite, in north-east Arabia, (Fleck and Hadley 1982). Elongated syn-shear plutons in Arabia are dated at 625–575 Ma (Duyverman et al. 1982; Hedge 1984). In the southern part of the shield, 577–529 Ma felsic dykes cut across a set NW–SE-trending strands of the Najd Fault System (Fleck et al. 1979). The Jibalah group was deposited in pull-apart basins that formed due to movement along elements of the NFS (Hadley 1974; Husseini 1989; Al-Husseini 2000; Johnson 2003). The minimum depositional age of the group is constrained by 540 ± 18 Ma andesitic flows within the group (Brown 1972). Deposition in the Al Jifn basin (Jibalah Group basins) is bracketed between 625 ± 4 Ma and 576 ± 5 Ma based on the crystallization ages of rocks below the basin and a felsite dyke cutting through the basin-fill, respectively (Matsah and Kusky 2001). In Jabal Jibalah area, the maximum age of faults activity is constrained by the crystallization ages of 574 ± 28 (Calvez et al. 1984), and 567 ± 6 and 581 ± 1 (Brown et al. 1989) on granites forming basement to the group. The Al Junaynah Group, which unconformably overlies the ~640 Ma granite, and was deposited along the N–S-trending Nabitah fault/shear zone, has been folded and dextrally sheared implying post 640 Ma fault activity. Similarly, to the west of the Nabitah fault and within the Asir terrane, the Ablah Group (641 ± 4–613 ± 7 Ma: Agar 1986; Doebrich et al. 2004) was deposited in N–S-trending marine basins that are intruded by Najd-related A-type granitoids dated at 617 ± 17 Ma and 605 ± 5 (Moufti 2001).

In conclusion, from the geochronological data presented, it is clear that the last ~100 Myr (~630–530 Ma) of the East African Orogeny was characterized by intense wrench tectonics manifested by the Najd Fault System that cuts mainly through the north and north-eastern parts of the Arabian shield and continues northwestwards into the central Midyan terrane of the Nubian shield.

16.3.3 Post-Amalgamation Shortening

Based on overprinting and superposition criteria and the relative timing and style of deformation, the post-amalgamation structures linked to shortening are placed into two main categories: convergence—or transpression-related. This subdivision takes cognizance of the following facts and relationships: (1) some depositional basins have been multiply deformed; thus, the rocks in these basins have been affected by more than one phase of folding; (2) the rocks in some depositional basins are lie with unconformity on deformed rocks in older basins; (3) in some basins, the folds are arranged in an en echelon pattern indicative, interpreted to be the result of late shearing.

16.3.3.1 Convergence-Related Shortening

In the literature on the ANS, the convergence-related shortening refers to all E–W to ENE–WSW shortening events that accompanied the Ediacaran terminal collision between the continental fragments of East and West Gondwana. Structures related to this tectonic event are recorded in basins of the Arabian and Nubian sectors of the ANS. Basins of the former include Murdama Group (Agar 1988; Kattan and Harire 2000), Bani Ghayy (Johnson 2003), Ablah and Fatima (Hamimi et al. 2012, 2014). Example of the Nubian basins includes Wadi Himur in the Southern Eastern Desert. In the Arabian basins, the shortening produced mesoscopic gently plunging open to isoclinal and intrafolial upright, N–S-trending folds with a well-developed vertical to steeply E-dipping axial planar foliation. Local W-verging overturned folds are not uncommon. Linear fabric elements include variably oriented mineral and stretching lineations. In Wadi Himur in the Allaqi-Heiani suture, slices of siliceous marble intercalated with thin conglomerate beds are in thrust contact with a thrust nappe comprising arc volcanics and ophiolitic serpentinite along the western side and ophiolitic amphibolite along the eastern side of the wadi. The shortening produced meso-to macroscopic, gently NNW-plunging, NNW–SSE-trending and asymmetric folds.

16.3.3.2 Transpression-Related Shortening

The deformation style, type of strain and arrangement of compressional ductile structures related to this shortening event indicate that the prevailing tectonic regime was regional-scale transpression, wherein bulk horizontal shortening components were related to regional shearing. Shear-related shortening can be categorized into easterly and northerly directed.

N–S to NNW–SSE Shortening

Preserved in Fatima basin, the northerly directed shortening produced a group of kinematically and geometrically related

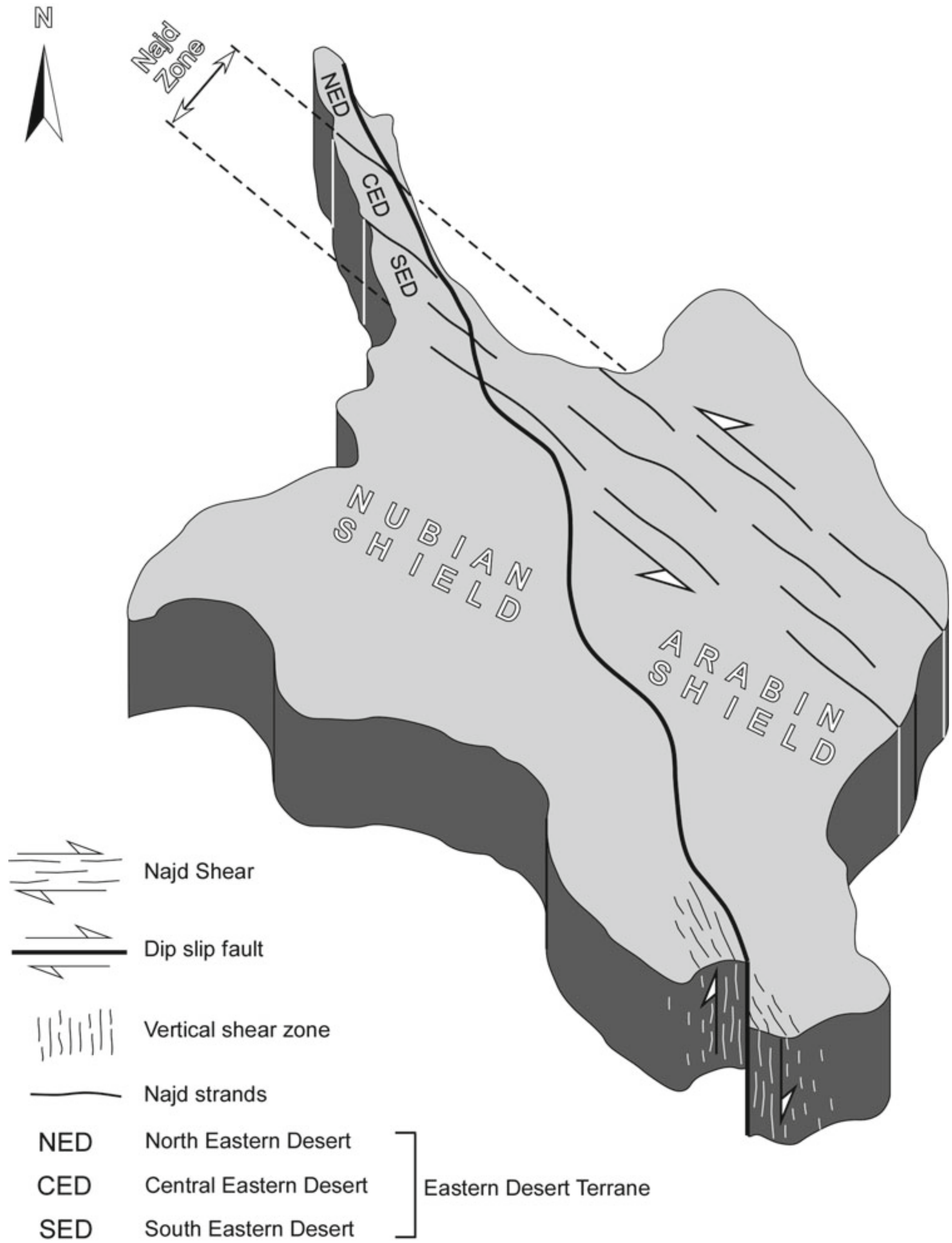

Fig. 16.3 A schematic diagram shows the differentially uplifted Arabian-Nubian Shield crosscut by the NW–SE-trending Najd Fault System (NFS)

thrusts and folds. This deformation event is manifested by fold-initiated thrusts and thrust-related NW to NNW- and occasionally N-verging overturned folds with gently NE to ENE plunging axes (Hamimi et al. 2014).

