Rezaeian M., 2008, Coupled tectonics, erosion and climate in the Alborz Mountains, Iran. PhD thesis, University of Cambridge; 219 p.

3-1 Motivation

The stratigraphic record of mountain building and erosion over geological time is contained within surrounding basins. From the erosional fluxes into these basins, information on orogen exhumation and its tectonic and climatic controls can be gleaned. Coarse-grained deposits prograding into subsiding foreland basins have systematically been attributed to phases of mountain building (Armstrong & Oriel, 1965; Allen *et al.*, 1991; DeCelles & Giles, 1996; Avouac, 2003), but can also be due to climatically driven changes in erosion rate (Amorosi *et al.*, 1999). Similarly, faulting and the formation of erosional unconformities within fringing basins can be related to the expansion and contraction of a mountain belt, but regional erosion may also be the result of a eustatic sea level drop. If the fingerprints of individual controls can be recognized, then the sedimentary record offers a uniquely detailed insight into the geological development of a region.

This chapter provides a summary of the Cenozoic stratigraphy of the Alborz Mountains and surrounding basins, and information on the emergence, deformation, and erosion of the Alborz fold-and-thrust belt contained therein. The approach is to integrate stratigraphic data extracted from the Stratigraphic Lexicon of Iran (Stocklin, 1972), geological maps and reports prepared by the Geological Survey of Iran (GSI), National Iranian Oil Company (NIOC), the Paleoenvironmental Atlas of Tethys (Dercourt *et al.*, 1993), and my own regional field investigation. A compilation of modern stratigraphic data on this scale has not been published, and it yields new insights into the history of the Alborz Mountains that could not have been obtained from individual sections.

In the last part of this chapter it is shown how the stratigraphy complements and reinforces the thermochronometric record presented in chapter 2. Furthermore, the history of erosion and exhumation of the Alborz Mountains is compared with equivalent records from two mainstays of the Tethyan orogenic belt, the Alps and the Himalayas, and, finally, all records are juxtaposed with the oxygen isotope record for the Cenozoic.

3-2 The Alborz Mountains-Regional Geology

The Alborz Mountains are an active fold-and-thrust belt across northern Iran, structurally related to Central Iran (Berberian, 1983; Alavi, 1996; Axen *et al.*, 2001a; Jackson *et al.*, 2002; Allen *et al.*, 2003a). A product of convergence between the two largely rigid domains of Central Iran and the South Caspian Basin/Eurasia, The Alborz is situated 200-500 km to the north of the Neo-Tethyan suture in the Arabia-Eurasia collision zone. Its south flank has geological affinities with Central Iran (Stocklin, 1968), while the northern flank has been influenced by events in the South Caspian basin. It has been proposed that both sides started behaving as a coherent tectonic unit in the early Pliocene, during a widespread tectonic reorganization in the Arabia-Eurasia collision zone (Axen *et al.*, 2001a; Allen *et al.*, 2004; Guest *et al.*, 2006c).

A generalised geological map of the Alborz Mountains, with the location of main structures, geographic names and stratigraphic type sections is shown in Figure 3.1. The regional geology is discussed in more detail below.