E–W to ENE–WSW to NE–SW Shortening

Structures related to this shortening event are recorded in Ablah and Maslum (Murdama) basins, in eastern and southern Arabia, and in Hammamat basins (in wadis Queih, Hodein and Um Gheig), the Central Eastern Desert, Egypt. In wadi Yiba, Ablah basin, the shortening produced N to NNW-oriented thrusts and W-verging, thrust-related overturned folds (Hamimi et al. 2014). In the southwestern margin of Maslum basin (Murdama Group basins), it produced en echelon NW–SE-trending folds that have been attributed to ductile shearing along the Ar Rika fault, one of the strands of the Najd Fault System (Johnson 2003). In some of the Hammamat basins, for example, in wadi Queih, this event produced NE-verging folds and the SW-dipping thrusts that accompanied a positive flower structure formed as a consequence of movement along Najd-related NW–SE-trending sinistral strike-slip faults (Abdeen et al. 1992; Abdeen and Warr 1998; Abdeen 2003; Abdeen and Greiling 2005). Shear sense criteria indicate sinistral shear in the

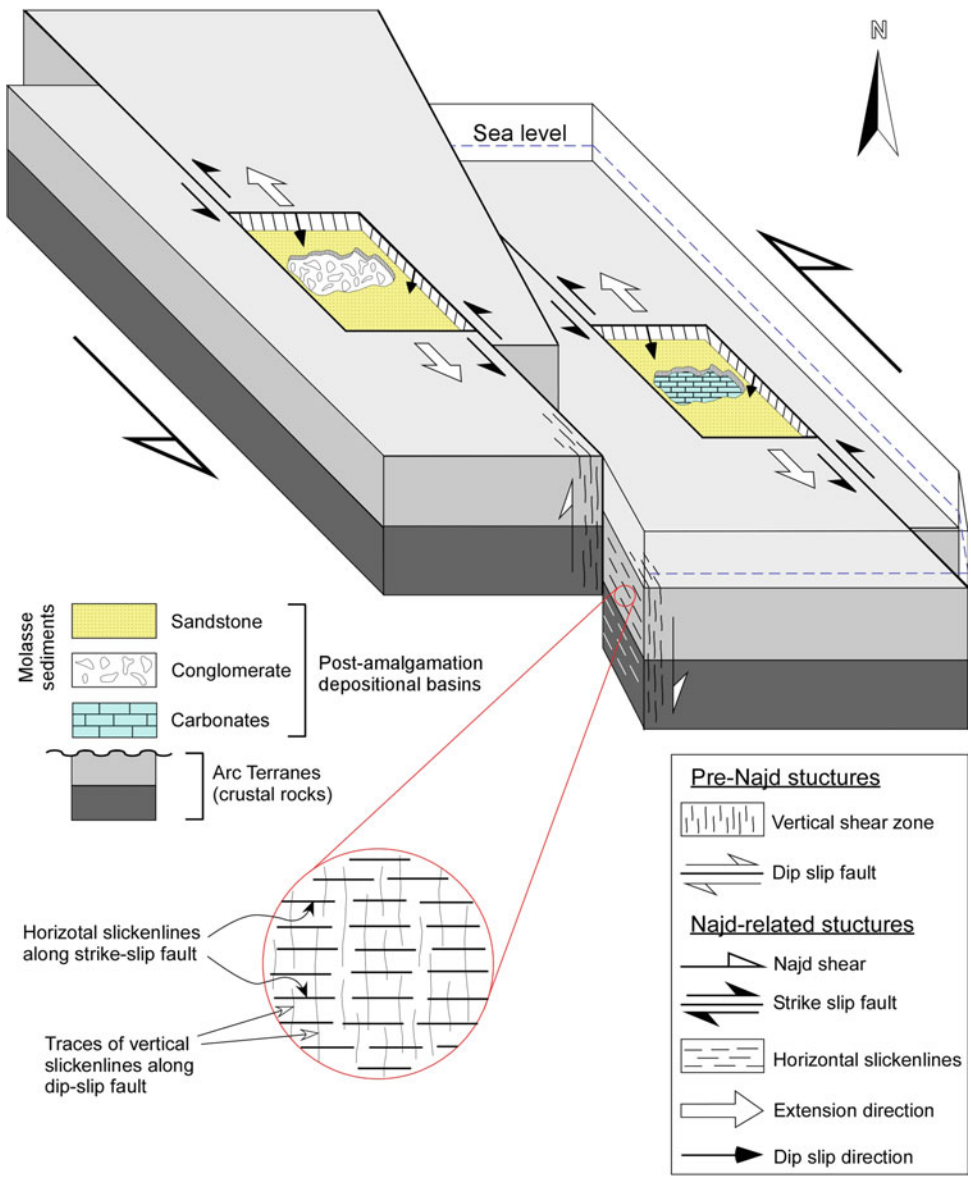

Fig. 16.4 A tectonic model shows pull-apart basins formed between overstepped and overlapped Najd strands that cut across the differentially uplifted Arabian-Nubian Shield. The carbonates and clastics are restricted to the subsided and uplifted parts of the shield, respectively

Hammamat and Maslum basins and dextral shear in the Ablah basin. In wadi Um Gheig, the Hammamat Group sedimentary rocks are affected by SW-dipping oblique slip reverse faults associated with open to tight horizontal to gently plunging NW–SE-trending, and NE-verging folds with axial planes ranging from vertical to inclined to horizontal. The inclined axial planes are parallel and sub-parallel to the NE-directed reverse faults (Abdeen 2003). In wadi Hodein area, Hamimi et al. (2014) mapped a post-amalgamation sedimentary succession composed of acidic volcanics intercalated with conglomerate that is folded about meso- and macroscopic NW–SE-trending, NW- and SE-plunging folds parallel to major NNW–SSE-trending sinistral shear zones. Kinematic indicator associated with deformed pebbles in conglomerate is consistent with SSE-directed tectonic transport (Abdeen et al. 2008).

16.3.3.3 Superposition and Fold Interference Pattern Between Compression- and Transpression-Related Folds

Although the rocks in most of the post-amalgamation basins are multiply deformed, only a few preserve more than one fold generation: to mention, the Murdama, Ablah, Fatima and some of the Hammamat basins. At meso- and macroscopic scales, superposition of the differently oriented folds that formed during the convergence- and transpression-related shortening produced conspicuous fold interference patterns. Kilometer scale dome and basin interference pattern (e.g. Ramsay 1967; Ramsay and Huber 1987) formed due to the superposition of NW- and NE-trending folds have been documented from the rocks of the Hammamat Group exposed between wadis Shihimiyya and Hammamat (Fowler and Osman 2001, Fig. 2). The same pattern has been recorded at the macroscopic scales in the rocks of the Hammamat Group in wadis Hammamat, Zeidun and Queih (Abdeen and Greiling 2005, Fig 2). In the Ablah Basin, superposition between the NW-verging transpressional and N–S-to NNW–SSE-trending compressional folds produced a well-developed interference pattern (Hamimi et al. 2014, Fig. 17d). It is noteworthy that in Fatima and Ablah basins, Hamimi et al. (2014) recorded a post-transpression local phase of folding, their F3, with structures plunging that is moderately to steeply SE-SSE and E. Superposition of F3 on the pre-transpression-F1 folds were also noted (Hamimi et al. 2014, Fig. 17e).

16.4 Discussion

16.4.1 Extension: Motives, Evidence, and Deformation vs. Collapse Extension

There is a general agreement that during the Ediacaran, the ANS experienced significant N–S-to NW–SE extension (Stern et al. 1984, Stern 1985, 1988; Johnson et al. 2011, and references therein). However, the nature and cause of such extension have been and are still controversial. Moreover, the reasons that account for some extensional features in one segment of the shield turned out to be inapplicable in the other segment (see below). Extension in the ANS has been interpreted to be the result of three main mechanisms: extensional deformation; extensional collapse; and wrench-related extension. However, the possibility that more than one mechanism could have acted together in some areas cannot be excluded.

16.4.1.1 Extensional Deformation

Extensional deformation refers to all structures formed as a consequence of crustal scale external stresses. At a regional scale, the stresses are most commonly related to relative plate motion either directly across a divergent plate boundary or indirectly when the stresses are the resultant of interaction of a number of plates. Extensional stresses when concentrated within a plate form a continental rift (e.g. the Gulf of Suez Rift: Patton et al. 1994; Khalil and McClay 2001) that may fully evolve and result in continental break-up and the formation of an ocean basin floored by oceanic crust (e.g. the Neoproterozoic splitting of Rodinia).

Evidence of Extensional Deformation

In addition to the low angle normal shear zones and detachments that have been dealt with in Sect. 16.3.1, other evidence in support of the extension includes dykes, extension-related depositional basins, post-orogenic A-type granites and bimodal volcanics (e.g. Blasband et al. 2000; Johnson et al. 2011). NE–SW-trending post-tectonic dykes are widespread in the northern part of the ANS, particularly in the Eastern Desert and Midyan terranes, and represent unequivocal evidence of northerly extension (e.g. Stern, 1984, 1985; Genna et al. 2002). They have been recorded from NE Egypt and Sinai (Stern 1984; Stern and Gottfried 1986; Eyal and Eyal 1987; Stern and Manton 1987; Greiling et al. 1994; Abdel-Karim and El-Baroudy 1995) from Jordan (Jarrar 2001, Jarrar et al. 1992, 2004), and from Saudi Arabia (Dodge 1979; Clark 1985; Genna et al. 2002). Extensive geochronological data obtained from bimodal, composite, felsic, mafic and pegmatitic dykes from the Midyan and Eastern Desert terranes (Table 16.1) constrain the period of extension between ~600 and ~540 Ma.

Sediment fill, geometry and orientation of, and syn-sedimentary structures within, some post-amalgamation depositional basins have been taken as evidence of late Ediacaran extension. For example, in the Eastern Desert, Egypt, NE–SW-oriented molasse-type Hammamat basins, some of which are bounded by NE–SW-trending or striking normal faults, have been interpreted to be extension-related (Grothaus et al. 1979; Stern 1985; Fritz et al. 1996). Similarly, the fault-bounded Saramuj Conglomerate Group, Wadi Araba, SW Jordan, comprises 600–550 Ma molasse-type sedimentary rocks, likely equivalent to the Hammamat Group deposited in extension-related NE–SW striking grabens (Jarrar 2001). Moreover, the group is crosscut by NE–SW-trending dykes implying that the dyking and sedimentary basin formation could have occurred during a single extension event. In Oman, at the northernmost tip of the ANS, Husseini (1989) attributed the fault-bounded NE–SW-oriented 620–580 Ma evaporite- and clastic-filled basins to NE–SW extension, thereby extending the upper time boundary of extension to 620 Ma.

Extension-related post-orogenic magmatic activity was very common in the ANS. The mainly epi-to mesozonal intrusions are of variable dimensions and shapes, i.e. dykes, sills, stocks, plutons and batholith. A-type granites are very widespread (Stern and Hedge 1985; Beyth et al. 1994; Moghazi et al. 1998; Garfunkel 1999; Jarrar et al. 2003; Mushkin et al. 2003; Moussa et al. 2008). The spectacular and voluminous exposures of alkaline granite led Stoeser (1986) to state that the ANS contains one of the largest alkaline granite fields in the world. The plutons being late-to post-tectonic in age are isotropic and typically discordant to the main rock fabric of the metamorphosed country rocks. Exceptions include highly deformed igneous bodies that are either shear-related or have been affected by a later shearing. Geochemically, the granitoids are enriched in LILE and have mostly alkaline, peralkaline, peraluminous and subordinate calc-alkaline geochemical signature indicative of a post-orogenic within-plate tectonic setting. Compositionally, they comprise medium to high-K granodiorite, granite, shoshonitic granite and shoshonite in increasing order of abundance. The granitoids are interpreted to be mantle-derived and intruded in an attenuated crust with minimal contribution from older crustal components (Gillespie and Dixon 1983; Stern and Hedge 1985; Pegram et al. 1980; Beyth et al. 1994; Greiling et al. 1996). Extension-related calc-alkaline magmatism is common in orogens with a long history of subduction (Hooper et al. 1995). This accounts for the association of post-orogenic calc-alkaline and alkaline intrusions in the ANS. Extension-related bimodal volcanics are widespread throughout the ANS. In the At Tuwawiyyah Formation at the base of the Murdama group (<670 to >650 Ma; Cole 1988) in the Maslum basin, bimodal volcanics of rhyolite, andesite, dacite and basalt composition are interbedded and inter-finger with a dominantly epiclastic succession of sandstone and conglomerate (Bois et al. 1975; Johnson 1996). Geochemically, the volcanic rocks have calc-alkalic and high-K calc-alkalic affinity, and their bimodal character implies extension-related sedimentation of the basal clastic units of the Murdama group (Johnson 2003). In the Hadha basin, the Bani Ghayy Group comprises bimodal rhyolitic, rhyodacitic, andesitic and basaltic volcanics interbedded with a clastic-dominated succession of conglomerate, greywacke, sandstone and siltstone (Johnson 2003). SHRIMP U-Pb zircon dating of the rhyolite yielded a crystallization age of 650 Ma (Johnson 2003), consistent with the maximum age of the Haml batholith (650–600 Ma) that intrudes the group. The bimodality of the volcanic rocks together with the fanglomerate depositional environment of the conglomerate, led Agar (1986) to interpret the group as having been deposited in fault-bounded (grabens) basins. In the northeast part of the Hibshi basin, bimodal volcanics of rhyolite and basalt composition are exposed.

16.4.1.2 Possible Models for Extensional Deformation

In the ANS, two possible models may account for the extensional deformation: orogen-parallel extension and orogen perpendicular shortening, and wrench-related extension.

Orogen-Normal Shortening and Orogen-Parallel Extension

A common geologic phenomenon during many orogenies is the switch in tectonic regime upon indentation from dominantly compressional during orogen-normal shortening to dominantly extensional during orogen-parallel extension. For examples, the Tauern Window, Eastern Alps (Royden and Burchfield 1989; Ratschbacher et al. 1989; Scharf et al. 2013; Favaro et al. 2015) and the Tibetan plateau, Himalaya (Tapponnier et al. 1986; Royden et al. 1997). Characteristically, the extension results in tectonic unroofing, and the formation of a system of normal faults and related, variably sized, rifts are oriented perpendicular to the direction of extension (Molnar and Tapponnier 1978; Tapponnier et al. 1981, 1986; Favaro et al. 2015). In the ANS, the late-to post-orogenic E–W to ENE–WSW striking normal faults that bound the metamorphic core complexes (gneissic domes), and the ENE–WSW to NE–SW-oriented molasse basins, and dyke swarms can be related to the orogen-parallel extension (e.g. Stern 1985; Shalaby et al. 2006; Johnson et al. 2011). Moreover, a short-lasted (605–595 Ma) orogen-parallel extension was proposed as a tectonic model to explain the mechanism of exhumation and formation of the metamorphic core complexes (Fig. 16.6) (Wallbrecher et al. 1993; Fritz et al. 1996; Loizenbauer et al. 2001). Preservation of the extension-related structures in the northern and north-eastern parts of the ANS, i.e. towards the periphery of the orogenic belt, strengthens the latter conclusion.

Wrench-Related Extension

Major transcurrent faults are very commonly associated with local domains of extension (e.g. Sylvester 1988, and references therein) that are located between overstepping divergent strike-slip faults (Fig. 16.5), at the releasing bends along curved strike-slip faults, and where the fault terminates along a horsetail splay (e.g. Sylvester 1988, and references therein). Depositional basins of variable sizes form in these extensional domains and range from sag bonds to pull aparts (Crowell 1974a, b; Schubert 1980; Garfunkel 1981; Mann et al. 1983; Şengör et al. 1985). The Jibalah group, Midyan terrane of the Arabian shield, is an excellent example of wrench-related basins. The Al Kibdi basin is a pull apart basin formed between two sinistral left-stepping strands of the Najd Fault System, whereas the Al Jifn basin is formed at the releasing bend of the Halaban-Zaraghat fault (Hadley 1974; Husseini 1989; Al-Husseini 2000).

16.4.1.3 Non-Tectonic Gravitational Collapse-Related Extension

Gravitational instability and resultant collapse is a very common phenomenon in many orogenic belts (i.e. Canadian Cordillera; Olivier and Teyssier 2001; Tibetan Plateau of the Himalaya: Dewey 1988; Dewey et al. 1993; Variscides: Henk 1997; Basin and Range Province: Dewey 1988b, Braun and Beaumont 1989; Gondwana: Yang et al. 2019). Typically, it is a late orogenic process that follows an early stage of collision, thrust stacking and crustal thickening that ends up with orogenic uplift (Coney and Harms 1984; Platt 1986; Dewey 1988b). Orogenic collapse is generally controlled by the amount and rate of uplift, which over a period