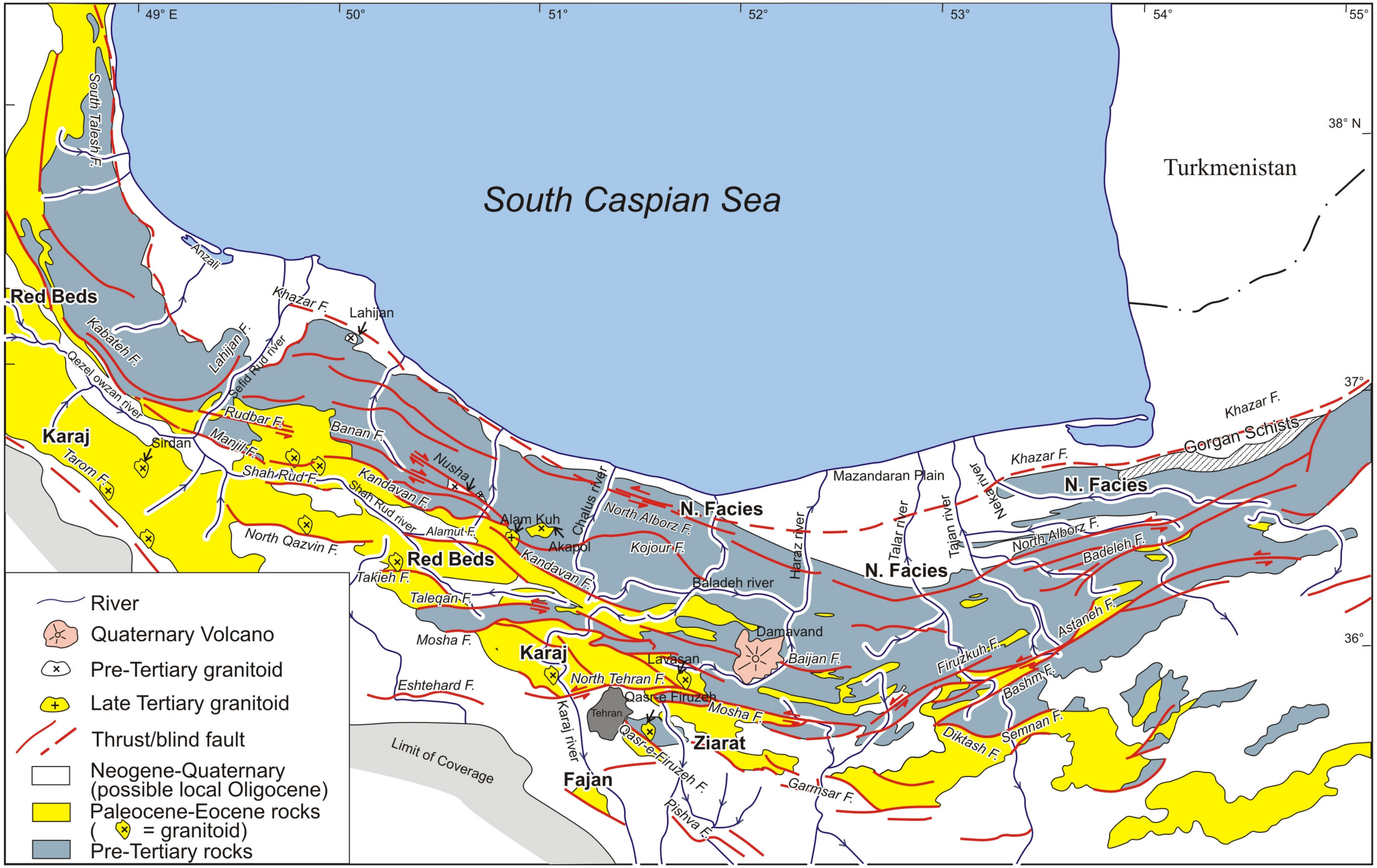

Fig. 3.1: Generalised geological-structural map of the Alborz (After Allen *et al.*, 2003a); some geological features were added after Berberian *et al.* (1985, 1996), Berberian & Yeats (2001), Guest *et al.* (2006b), and Nazari (2006). Main geographic features and important stratigraphic section locations (**Fajan, Karaj and Ziarat formations; N. Facies, and Red Beds**) are displayed.

3-2-1 The Southern flank of the Alborz

Marine platform conditions prevailed in the Alborz region during the Palaeozoic. A basement block containing the Alborz and Central Iran separated from Gondwana in the Ordovician-Silurian, as a part of the Paleo-Tethyan rifting. Rifting was followed by renewed continental shelf deposition from the Middle Devonian to the Middle Triassic, when the Alborz-Central Iran block collided with Eurasia. The collisional suture is assumed to lie in the north (Gorgan), northeast (Mashhad), and northwest (NE Talesh) of the current Alborz mountain belt (Stocklin, 1974; Clark, 1975; Berberian & King, 1981; Berberian, 1983; Alavi, 1996; Stampfli *et al.*, 2001). Gorgan Schists, in NE Alborz, represent part of the Paleo-Tethys suture zone and consist of low grade meta-pelitic and meta-volcanic complexes of the Late Ordovician age; it is overthrust southward above a strongly deformed Late Palaeozoic to Middle Triassic succession (Geological Survey of Iran, 1991a; Ghavidel-syooki, 2007).

After collision, and during renewed rifting in the Early Jurassic-Turonian, siliciclastic molasse sediments of the Shemshak/Kashafrud Formation were deposited in the Rhaetic-Liassic foreland. Sedimentary conditions changed to a transgressive marine environment with deposition of shelf carbonates during the Late Jurassic and Cretaceous (Berberian, 1983). The Upper Cretaceous sequence is composed of marine calcareous marls, but displays different facies between the west and the east Alborz. In the west and north it contains tuffaceous sediments and lavas, but volcanic activity diminished toward the south and the east (Davies *et al.*, 1972; Clark *et al.*, 1975; Yassini, 1981).

At the base of the Tertiary sequence, a polygenic, basal conglomerate unconformably overlies the Mesozoic formations in the southern Alborz. This conglomerate, along with Paleocene to Early-Middle Eocene limestones, has filled a set of topographic depressions formed by a phase of substantial folding and uplift in the Late Cretaceous (Stocklin, 1972; Huber, 1977b). In the north, the Lower Paleocene shallow marine sediments conformably overlie the Cretaceous carbonates (Yassini, 1981; Mousavi Ruhbakhsh, 2001).

Regional extension of southwest Asia in the Eocene (Vincent *et al.*, 2005), caused high heat flow and magmatism, affecting the whole area overriding the Neo-Tethys subduction zone, including eastern Central Iran and the southern Alborz. The northern Alborz and Kopeh-Dagh do not appear to have been much affected. Magmatism resulted in the formation of a thick continental-submarine volcano-sedimentary succession and extensive plutonism throughout Iran (Emami, 2000). The area of outcrops of Eocene to Miocene age is estimated at ~9000 km^2, that is ~56% of the summed outcrop area of all plutons of Late Precambrian to Miocene age in Iran (Ghalamghash, 1998).