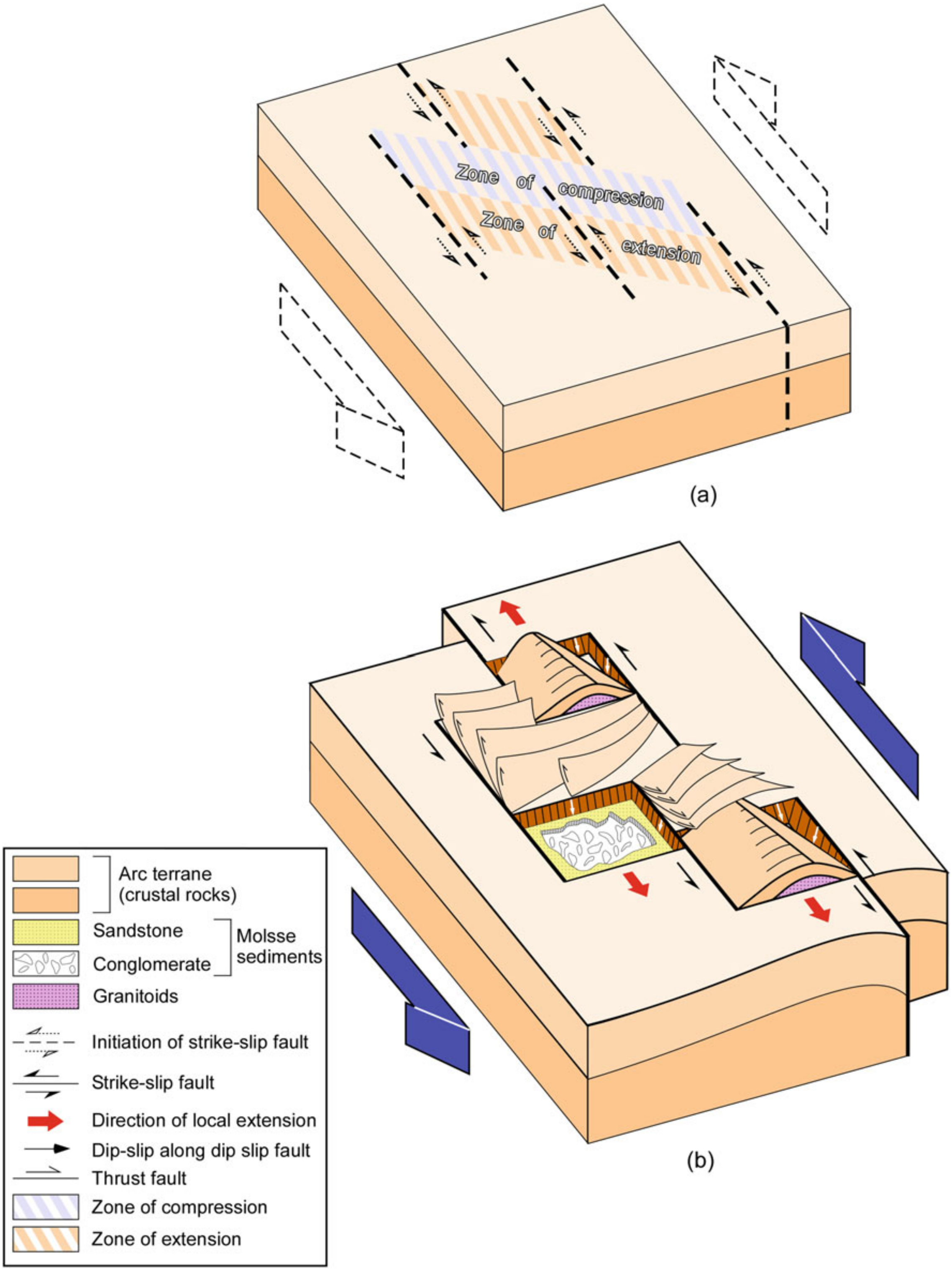

Fig. 16.5 **a**, **b** Schematic diagrams show the potential of formation of alternating domains of compression and extension between overstepped convergent and divergent strike-slip faults, respectively, during initial **a** and progressive **b** wrenching. The domains of compression and extension develop into thrusts and pull aparts, respectively. Progressive wrenching would lead to formation of pull apart basins and exhumation of the structurally lower metamorphic core complexes

of millions of years and an uplift rate of 3–6 mm/yr which is very common in orogenic belts (Saini et al. 1978; Cliff et al. 1985; Copeland et al. 1987; Butler and Prior 1988) would result in a substantial topography. As a corollary, collapse takes place to re-equilibrate the overthickned crust back to a normal (∼20–30 km) thickness (Dewey 1988a, b; Dewey et al. 1993). An elevation of 3 km has been taken as a threshold above which mountain belts start collapsing (Dewey 1988b). Factors that cause orogenic uplift include (1) crustal underplating, (2) lithospheric thinning due to mantle delamination and/or decoupling, and hotspot jetting (Dewey 1988b; Platt and England 1993) followed by (3) extension-related magmatic activity in the thinned crust (e.g. Lister and Davis 1989; Lister and Baldwin 1993; Warren and Ellis 1996) followed by the upward ascent of mantle material at the root of the orogen (Fritz et al. 1996, 2002; Neumayr et al. 1998; Bregar et al. 2002). Mechanically, orogenic collapse occurs when (1) the vertical compression caused by the weight of the over-thickened crust overcomes the horizontal compression acting across on it (i.e. $\sigma_V > \sigma_H$). In this case, the mountain belt would collapse under its own weight, (2) plate boundary forces switch from compressional to extensional (Variscides: Henk 1997), (3) there is a drastic decease in the strength and viscosity of the crust caused by rheological modifications wherein thermal relaxation, radiogenic (advective) heating and high geothermal gradient culminate in crustal melting and magma generation at middle to upper crustal levels (i.e. Vanderhaeghe and Teyssier 2001). Late orogenic collapse has been reported from different parts of the ANS. In wadi Kid area, South Sinai, Blasband et al. (1997, 2001), attributed the exhumation of the metamorphic core complex (see Sect. 16.3.1.1), together with the NE–SW-trending dykes and oriented depositional basins to collapse-related extension reminiscent to the Mesozoic and Early Cenozoic orogenic collapse in North America Cordillera (e.g. Sturchio et al. 1983a). They further concluded that gravitational instability and collapse were active during the late stages of Pan-African orogeny in the ANS. In a similar way in the Eastern Desert, Greiling et al. (1994) interpreted a ∼20 Ma period (575–595 Ma) of extensional collapse wherein normal faults, molasse basins and core complexes were formed. However, according to Greiling et al. (1994), the extensional collapse was not the last tectonic event to affect the Pan-African where they attributed the widespread NNW-directed thrusts and folds recorded in the greenschist facies-dominated eugeoclinal succession to a later phase of NNW–SSE shortening. The northerly directed thrusts were also overprinted by a phase of transpression. Fowler and El Kalioubi (2004) interpreted the top-to-the NW low angle shear zone in the Neoproterozoic cover nappe in the Eastern Desert, Egypt, as a collapse-related tectonic nappe emplaced by gliding-spreading mechanism to be a consequence of crustal thickening following the accretionary tectonics. The younger granites in the Eastern Desert have been interpreted to be extensional collapse-and/or rift-related intrusions (Greiling et al. 1994; Farahat et al. 2007; Moussa et al. 2008). According to Greiling et al. (1994), the extensional collapse event can be bracketed between 595 Ma and 575 Ma. Acceptance of the extensional collapse model to interpret the post-amalgamation extension-related features in the ANS is dependent on answering two main questions: Was there a sign of significant uplift that exceeded the threshold value? and was there taphrogenic extension-related significant magmatism? Regarding the question on uplift, it is important to establish whether the process of uplift and consequently the collapse was a regional event throughout the whole ANS or restricted to specific parts of the shield. The second question has been dealt with in Sect. (16.4.1.1) and will not be discussed further here.

Was There a Significant Uplift Throughout the ANS?

Following England and Molnar (1990), the term uplift refers to the displacement of rocks in an opposite direction to gravity. There is a growing body of evidence that during the late Cryogenian-Ediacaran, significant crustal thickening and uplift linked to arc-accretion took place in different parts of the ANS. Crustal stacking and thickening have been bracketed between 630 Ma and 600 Ma (Greiling et al. 1996; Kröner and Stern 2004) and between 597 Ma and 584 Ma (Fritz et al. 2002; Abdel-Naby et al. 2008; Abu El-Enen et al. 2016). In the text that follows, crustal thickening and uplift will be dealt with from three perspectives: structural, metamorphic and depositional. From the structural point of view, in Wadi Kid area, South Sinai, Egypt, Blasband et al. (2000) identified accretion-related upright isoclinal NE–SW-trending folds, which they interpreted as evidence of crustal thickening and hence uplift. Generally speaking, a high metamorphic grade of upper amphibolite facies conditions recorded in many metamorphic terranes has been related to crustal thickening during orogenesis (Spear et al. 1991). All high grade gneissic domes that have been interpreted as metamorphic core complexes in the Central and Southern Eastern Desert (El-Gaby et al. 1990; Wallbrecher et al. 1993; Fritz et al. 1996; Loizenbauer et al. 2001; Abd El-Naby et al. 2008) and Sinai (Blasband et al. 1997, 2000; Brooijmans et al. 2003; Abu-Alam and Stüwe 2009; Abu El-Enen and Whitehouse 2013) have been metamorphosed at upper amphibolite facies conditions. The PT conditions have been estimated for some of these core complexes. In the Meatiq dome, Neumayr et al. (1998) estimated metamorphic conditions of 610–690 C at 6–8 kbar. Moreover, pressure in excess of 8 kbar has been interpreted based on kyanite relics (Neumayr et al. 1998). In the South Eastern Desert, collision-related crustal stacking and thickening have been documented in the Hafafit metamorphic core complex, and based on geothermobarometry and pseudosection calculations, a volcano-sedimentary succession has been metamorphosed at upper amphibolite facies conditions of 570–675 C and 9–13 kbar (Abu El-Enen et al. 2016). According to these authors, the metamorphism and deformation were related to the collision between East and West Gondwana with the metamorphic peak reached at an average crustal depth of 33 km, followed by a phase of isothermal decompression that they related to the rapid exhumation accompanied wrenching. Age data from Fritz et al. (2002) and Abd El-Naby et al. (2008) indicate the core complex was exhumed between 593 Ma and 580 Ma. In a similar fashion, Abu-Alam and Stüwe (2009) and Abu El-Enen (2011) interpreted the Feiran-Solaf metamorphic core complex, central Sinai, to have formed during a single PT path with a metamorphic peak estimated at temperature of ~700 C and pressure of 7–9 kbar, followed by a phase of isothermal decompression. According to the authors, a transpressive tectonic regime accounts for the concurrent isothermal decompression and the associated shortening. Additionally, migmatitic biotite and hornblende gneisses of the Feiran Solaf core complex recorded upper amphibolite facies conditions of 640–700 C and 4–5 kbar (Eliwa et al. 2008).

The type of post-amalgamation sedimentary basin, the nature of basin-fill and the nature of contact between the basin and the underlying basement rocks provides a direct clue for significant uplift. The fault-bounded Hammamat sedimentary basins are dominantly filled with molasse-type sedimentary facies (Akaad and Noweir 1969, 1980; Grothaus et al. 1979; Eliwa et al. 2006; Shalaby et al. 2006; Abd El-Wahed 2010) indicative of rapid uplift and erosion of the source area (e.g. Mitchell and Reading 1978; Miall 1978). In wadis Hammamat (the type locality) and Kareem in the Central Eastern Desert, the basins are filled, respectively, with 4000 and ~7000 m thick succession of clastic rocks composed dominantly of polymictic conglomerate, sandstone, greywacke and siltstone (Akaad and Noweir 1969 1980; Fritz and Messner 1999; Abd El-Wahed 2009). Moreover, as a sign of sedimentation in association with tectonism, particularly extensional, some of the Hammamat basins were interpreted to be intermontane basins (Fritz et al. 1996; Fritz and Messner 1999; Abd El-Wahed 2010, and references therein) bounded by normal faults as well as intra-basinal syn-sedimentary normal faults (Grothaus et al. 1979; Fritz et al. 1996). All post-amalgamation basins contain thick piles of sedimentary, with subordinate volcanics, rocks the base of which rest unconformably on basement rocks composed of the accreted arc terranes (Johnson 2003; Johnson et al. 2011; Hamimi et al. 2014, and references therein) pointing to the autochthonous character of the basins. Sediments shed from the uplifted and eroded basement rocks were deposited as detritus in these basins. Johnson (2003) inferred uplift and erosion in the range of 10–15 km prior to deposition of the 8000 m thick, detrital-dominated, Murdama Group which lies unconformably on greenschist—to amphibolite-, and locally, granulite-facies rocks of the Suwaj and Siham sub-terranes of the Afif complex (Cole 1988). In the framework mineralogy triangular diagram for provenance discrimination, the sandstone (Zaydi Formation) of the Maslum basin (Murdama group basins) plots in the magmatic arc field (Greene 1993; Johnson 2003). The latter result supports the notion that the underlying highly eroded arc terranes were a significant source of detritus for the post-amalgamation basins. The Hibshi formation (Hibshi basin) is a thick, $\geq$ 5000 m, succession of volcanic, volcaniclastic and epiclastic rocks, the base of which unconformably overlies the Ha'il basement terrane on the north (Johnson 2003). The basin has been interpreted to be a fault-controlled continental basin (Williams et al. 1986). The formation occupies a faulted syncline structure, which led Johnson (2003) to interpret it as representing a major subsidence. Rocks of the Antaq and Al Kibdi basins (Jibalah basin) unconformably overlie the Suwaj terrane on the west and Siham arc, respectively (Johnson 2003). The Jurdhawiyah Group, in the Safih basin, oversteps the erosive contact between the Murdama Group and the underlying arc rocks of the Suwaj sub-terrane (Johnson 2003). Similarly, the Fatima Group (Fatima basin) rests unconformbly on >757 Ma basement rocks comprising high grade gneisses, amphibolites, schist and andesite (Hamimi et al. 2014). By contrast, significant carbonate units of considerable thickness have been recorded in some basins. Variably sized limestone lenses (tens of meters to 300 m thick) and a succession of 1000 m thick of carbonaceous and stromatolitic limestone of the Farida formation are recorded in, respectively, the Marghan and Maslum basins of the Murdama group basins (Johnson 2003). Limestone (1000 m thick) and 150–800 m thick carbonate sequence including oolitic, stromatolitic limestone and dolomite (Kattan and Harire 2000) are recorded in the Mujayrib and Hadha basins, respectively, of the Bani Ghayy group basins. Moreover, the greywacke and siltstone of the Mujayrib basin (Bani Ghayy group basins) bear the sedimentological features characteristic of a Bouma sequence (Agar 1986). The above-mentioned features (carbonate units and Bouma sequence) are indicative of deposition in a sub-aqueous shallow marine conditions (Agar 1986; Wallace 1986) and imply that parts of the eastern Arabian shield have been submerged under marine water prior to or during the deposition of the Murdama and Bani Ghayy groups (e.g. Johnson 2003). In a similar fashion, the Fatima Group, Jeddah terrane, is differentiated into three units (Nebert et al. 1974): a shallow marine-platform carbonate-dominated middle unit (Basahel et al. 1984) that is composed essentially of stromatolitic fossiliferous limestone, and sandwiched between two clastic-dominated units composed of sandstone, siltstone and conglomerate (Hamimi et al. 2014). Similarly, the Ablah group, Asir terrane, is composed of two marble units (lower and upper) interbedded with two clastic units (Hamimi et al. 2012, 2014). The carbonate-dominated units are interpreted as having been deposited in shallow water, sub-to intertidal environments (Hamimi et al. 2014). It is noteworthy that there is a strong evidence of a second cycle of erosion and uplift after deposition of the Murdama and Bani Ghayy groups and prior to the deposition of the younger Jibalah, Hibshi and Jurdahwiyah groups. This is indicated by (1) folding of the Murdama and Bani Ghayy groups, (2) presence of an erosive surface between the folded Murdama group and the overlying Jurdhawiyah group and (3) the exhumation of rapidly cooled epizonal granites beneath the unconformities at the base of the post-Murdama/Bani Ghayy Jibalah, Hibshi and Jurdahwiyah basins (Agar 1986; Cole 1988; Al-Saleh et al. 1998).

In conclusion, it is clear that, the ANS preserves strong evidence of periodic uplift during the Ediacaran. Rapid erosion of the uplifted amalgamated arc terranes provided vast amounts of detritus that filled the molasse-type Hammamat basins and constituted the clastic-dominated basal units of the Arabian basins. The Arabian shield probably experience at least two cycles of uplift separated by a period of rapid erosion, subsidence and deposition of the Murdama, Bani Ghayy, Fatima and Ablah groups in shallow marine environment. Intermittent and insignificant small cycles of uplift may account for the clastic-dominated units interbedded with the shallow marine carbonate facies. However, deposition of the clastic and non-clastic successions in shallow marine environments cannot be excluded. On the other hand, the persistence of continental facies and scarcity of proper marine deposits within the molasse-type Hammamat basins imply that substantial pars of the Nubian shield had significant height prior to and during deposition of the Hammamat sediments (Figs. 16.3 and 16.4). Preservation of evidence of subsidence in the Arabian basins relative to those in the Nubian part of the shield can be interpreted in terms of differential uplift with greater uplift rates in the latter basins relative to the former ones (Fig. 16.3). Conversely, differential subsidence may also account for the drastic change in lithologies in both shields. In the latter case, compared to the Arabian shield, the subsidence was not that efficient in the Nubian region which remained high enough to ensure that no sea water covered the shield. The significant uplift, particularly, in the Nubian section, the fault-bounded (grabens) basins and the widespread coeval extension-related magmatic activities imply that gravitational extensional collapse model could have been active and explains the extensional features observed mostly in the post-amalgamation Hammamat basins in the Nubian shield, and to a much lesser extent, in some of the basins in the Arabian shield.