The Eocene marine volcano-sedimentary sequence in the southern Alborz is ~3-4 km thick. It extends along the length of the Alborz, with the greatest outcrop in the west (Hajian, 1996) and tapers, becoming less continuous to the east (Emami, 2000; Moin-Vaziri, 1996). The marine succession is topped by Late Eocene evaporites and limestones. These are found in the Central Alborz (Hubber, 1977b), but in the SW Alborz volcano–sedimentary deposition, mainly subaerial, continued into the Oligocene. The acidic volcanic rocks are regarded as a different stratigraphic unit which rests unconformably on the Eocene volcani-sedimentary rocks (Clark *et al.*, 1975). In turn, they are uncomfortably overlain by light-coloured Neogene strata, with a basal conglomerate reported from some outcrops (Stocklin & Eftekhar-

Nezhad, 1969). These Neogene beds are equivalent to the continental-lagoonal clastics and volcanics of the Oligocene Lower Red Formation in Central Iran (Stocklin, 1972; Emami, 1991).

In the Late Oligocene a last marine transgression occurred. A shallow sea covered much of the Central Iran (Rahimzadeh, 1994), with widespread deposition of carbonates (Qom Formation). The carbonates of the Qom Sea pinch out in the north against the southern flank of the Alborz Mountains and interfinger with detrital, fluvial and near shore sediments in the mountains. This indicates the existence of subaerial relief to the north of the marine basin (Stocklin, 1972). Structural depressions inside the emergent Alborz Mountains were filled with continental clastics, including red beds and playa evaporites (Huber, 1977a). Following regression in post-Burdigalian times, a thick sequence, up to 5 km, of hematite stained, continental-lagoonal sediments was deposited over the marine carbonates mainly to the south of the Alborz (Huber, 1977b; Emami, 1991; Rahimzadeh, 1994).

In the western Alborz, major outcrops of the Neogene terrestrial and volcanic rocks occur in several intermountain basins (Annells *et al.*, 1975; Clark *et al.*, 1975). These clastic sediments were sourced from the highlands of the emerging Alborz. The red coloured marls, sandstones, evaporites and conglomerates, with or without volcanic rocks, are attributed a wide range of ages from Oligocene to Pliocene. They are collectively known as the Neogene Red Beds (Stocklin & Eftekhar-Nezhad, 1969; Davies *et al.*, 1972; Stocklin, 1972; Annells *et al.*, 1975; Clark *et al.*, 1975). Within them, the Miocene-Pliocene interval is composed of alluvial-fluvial conglomerates eroded from the uplifting Alborz range. These conglomerates were folded in the Late Pliocene and/or Pleistocene, and they are uncomfortably overlain by Quaternary alluvial formations (Rieben, 1955).

3-2-2 The Northern Alborz

The Northern Alborz has a different Cenozoic geological history. A long period of non-deposition preceeded the Early Miocene (Sussli, 1976; Berberian & King, 1981). Neogene marine strata overlie Late Cretaceous-Early Paleocene limestones and are succeeded by coarse, continental clastic beds of Pliocene age (Stocklin, 1972).

In the Early Pliocene, the inland Caspian Sea, experienced a catastrophic sea level drop to -600 m. This occurred in late Messinian, and coincided with an equally dramatic sea level fall, salinity crisis and desiccation of the Mediterranean Sea between 5.96 and 5.33 Ma. The marine area was reduced to half of the present size (Reynolds *et al.*, 1998; Zobakov, 2001; Huseynov *et al.*, 2004; Smith-Rouch, 2006), allowing deltas of the incoming rivers to prograde far into the basin interior, where massive volumes of sediment were deposited (Smith-Rouch, 2006). In the northern Alborz, the Pliocene sequence consists of conglomerates with intercalations of sandstone and mudstone, overlain by Upper Pliocene marls, sandstones and conglomerates. This transition is unconformable in some places and gradual elsewhere (Stocklin, 1972; Yassini, 1981).

Neogene formations with Para-Tethyan facies do not crop out south of the North Alborz fault. The thickness of Late Pliocene-Quaternary strata north of this limit of Para-Tethyan deposition increases dramatically from east to west and from onshore to offshore along the South Caspian coast line, in exploration wells of the National Iran Oil Company (Yassini, 1981; Mousavi Ruhbakhsh, 2001). This implies increasing subsidence towards the western part of the Caspian Sea, where the Sefid Rud river is a major source of sediment.

3-3 Radiometric Geochronology

The geology of the Alborz Mountains has been explored over the last 150 years, but few age determinations are available for the area. Extant dates have been mostly obtained in the last decade, using a variety of methods. These dates combined with biostratigraphic records, and thermochronometric data reported in chapter 2 constrain the geological and tectonic history of the range. In this section, radiometric age constraints are reviewed. Locations referred to here can be found in Figure 3.1.