16.4.2 Wrenching

One of the robust and widely accepted mechanisms to account for late orogenic wrenching is the “extrusion” or “escape tectonics” that was introduced by Molnar and Tapponnier (1975) to explain the widespread late tertiary (25–5 Ma) intracontinental right-lateral strike-slip faults in the southern part of the Tibetan plateau following terminal collision between the Indian and Eurasian plates at the beginning of the Miocene ($\sim$25 Ma). The model proposes that following collision is one of the continents (India) acted as an indentor facilitating the “escape” of the immediately adjacent sector of Eurasia eastwards towards the oceanic free-face. This escape is being accommodated along a system of orogen-parallel strike-slip and transform faults (Molnar and Tapponnier 1975). Hence, it is the position of the rigid indentor that determines the loci of crustal thickening and concentration of the strike-slip/transform faults, whereas the facing direction of the oceanic free-face determines the movement direction of the continental block and, consequently, the dominant sense of shear along the wrench/strike-slip faults. The same model was used by Dewey et al. (1986) to account for the westward escape of Anatolia from the Arabian/Eurasian collision zone. Similarly, in the ANS, the wrenching along the Najd Fault System has been interpreted in the light of the “escape” tectonics model (e.g. Johnson et al. 2011; Hamimi et al. 2019, and references therein). In that model, the terminal collision and indentation between East and West Gondwana were followed by tectonic escape of one of the continental plates and the widespread development of NW–SE striking sinistral strike-slip faults. According to Fleck (Fleck et al. 1979), Moore (1979) and Schmidt et al. (1979), the rigid indentor is positioned to the east (east of the Idsas suture), and hence, the NFS was formed as a consequence of the south-eastward movement of the Nubian (south of the Central Eastern Desert, Egypt)/south Arabian part of the shield relative to north Arabia and the Northern Eastern Desert of Egypt. However, geochronological (Glennie et al. 1974; Stacey et al. 1984) and isotopic (Duyverman et al. 1982) data, and the absence of proper evidence for a significant crustal thickening and high grade metamorphic rocks indicative of continent–continent collision preclude the existence of a continental rigid indentor east of Idsas suture (e.g. Stern 1985). It is more appropriate, for the aforementioned reasons, that during the terminal collision between East and West Gondwana, the Tanzanian craton acted as the rigid indentor (Bonavia and Chorowicz 1992) allowing the north-westerly escape of the ANS towards the Paleo-Tethys ocean (Fig. 16.1) (Stern 1994, Kusky and Matsah 2003). Based on: (1) the lack of significant uplift accompanied the Najd faulting, (2) the lack of the characteristic crustal thickening, particularly in the Arabian part of the shield, that accompanies the continent–continent collision, (3) the overlapping dates between the extension (rift)-related magmatism (see Sect. 16.4.1.1) and Najd wrenching, (4) synchrony between Najd faulting and suturing, and (5) the spatial and temporal relation between the Najd faults and the deposition of extension-related post-amalgamation sedimentary succession, Stern (1985) and Al-Husseini (2000) proposed an alternative kinematic model to account for the Najd faulting. In that model, the NFS was formed as a consequence of late Ediacaran NW–SE directed crustal scale extension within the newly formed EAO continental crust. The extended crust progressively developed into, mostly, preferentially oriented continental rifts, localized mainly to the north and north-eastern parts of the ANS (Stern 1985, 1994) that had acted as depocentres for the post-amalgamation volcano-sedimentary successions and controlled the loci of the extension-related magmatic activities.

16.4.3 Shortening: Convergence- and Transpression-Related

As documented in Sect. 16.3.3, the post-amalgamation shortening includes all collision- and wrench-related structures formed in response to directed tectonic-related compression. In terms of tectonics, we refer to this category as active tectonics-related structures to discriminate it from the non-tectonic category in which "contraction" structures might have formed passively (see below).

16.4.3.1 Active Tectonics-Related Structures

There is agreement that during the Ediacaran, the terminal collision between East and West Gondwana took place along an E–W to ENE–WSW direction, and that pure shear was the main tectonic regime (Johnson et al. 2011; Fritz et al. 2013, and references therein). Coaxial ductile deformation accompanied this tectonic event include the N–S-to NNW–SSE-trending upright and locally W-verging folds in Murdama, Ablah, Bani Ghayy and Fatima group basins in the Arabian shield, and in a few localities in the Eastern Desert terrane of the Nubian shield. Despite the dominant pure shear regime, some collision-related transpressional structures have been recorded (e.g. Fatima basin; Hamimi et al. 2014). These structures are oriented E–W to ENE–WSW, which implies a shift of $\sim 90^{o}$ from the dominant stress field (i.e. N–S versus E–W shortening). Such disturbances in stress field direction are mostly attributed to reactivation of favourably oriented, inherited, accretion-related and lineaments (faults) producing local stress fields. For example, in the Fatima basin, the accretion-related NE–SW-oriented wadi Fatima dextral shear zone (pre-dates deposition of the post-amalgamation Fatima Group) was dextrally reactivated during the E–W terminal collision and produced a localized N–S oriented shortening component that gave rise to the earliest structures preserved in the Fatima basin. Other possible examples of collision-related reactivation of pre-existing basement faults include the reactivation of the contemporary N–S-trending arc-arc, Oko and Hamisana, and arc-continent, Keraf, suture zones. The transpression structures in these shear zones; dextral in the Hamisana and sinistral in the Oko and Keraf (Abdelsalam 1994; Abdelsalam and Stern 1996; Johnson et al. 2011) overprint structures related to an earlier phase of collision-related E–W compression. It is noteworthy that some of the suture zones in the ANS have reactivation dates that are very comparable and/or overlap with some of the movements along the Najd faults (e.g. Johnson et al. 2011).

In a similar way, reactivation of variably oriented basement structures would result in local stress fields with shortening components that apparently deviate from the dominant stress field. Other factors that could have contributed to the deviation of the stress field from the dominant E–W direction include deformation partitioning (e.g. Abu Sharib and Bell 2011; Bell and Sanislav 2011; Abu Sharib 2015) and reorientation of some structures during later events.

For more than half a century, documented research has demonstrated that the Najd Fault System is a crustal scale, brittle to ductile shear zone dominated by NW–SE-trending sinistral strike-slip faults (Fig. 16.4) with a minor set of conjugate NE–SW-trending dextral strike-slip faults (Brown and Jackson 1960; Delfour 1970; Brown 1972; Brown and Coleman 1972; Moore 1979; Schmidt et al. 1979; Davies 1984; Stern 1985; Johnson et al. 2011). As in the case of major transcurrent faults, the NFS produced a complex array of superimposed structures that have classical en echelon arrangements (Sylvester 1988, and references therein). These structures include as follows: the Riedel (R) shears (synthetic strike-slip faults; loosely referred to as the Najd trend), conjugate Riedel (R′) shears (antithetic strike-slip faults), P-shears (synthetic strike-slip faults), Y-shears (synthetic strike-slip faults parallel to the principal displacement zone), in addition to folds and reverse faults, and normal faults that, respectively, form perpendicular and parallel to the incremental shortening axis. For a detailed description of strike-slip fault systems, their mechanics, and associated structures, the reader is referred to Sylvester (1988). Complexities of the Najd-related shortening arise from the fact that discrepancies in stress fields cause localized shortenings that produce very variably oriented structures, which require careful study and analysis to ensure they are not interpreted as due to overprinting rather than of a single major shear event. Moreover, generally speaking, the compression accompanied movement along the dominant NW-trending Najd strands is oriented in an almost E–W direction (e.g. Abdeen and Abdelghaffar 2011). The latter observation implies that in places, the Najd-and collision-related structures share a common shortening direction and requiring sound field data including unequivocal kinematic indicators to avoid an erroneous interpretation. Discrepancies in the stress fields could be attributed to: (1) local shortening components produced between two overlapping faults or along a restraining bend of an anastomosing fault during movements along the R, R′, Y and P-shears, (2) local domains of interfering shortening produced due to superposition of the shears, (3) local shortening that arise from the reactivation of favourably oriented pre-existing basement lineaments, and (4) the sequential development of shears (e.g. earlier dextral followed by later sinistral) could result in cases where early formed shear-related structures have structures related to the later shearing superimposed. For example, it is widely accepted that the Najd regime started with dextral shear and culminated with dominant sinistral movement. Shear-related structures characteristic of movement along the Najd strands include the en echelon arrangement of folds in the sedimentary rocks filling many of the post-amalgamation depositional basins (see Sect. 16.3.3.2) and distinctive NW–SE sinistral faults. In profile view, some of these faults form typical flower structures comprising a system of folds and thrusts (Abdeen et al. 1992; Abdeen 2003; Abdeen and Greiling 2005). Examples of reactivated basement faults include the N–S-trending Nabitah and Um Farwah shear zones. The Nabitah shear zone marks the suture between the Tathlith and Asir terranes that formed during the Nabitah orogeny (~680–640 Ma) and shows consistent dextral shearing (Johnson et al. 2011). Um Farwah, located within Asir terrane to the west of the Nabitah fault, is an ophiolite-decorated and accretion-related shear zone that has been reactivated during Najd activity. It delineates and intersects the boundary between the Ablah Group and the Asir arc terrane, at its northern and the central parts, respectively (Moufti 2001). In the Ablah Group, folds and thrusts orientation as well as fold vergence are consistent with sinistral sense of shearing along the reactivated Um Farwah shear zone (Johnson et al. 2011; Hamimi et al. 2014). The reactivation enhanced crustal melting and emplacement of the 617 ± 17 and 605 ± 5 Ma A-type granitoids (Moufti 2001) that intrude the Ablah Group. Other examples include the reactivation of the NW–SE to N–S-trending Hulayfah-Ad Dafinah-Ruwah suture zone (Johnson et al. 2011).

16.4.4 The Eastern Desert Low Angle to Sub-Horizontal Shear Zone: A Shortening-(Tectonic) versus Extensional Collapse-(Non-Tectonic) Related Fabric!

A characteristic feature of the Neoproterozoic rocks of the Central and Southern Eastern Desert and Sinai, Egypt, is the presence of a number of tectonic windows exposing upper amphibolite facies gneissic (dominantly granitoid ortho-gneisses and quartzofeldspathic para-gneisses) domes that are elongated with their long axes oriented in a NW–SE direction and have been widely accepted as metamorphic core complexes (see Sect. 16.3.1). A major low angle to sub-horizontal mylonitic shear zone separates the high grade gneissic domes from a structurally overlying carapace of greenschist facies eugeoclinal units that represent thrust sheets (Ries et al. 1983; Sturchio et al. 1983a, b; Habib et al. 1985; Blasband et al. 1997, 2000; Fowler and Osman 2001) separated by sheared contacts (Ries et al. 1983). The eugeoclinal tectono-stratigraphic succession includes island arc associations (Stern 1981; Habib 1987; Abdel-Kari 1994), ophiolitic melange rocks (serpentinites, metagabbros and metavolcanics; El-Sharkawy and El-Bayoumi 1979; Nasseef et al. 1980; Shackleton et al. 1980; Ries et al. 1983; Ali et al. 2020) and Hammamat molasse sediments (Akaad and Noweir 1969; Grothaus et al. 1979; Messner 1996; Naim et al. 1996; Kamal El-Din et al. 1996; Abd El-Rahman et al. 2010; Abu Sharib et al. 2019). These are the “Pan-African Nappes” of Ries et al. (1983), Habib et al. (1985), and El Gaby et al. (1988), the “eugeoclinal thrust sheet/complex” of Andresen et al. (2009) and the “Eastern Desert Shear Zone” of Andresen et al. (2010). West of the Meatiq gneissic dome, the Hammamat Group rocks and the eugeoclinal succession is imbricated and folded together (Fowler and Osman 2001; Loizenbauer et al. 2001). The low angle shear zones are very crucial in the interpretation of the tectonic evolution of the Precambrian rocks in Egypt. However, despite the consensus regarding the tectonic transport direction with very consistent top-to-the NW to NNW shear sense criteria (Ries et al. 1983; Habib et al. 1985; Shackleton 1986, 1994; Greiling et al. 1994; Fritz et al. 1996; Greiling 1997; Loizenbauer et al. 2001; Shalaby et al. 2005; Abd El-Wahed 2008; Andresen et al. 2009; Abd El-Wahed and Kamh 2010; Abd El-Wahed 2014; Abdeen et al. 2014), the nature and kinetics of the shear zones are controversial. They have been interpreted as compression—(Ries et al. 1983; Sturchio et al. 1983), extension—(Fritz et al. 1996, 2002), and transcurrent-related (Loizenbauer et al. 2001) high strain zones, or as a result of interplay between two or more tectonic regimes (Loizenbauer et al. 2001). The variable tectonic models of the low angle shear zones have been used primarily to account for the exhumation of the spatially associated gneissic domes (op.cit.).

NNW-directed thrusts and associated E–W to ENE–WSW-trending NW-verging folds affect the molasse-type Hammamat Group rocks in the Um Had and Queih basins of the Central Eastern Desert (Ries et al. 1983; Abdeen et al. 1992; Greiling et al. 1994; Abdeen et al. 1996; Naim et al. 1996; Abdeen and Warr 1998; Fowler and Osman 2001). Similarly, E–W-trending folds have been recorded in the Hammamat basins in wadis Karim, Messar, Um Gheig, and Zeidun, Central Eastern Desert (Greiling et al. 1994; Abdeen and Greiling 2005). Moreover, the Hammamat Group rocks in wadi Muweih have been affected by NNW-directed thrusts and associated foliation (Ries et al. 1983). At lower stratigraphic levels of the Hammamat succession, the deformation intensifies and results in the mylonitic and phyllonitic foliation (Ries et al. 1983; Fowler and Osman 2001). In wadi Hammamat, the type locality, a similar conclusion was reached by Messner (1996) who noted an increase in the degree of shearing and metamorphism towards the base of the Hammamat Group. From the metamorphic point of view, the low angle shear zones record a regional phase of retrogression (Fowler and Osman 2001).

The debate regarding the kinetics of the low angle mylonitic shear zones can be settled if the compelling question of whether the shear zones are accretion-or post-accretion-related tectonic feature is convincingly answered. Answering this question would be of a great significance in interpreting the tectonic evolution of this essential part of the ANS. Except for Greiling et al. (1994), all the authors who advocated for compression as the prime factor in the formation of the shear zones, interpreted the NNW to NW-ward directed thrusts and the associated folds as accretion-related structures. As previously explained, the shear zone affects the sedimentary rocks of the Hammamat Group as a component of the eugeoclinal succession. Moreover, the molasse sequence has been recorded to be imbricated and folded together with the eugeoclinal succession (e.g. Fowler and Osman 2001; Loizenbauer et al. 2001). Similarly, in the Allaqi-Heiani suture zone, thin slices of post-amalgamation metasedimentary successions comprising marble, quartzite lenses and thin bands of conglomerate are tectonically interleaved and imbricated with an ophiolitic assemblage of amphibolite, serpentinites and island arc rocks (Abdeen and Abdelghaffar 2011). The tectono-stratigraphic units have been affected by accretion-related N–S shortening that produced the NNE-dipping low angle thrusts and associated SSW-vergent folds implying SSW-ward tectonic transport (Abdeen and Abdelghaffar 2011). The latter conclusion clearly contradicts the general consensus in the literature that deposition of the molasse-type Hammamat Group post-dated arc-accretion. Moreover and in terms of relative timing, in the kid metamorphic core complex, Sinai, Blasband et al. (2000) have dated the arc-collision event as well as the top-to-NW sub-horizontal shear zone. The former event has been dated at 750–650 Ma that is consistent with the published age range for arcs accretion (800–700 Ma) in different parts of the ANS (e.g. Bentor 1985; Stern and Hedge 1985; Stoeser and Camp 1985; Kröner et al. 1992; Stern 1993; Greiling et al. 1994; Abdelsalam and Stern 1996), whereas activity of the shear zone has been dated at 620–580 Ma. The geochronological results reveal explicitly that arc-accretion and shear zone formation are two irrelevant tectonic events that are temporally separated by at least 20 Ma. Moreover, the geochronological results have been augmented by field evidence where accretion-related folds are traversed by shear zone-related foliations (Blasband et al. 2000). In addition to that, the N–S to NNW–SSE shortening that produced the shear zones and associated structures does not match the E–W to ENE–WSW-directed compression that accompanied the terminal collision and/or the Najd transpression.

Consequently, for the above-mentioned reasons, it is argued that the low angle shear zones represent a distinct late post-amalgamation extension-related event (Fig. 16.6) that was coeval with the other extension-related features (see Sect. 16.1) not related to transtensional domains along the Najd faults.

In conclusion, the eugeoclinal nappe with the basal sub-horizontal dominantly top-to-the N to NNW-directed shear zones can be interpreted as a spreading nappe (e.g. Merle 1989; Fowler and El-Kalioubi 2004) with strain increasing dramatically downwards towards the basal contact with the gneissic domes, as well as along the internal shear zones (gliding surfaces) separating the different tectono-stratigraphic units of the eugeoclinal successions. The reverse sense of movement along these shear zones implies, contrary to Fowler and El Kalioubi (2004), a pure spreading rather than gliding-spreading mechanism. The nappe emplacement could have been synchronous with or immediately after the post-orogenic extension-related magmatism, which decreased significantly the shear strength of the crust and facilitated the spreading (e.g. Vanderhaeghe and Teyssier 2001). The overturned, intrafolial and thrust-related folds could have formed due to crumpling of the moving crustal blocks in the direction of spreading in a similar way overturned, and slump-related folds are formed in sliding soft sediment. The change in fold style from open to tight and from upright to overturned to recumbent may be attributed to the strain gradient and the degree of shearing, which in turn are directly related to its position within the spreading nappe. The strain gradients within a spreading nappe increases from top-to bottom and from rear to front (Merle 1989). The dominant top-to-the-N to NNW tectonic transport implies that the general slope responsible for the nappe emplacement was facing north. Moreover, the local