-The first radiometric dating on the Tertiary rocks of the Alborz was conducted on the Qasr-e-Firuzeh intrusive rocks, E Tehran (Davari, 1987); K/Ar dates indicate that magmatic emplacement occurred at 41 ± 4 Ma (Middle Eocene).

Since 2001 several more radiometric dates have been reported as follows:

- Lahijan intrusive rocks on the Caspian coast (Guest *et al.*, 2006c) with U/Pb age of 552 ± 6.
- Nusha pluton in the NW Alborz: U/Pb ages of 97 ± 2, 98 ± 1 and 100 ± 1.7 Ma. (Axen *et al.*, 2001b; Guest *et al.*, 2006c).
- Akapol pluton intruded at 56.6 ± 2 Ma, cooled to ~150ºC by ca. 40 Ma, and stayed near that temperature until at least 25 Ma. The nearby Alam Kuh granite intruded at 6.8 ± 0.1 Ma and cooled rapidly to ~70 °C by ca. 6 Ma, according to U/Pb, 40Ar/39Ar, and apatite (U-Th)/He dating (Axen *et al.*, 2001a).
- (U-Th)/He and 40Ar/39Ar dates of the Damavand composite volcano indicate that volcanic activity lasted from 1.8 Ma until 7 ka. The current cone (the Young Damavand; ca. 600-7 ka) lies slightly to the south of the eroded remnants of the Old Damavand cone (ca. 1780-800 ka) (Davidson *et al.*, 2004).
- In upstream of Shah Rud valley, basalt flows and interbedded lagoonal, shallow marine rocks, unconformably overlying lavas of the Eocene Karaj Formation (Guest *et al.*, 2006a), have 40Ar/39Ar ages of 32.7 ± 0.3 and 32.9 ± 0.2 Ma.
- A micro-diorite dike intruded into the basal lacustrine-fan conglomerate facies, in the previously mentioned place, was dated with 40Ar/39Ar to 8.74 ± 0.15, constraining the age of the syncontractional facies unconformably overlying older sediments (Guest *et al.*, 2006a).
- A dike cutting faults in the SW Alborz (upstream Shah Rud basin) has 40Ar/39Ar dates of 6.7 ± 0.1 to 8.74 ± 0.15 Ma, implying fault offset before 9 Ma (Guest *et al.*, 2006a; 2007).
- In the Taleqan basin, andesitic lava flows overlying undeformed, subhorizontal alluvial and fluvial sedimentary rocks have 40Ar/39Ar ages from 2.86±0.83 to 0.24±0.03 Ma, constraining the most recent deformation of the basin (Guest *et al.*, 2006a; 2007).
- In the Alamut basin, lava flows capping the Middle-Upper Miocene sediments have 40Ar/39Ar dates of 0.31 ± 0.04 and 0.51 ± 0.06Ma (Guest *et al.*, 2007).
- 40Ar/39Ar dates of the Lavasan intrusive body in NE Tehran and volcanic rocks of the Karaj Formation in E Tehran by P. Ballato (unpublished data-Potsdam University) indicate magmatic emplacement at 38.47 ± 0.1 and volcanic activity at 36.02 ± 0.15Ma.
- In addition to this, I have obtained a U/Pb date of 35±5 Ma for a sample from Sirdan granite in the SW Alborz, indicating magmatic emplacement in the Middle-Late Eocene.

This compilation reveals that three significant magmatic phases have affected the Alborz region in the Late Cretaceous, Paleogene (intensified in the Middle Eocene) and Late Miocene times. They were followed by volcanic activity in the Damavand area during the Quaternary.

Sedimentary rocks in the Alborz Mountains have been dated with bio-stratigraphic methods, but ages of continental, clastic rocks are poorly constrained.

3-4 Tertiary Stratigraphic Framework

It is clear from the preceeding section that the Alborz region has had two distinct tectono-sedimetary domains during the Cenozoic: (i) the Caspian Sea (Northern), and (ii) the Southern facies (Salehi Rad, 1979). The 'Early Alborz' has emerged gradually along the main structures of the North Alborz and Talesh faults, currently located within the northern margin of the mountain belt (Berberian & King, 1981). These faults appear to define the structural boundary between two domains which are related to the eastern Para-Tethys, and Central Iran to the north and the south of the Alborz, respectively. Moreover, there appear to have been important gradients in the rates and styles of deposition along the axial trend of the Alborz Mountains. To capture the contrasts between the northern and southern domains, and the lateral trends in the latter, detailed stratigraphic observations have been summarised in three stratigraphic columns, one each for the SW, S-SE, and N Alborz facies (plate 3.1).

3-4-1 The Caspian Sea (Northern) Facies

North of the North Alborz-Talesh fault zone, the sedimentary sequence of the Caspian Sea consists of Cretaceous and younger rocks. In the northwest Alborz, the Upper Cretaceous sequence comprises tuffaceous sediments with lava and rare calcareous strata (Davies *et al.*, 1972; Clark *et al.*, 1975); the sequence grades laterally to silty marl and calcareous marl in the northeast Alborz (Yassini, 1981), implying that the Cretaceous volcanic activity diminished toward the east (Berberian, 1983).