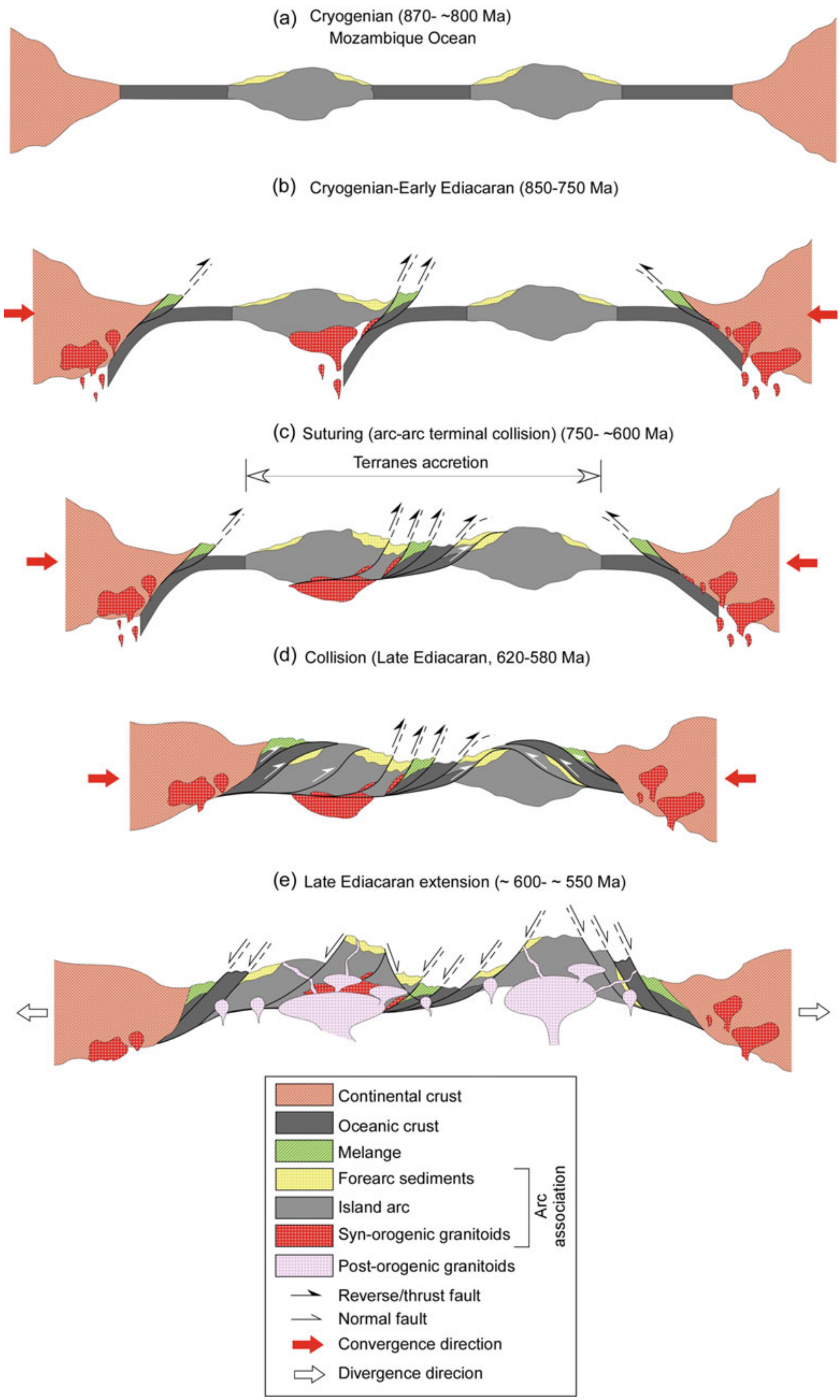

Fig. 16.6 Tectonic model shows a complete Wilson cycle of the Arabian-Nubian Shield. **a** Break-up of Rodinia supercontinent and opening of the Mozambique Ocean. **b** Convergence through ocean–ocean and ocean–continent subductions and intrusion of syn-orogenic granitoids. **c** Suturing of arcs (terminal collision) and uplift of the accreted terrane. **d** Arc-continent collision and further uplift of the accreted terranes. **e** Extension (collapse-and/or deformation-related), intrusion of post-orogenic granitoids, crustal thinning and exhumation of the structurally lower metamorphic core complexes

opposite (S-to SSE-ward) sense of shear along the thrusts and shear zones, and fold vergence most probably accompanied local irregularities in the paleo-slope and/or spreading in opposite directions around topographic highs (gneissic domes?). Accordingly, we interpret the NNW to N-directed thrusts, the low angle shear zones and E–W to ENE–WSW-trending folds as "passive" non-tectonic structures that formed as a consequence of gravitational instability and collapse of the orogenic belt during the late Ediacaran.

16.4.5 Inversion Tectonics and Basins Inversion

Inversion tectonics refers to the reversal of slip direction along faults when the associated tectonic regime changes from extensional to compressional or vice versa (Cooper and Williams 1989). It is positive when normal faults are reactivated as reverse faults and negative when the opposite change takes place (Williams et al. 1989; Hayward and Graham 1989). Well-documented examples of inversion have been recorded in many orogenic belts: the Alps (Ziegler 1989; De Graciansky et al. 1989), the Variscides (Coward et al. 1989) and the Rockies (Powel and Williams, 1989). Reactivation of basin-bounding faults during positive inversion leads to closure and uplift of the basin in what is known as "basin inversion".

In the ANS, post-amalgamation basins are mostly fault-bounded (Johnson 2003; Johnson et al. 2011, and references therein), implying components of extension perpendicular to the strike of the bounding faults. Basin-fill sequences folded about axes trending parallel to the bounding faults are indicative of basin closure, inversion and uplift. For example, the Idayri Basin in the, Jurdhawiyah group basins, is bounded by the E–W trending Shara fault (Johnson 2003, Fig. 8) and is affected by E–W-trending anticlines, synclines and chevron folds (Johnson 2003).

The Mujayrib Basin (part of the Bani Ghayy group basins) is a NNW-trending graben affected by N–S-trending folds having steep east-dipping axial planes parallel to steeply east-dipping reverse faults defining the eastern margin of the basin (Johnson 2003). Similarly, the Hammamat Group sedimentary rocks are affected by NW–SE-trending folds, and juxtaposed against a nappe complex (Um Gheig area: Abdeen 2003; Hamimi et al. 2014), Dokhan volcanics (wadi Atalla: Fowler and Osman 2001) and pelitic metasedimentary succession (wadi Um Had: Abu Sharib et al. 2019) by NE-and/or SW-dipping thrusts. In the case of the Hammamat basins, the parallelism between the direction of folds and thrusts and that of basins elongation imply that the bounding thrusts most probably may have been the original basin-bounding faults that were reactivated during inversion. The fact that the basin-fill sequences are folded about axes oriented parallel to the basin elongation direction reveals the same inversion axis, i.e. the axis of compression and extension did not change during inversion. The E–W oriented Jurdhawiyah basin unconformably overlying the folded rocks in the N–S oriented Murdama basin indicates a complex tectono-sedimentary history that involved basin opening, closure and uplift, and reopening with a 90° switch in stress field direction.

16.4.6 Complications of Tectonic Interpretations: A Regional Single Versus Multi-models

In the previous sections, it has been demonstrated that the geochronological data for the dyke swarms, A-type granitoids, some of the post-amalgamation depositional basins, and the activity of faults in the Najd system are temporally within error. The synchrony of the extension-related magmatic activities (preferentially oriented dykes, bimodal volcanics, and A-type granites) and the activity of the Najd Fault System, as well as the spatial and temporal association of the depositional basins and extension-related bimodal volcanics, led Stern (1985) to link the formation of the Najd Fault System to late Proterozoic crustal scale N–S-directed continental extension, without significant crustal thickening. The manifestation of the extension is the E–W oriented grabens that controlled the deposition of Hammamat Group in Egypt and Hibshi and Jurdhawiyah groups in Arabia. On the other hand, Blasband et al. (1997, 2000) used the same criteria to confirm a late Proterozoic extensional collapse of a thickened crust and exhumation of core complex in the Nubian shield. Additionally, differential uplift across the ANS allowed the temporal deposition of clastic- and shallow marine-dominated successions in post-amalgamation basins, and hence the extensional collapse model, which could have been applicable to some parts of the shield, is inapplicable to other parts. Moreover and among the disagreements, the NFS has been interpreted as a crustal scale, indentation-related, transcurrent fault system formed, as a consequence of tectonic escape (Johnson et al. 2011, and references therein) reminiscent to the intensive E–W oriented strike-slip fault system in Tibet and southern China (Dewey 1988; Dewey et al. 1988). For the above-mentioned reasons, many of the post-accretion features, including deformations, may fit into different tectonic models rather than being linked to a unique regional single tectonic model.

16.5 Conclusions

Post-accretion (arcs and terranes suturing) depositional basins in the ANS preserve a record of compression, extension and wrenching tectonic regimes that produced a complex array of temporally and/or spatially overlapping structures. Active tectonics involved east-west-directed shortening that accompanied the pure shear-related terminal collision between east and west Gondwana, and simple shear-related transpression due to subordinate collision-related reactivation of pre-existing basement faults and dominant activity along the Najd Fault System. Passive tectonics is attributed to the extensional gravitational collapse in the Nubian part of the shield and involved the spreading of a tectonic nappe along low angle to sub-horizontal reverse-sense shear zone and the formation of low angle normal-sense shear zones. Displacement along the Najd Fault System is attributed either to indentation and tectonic escape or to north-south-directed crustal scale continental extension. The Najd system is associated with a major component of north-south-directed extension, and hence, the wrenching and extension share common criteria including extension-related preferentially oriented dyke swarms, igneous (plutonic and volcanic) activity and deposition of volcano-sedimentary successions within fault-bounded basins. The post-accretion deformation events across the ANS during the Ediacaran are the end result of the interplay between more than one tectonic regime that involved shortening, extension and wrenching in addition to a localized non-tectonic extensional gravitational collapse.

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