Paleogene strata are absent in northern Alborz with the exception of a few locations where the lower Paleocene (Danian) marine sediments overlie the Upper Cretaceous and older formations without distinct unconformity (Davis *et al.*, 1972; Sussli, 1976; Salehi Rad, 1979; Yassini, 1981). Lack of Eocene-Oligocene strata over most of the Talesh and the northern Alborz has been attributed to mountain building along the Talesh and North Alborz faults and consequent erosion (Berberian & King, 1981), which may have excised Paleogene deposits at a later time.

The Neogene and the Quaternary strata of the Caspian sequence have been described in several cross sections (Stocklin, 1972; Salehi Rad, 1979; Yassini, 1981; Mousavi Ruhbakhsh, 2001). These sections are well correlated with oil exploration wells and outcrops to the northwest and the east in Azarbaijan and Turkmenistan. The Neogene sequence has been affected by relative sea level change of the Caspian Sea against the uplifting Alborz. This has resulted in erosion or non-deposition, interrupting the geological record of the Caspian facies in the northern Alborz (Plate 3.1). The stratigraphic attributes of several type sections (Fig. 3.1 for locations) described by Yassini (1981) can be summarised in the follows.

The Middle Miocene (Langhian) Red Marl Formation, first reported by A. Erni in 1931 (Stocklin, 1972) consists of purplish-red marine marls with intercalated limestone, sandstone, red conglomerate, basalt, and gypsum. This formation unconformably overlies Late Cretaceous or Early Paleocene strata (Yassini, 1981; Mousavi Ruhbakhsh, 2001), indicating an erosion phase before onset of marine deposition. It is succeeded by the Spanidontella Beds of green-grey clay, marls, sandstone and bioclastic deposits with shells of *Spanidontella* sp. The Pholas Beds of Upper Miocene age follow conformably (Stocklin, 1972; Yassini, 1981). They are composed of clay, sandstone, marl, and marly limestone containing shells of *Pholas* sp, and grade upward into the Upper Miocene Sarmatian Beds (Stocklin, 1972; Yassini, 1981). The upper part of the Sarmatian Beds is missing due to a Pliocene erosion phase, possibly associated with regression of the Caspian Sea (Stocklin, 1972; Yassini, 1981). A thick sequence (up to 1700m) of conglomerate with interbedding marls, sandstones and fossilferous limestone of the Continental Series or Brown Beds unconformably overlies the Upper Miocene strata. The time gap between the Sarmatian Beds and the Continental Series is ill defined, but may be as long as several million years (Yassini, 1981; Sacchi & Horv´ath, 2002).

The Continental Series is the oldest Cenozoic clastic continental sediment in the northern Alborz. It is composed of well-rounded clasts of Paleozoic rocks, as well as Eocene components, and indicates substantial exhumation in the northern Alborz hinterland during the Early Pliocene (Sussli, 1976; Yassini, 1981). The Continental Series is succeeded by Upper Pliocene strata of the Akchagyl unit consisting of conglomerate, sandstone and marl at the base, and loess at the top. A distinct unconformity at the base of Akchagyl in the Upper Middle Pliocene has been observed in NIOC exploration wells and seismic profiles in the South Caspian Sea (Yassini, 1981; Mousavi Ruhbakhsh, 2001). In turn, the Akchagyl unit is covered by Quaternary strata with a thickness of up to 2.6 km. The Quaternary strata were deposited in an area of active subsidence along the Caspian fringe and in front of the uplifting Alborz Mountains.

Inside the Alborz Mountains, the Continental Series sequence has been displaced vertically by up to 3500 m by thrusting along the Khazar fault since ~2 Ma (Berberian, 1983): it sits at ~1000 m above the sea level south of the Khazar fault and is found in deep wells in the South Caspian Basin below 1600-2000 m of younger sediments, indicating that rapid basin subsidence has also played a role in the vertical offset (Berberian, 1983). The subsidence rate increased substantially from the east to the west and from onshore to offshore. The depth at which the base of the Akchagyl Formation is observed in drilling wells increases from around 600-700 m in the east (Gorgan-Gonbad), to 1300-1400 m in the centre (Mazandaran), and 2610 in the west (Anazali) (Yassini, 1981; Mousavi Ruhbakhsh, 2001).

The Quaternary succession begins with the Apsheron Formation, composed of green-blue-grey marls and fine grained sandstones intercalated with volcanic ash. It is overlain by poorly consolidated marine muds and sands, with thin layers of gravels belonging to the Ancient Caspian Stage. This in turn is overlain by the Recent Caspian Stage consisting of unconsolidated sands and gravels (Sussli, 1976; Yassini 1981). In the Gorgan area of the eastern Alborz, early Pleistocene loess deposits are set within the Recent Caspian Stage (Salehi Rad, 1979). They may be related to cold interstadial phases with steppe-like climate (Huber, 1977b).

Landslides, dammed lakes and fine laminated deposits are prominent features in the northern Alborz. Many of large landslides occurred during cold stages in the Pleistocene when the climate may have been considerably wetter than it is today. The landslides have dammed rivers and formed temporary lake basins that have since been filled with alluvial deposits, Gilbert-type fan deltas and fine grained lake beds (Annells *et al.*, 1975; Davies *et al.*, 1972; Sussli, 1976).

3-4-2 The Southern Facies

3-4-2-1 Paleogene Formations

The Upper Cretaceous of the southern Alborz shared depositional conditions with the platform areas of the Central Iran (Hubber, 1977b; Emami 1991). Deposits from this epoch are composed of reef limestone with sandy-silty intercalations across the whole region, with volcanic intercalations in the west (Clark *et al.*, 1975).

Cretaceous strata are unconformably overlain by a thick sequence of Paleogene deposits in the southern flank of the Alborz. These deposits thin out rapidly around the current main drainage divide of the mountain belt, and are absent further north. The northern part of the Alborz region appears to have been emergent at the Late Cretaceous-Paleocene boundary (Davies *et al.*, 1972; Clark *et al.*, 1975; Berberian & King, 1981), or sediments were deposited and then completely eroded as far as the southern margin of the South Caspian Basin (Allen *et al.*, 2003a). The latter suggestion is not warranted since there is no thermochronological evidence of selective, deep erosion in the northern Alborz at this time.

The Paleogene sequence begins with the Paleocene Fajan Formation composed of conglomerates, red sandstones, and sandy marls (Dellenbach, 1964; Stocklin, 1972). It is closely associated, and in some places interfingers with nummulite-bearing reef-type limestones of the Paleocene to Middle Eocene Ziarat Formation. The Ziarat Formation further contains tuffs, conglomerates, gypsum and marls (Dellenbach, 1964; Stocklin, 1972). Calcareous outcrops of the Ziarat Formation are common above base conglomerates of the Fajan Formation. Where they are absent, Eocene volcano-sedimentary rocks of the Karaj Formation (Dedual, 1967) uncomformably overlie the older strata (Stocklin & Eftekhar-Nezhad, 1969; Clark *et al.*, 1975). Lateral interfringing of the Ziarat limestone and the Karaj Formation has been observed in the western Alborz (Stocklin, 1972).

Beginning in the Middle Eocene, widespread magmatism affected much of Iran. It is noticeable specifically in three distinct zones: the southern Alborz, the Urumiyeh-Dokhtar magmatic assemblage, and eastern Central Iran (Emami, 2000). In the Alborz, there was an east-west gradient in magmatic activity, based on stratigraphy. The intrusive and extrusive rocks reach their greatest outcrop and thickness in the southwest Alborz, close to the Urumiyeh-Dokhtar magmatic centre. They gradually thin to the north and east and are absent from the easternmost and the northernmost Alborz (Hajian, 1996), where they are replaced by a non-magmatic sequence, dominated by pure marine shales and limestones (Stocklin, 1972).

The Paleogene magmatic sequence of the Alborz consists mainly of the largely submarine Karaj Formation of Middle Eocene age (Dedual, 1967), including tuffs and lava intercalations (Emami, 2000). In the type section in the Karaj valley (Fig. 3.1 for the location) the formation has been subdivided into five members (Dedual, 1967; Stocklin, 1972), from the bottom up : 1- The Kandavan Black Shale (thickness unconstrained); 2- The Upper Tuff (917m): mostly green tuff with intercalation of tuffaceous shale, tuffaceous sandstone, and calcareous shale; 3- The Astara [Asara] Shale (167m): calcareous shale with subordinate beds of tuff and tuffaceous shale; 4- The Middle Tuff (1177m): thick bedded glass and ash tuffs; and 5- The Lower Shale (1055m): greyish-black calcareous and siliceous shale with lava near the base.

In the central Alborz, the Eocene green tuffs and related rocks have a thickness of more than 3320 m. They are overlain unconformably by the Oligocene terrestrial sediments of the Lower Red Formation (Stocklin, 1972; Hubber, 1977b; Rahimzadeh, 1994). East of Tehran, the Eocene volcani-sedimentary strata are succeeded instead by lagoonal and reef deposits of the Late Eocene Kond Formation (Dellenbach, 1964). This formation may be equivalent to the Kandavan Shale of the Karaj valley (Stocklin, 1972). Equivalent rocks have not been reported in the western Alborz.

In the western Alborz, the Karaj Formation has a different range of lithofacies. It is described in two divisions: the Kordkand and the Amand members (Stocklin & Eftekhar-Nezhad, 1969). The formation reaches its greatest thickness, up to 4000 m, and widest distribution in the Tarom and the southern Talesh mountains (Stocklin & Eftekhar-Nezhad, 1969; Stocklin, 1972). In this area, the Karaj Formation consists of a variety of lava flows and associated tuffaceous beds including tuffaceous sandstones and mudstones deposited in a marine environment (Stocklin & Eftekhar-Nezhad, 1969). The Paleogene strata of the western Alborz are much more magmatic than in the central-east Alborz. Including the Oligocene, subaerial volcanics (equivalent to the Lower Red Formation of Central Iran) their thickness reaches up to 6 km. The Akapol pluton formed in this area in the Late Paleocene, 56.6±2 Ma (Axen *et al.*, 2001a), possibly as a precursor of massive magmatism in the Middle Eocene. U/Pb, K/Ar and 40Ar/39Ar ages of intrusive rocks in Sirdan in SW Alborz, Qasr-e-Firuzeh in E Tehran (Davari, 1987), Karaj Formation volcanics and Lavasan in NE Tehran all are Middle Eocene.

From the Middle Eocene, rare horizons of red sediments, laterite and ignimbrite (welded tuff) appear within the submarine sequence of the Karaj Formation, implying occasional emergence (Davies *et al.*, 1972). A wholesale shift to subaerial volcanics occurred in the Oligocene (Annells *et al.*, 1975; Clark *et al.*, 1975; Emami, 2000). Early Oligocene volcanic rocks have red conglomerates at their base in some outcrops (Stocklin & Eftekhar-Nezhad, 1969), and an unconformity separates them from underlying Karaj rocks in several sections (Clark *et al.*, 1975).

The only radiometric constraint on the timing of this shift from marine to subaerial deposition is a 40Ar/39Ar study in the Neogene basins of the west-central Alborz (Guest *et al.*, 2006a), where basalt flows interstratified with lagoonal rocks unconformably overlie marine lavas of the Eocene Karaj Formation. The basalts are dated at 32.7 ± 0.3 and 32.9 ± 0.2 Ma, *i.e.* Eocene-Oligocene transition. Other intrusives have cut the Oligocene volcanics (Clark *et al.*, 1975). Their ages are poorly constrained, because overlying sedimentary strata are not well dated.

Red and greenish evaporitic silt, marl and sandstone with volcanic flows and pyroclastics of the Lower Red Formation (Stocklin, 1972) were deposited in several lagoonal basins following regression of the Eocene sea associated with Eocene-Oligocene uplift in Central Iran (Rahimzadeh, 1994). The facies are different from place to place. In general, they become more conglomeratic and interfinger with subaerial, basic lava flows to the west. Brackish facies with gypsiferous marl, shale, volcano-clastic and sandstone dominate further east (Rahimzadeh, 1994).

Following a transgression in the Middle-Late Oligocene along the Tethyan Seaway (*e.g*., Rogl, 1999; Harzhauser *et al.*, 2002; 2007), marine conditions returned to much of the Central Iran, peaking in the Early Miocene (Stocklin, 1972; Rahimzadeh, 1994). In this interval, limestones of the Qom Formation were deposited in Central Iran, but this interval is poorly represented in the stratigraphy of the Alborz. Marine limestone deposits are found locally in the south flank of the Alborz. A distinct basal limestone rests comformably on the Lower Red Formation and is overlain transitionally by the Upper Red Formation (Stocklin, 1972). In some outcrops in the west Alborz this limestone is conglomeratic with tuff intercalations in its lower part (Stocklin & Eftekhar-Nezhad, 1969). In the Oligocene-Miocene sea, the carbonate shelf graded northwards beyond latitude ~35º N into detrital, fluvial and near shore sediments (Dercourt *et al.*, 1993). East of longitude ~54º E red gypsiferous marls and sandstones were deposited.

Following a post-Burdigalian regression, continental red sediments of the Upper Red Formation were deposited on the marine sediment of the Qom Formation. The contact is unconformable, erosional with a basal conglomerate marking where the basin margin was exposed in the southern Alborz (Huber, 1977b; Rahimzadeh, 1994). The Upper Red Formation is composed of gypsiferous marl and sandstone, getting lighter in colour in the upper part where evaporitic deposits are volumetrically more important (Stocklin, 1972). Upper Red strata have accumulated in great thickness, up to 6.5km (Ballato *et al.*, 2008), along the southern front of the Alborz Mountains on fan deltas and mud flats in basins (Huber, 1977a). Further north, within the Alborz Mountains, there is no distinct boundary between the Qom Formation and URF or LRF. Similarity of the Oligocene-Miocene deposits and the Red Beds makes it difficult to differentiate between the Upper Red Formation, the Lower Red Formation, and non-marine portions of the Qom Formation (Stocklin, 1972). Therefore, the totality of this red stained, subaerial sequence is referred as the 'Neogene Red Beds' or the 'Neogene deposits' in several sections (Stocklin & Eftekhar-Nezhad, 1969; Davies *et al.*, 1972; Stocklin, 1972; Clarck *et al.*, 1975; Annells *et al.*,1975). Moreover, the Neogene Red Beds are indistinguishable from the overlying Pliocene conglomerates (Stocklin & Eftekhar-Nezhad, 1969; Stocklin, 1972). An erosional unconformity separates them along the south margin of the Alborz (Stocklin, 1972), but elsewhere the transition is conformable and/or gradual. The age of the upper part of the Upper Red Formation is not constrained due to lack of diagnostic fossils (Stocklin, 1972).

3-4-2-2 The Neogene Red Beds

The Neogene Red Beds record, in detail, the emergence and exhumation of the Alborz Mountains. A sequence of up to 3,500 m of terrestrial deposits including conglomerates, finer clastics and evaporates, and without marine intercalations has accumulated in several intramontane basins within the western Alborz, which have been displayed in Figure 3.1 as Neogene-Quaternary outcrops interior the mountain belt. These basins are fault bounded, tectonically controlled depressions (Stocklin & Eftekhar-Nezhad, 1969; Davies *et al.*, 1972; Annells *et al.*, 1975; Clark *et al.*, 1975). The spatial variation in facies from proximal to distal, the absence of marine beds, and scarcity of diagnostic fossils make stratigraphic correlation difficult (Annells *et al.*, 1975).

The Neogene Red Bed sequence rests uncomformably on the Karaj Formation or older formations. In general, it coarsens up, beginning with fine-grained deposits and evaporites, but a basal conglomerate lines the basin margins. The bulk of the Red Beds consists of conglomerate units with both conformable and unconformable boundaries (Davies *et al.*, 1972; Annells *et al.*, 1975; Clarck *et al.*, 1975). Three main subunits Ng1, Ng2 and Ng3 have been recognized and attributed to separate accumulation phases (Stocklin & Eftekhar-Nezhad, 1969; Clark *et al.*, 1975). They are summarised in a schematic diagram in Figure 3.2. Their strata display a broad range of lithologies, and consist of volcanics, conglomerates, sandstones, evaporite-free mudstone, gypsiferous mudstone and non-marine limestones (Stocklin & Eftekhar-Nezhad, 1969; Annells *et al.*, 1975; Clark *et al.*, 1975). Notably, volcanic rocks mainly of trachytic composition are an important component of the Neogene redbeds in the northwest of the western Alborz (Clark *et al.*, 1975). Magmatism has persisted into the Late Tertiary. The Alam Kuh granite was intruded at 6.8 ± 0.1 Ma and cooled to near-surface temperatures by 6 Ma (Axen *et al.*, 2001a).

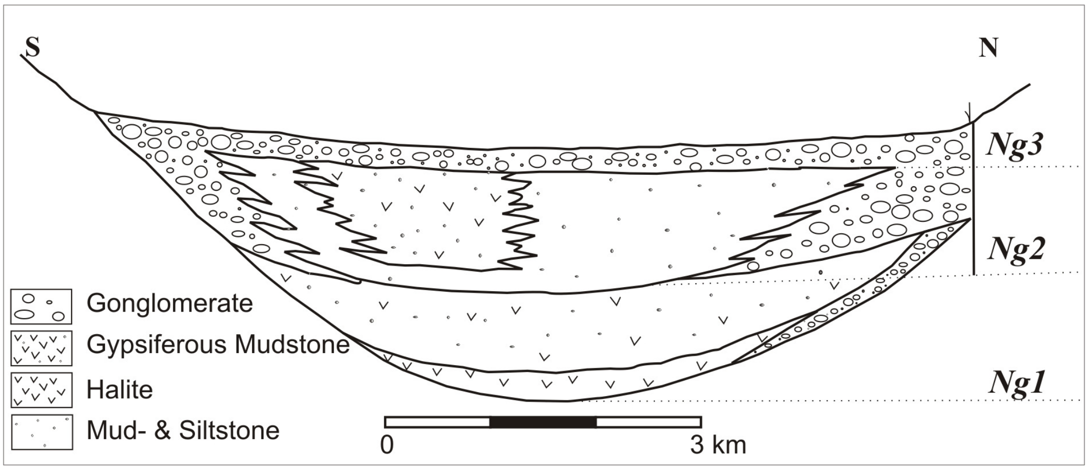

Fig. 3.2: A schematic stratigraphic section of three subunits of Neogene Red Beds in Shah Rud-Alamut basin, using several interpretive transverse sections (Annells *et al.*, 1975).

<u>The Lower subunit (Ng1)</u>:

This subunit is probably Oligocene-Early Miocene in age, based on stratigraphy and lithofacies correlation. It is overlain by calcareous beds of Early Miocene age further to the west, which may be equivalent to the base of Ng2 (Clarck *et al.*, 1975). At the base of subunit Ng1 a halite layer is described in the central part of the Shah Rud-Alamut basin by Annells *et al.* (1975) (Fig. 3.2). The hypersaline-lagoonal lithofacies of this deposit is considered to reflect the last marine transgression in the Tertiary, but the intramountain basins probably never became fully marine. At their northern margin, the hypersaline sediments interfinger with a conglomerate, with interlayered tuffs and agglomerates in some outcrops (Annells *et al.*, 1975). They are succeeded by gypsiferous mudstone or marl with agglomerate, and in some cases, sandstones and conglomerates (Stocklin & Eftekhar-Nezhad, 1969; Annells *et al.*, 1975; Clark *et al.*, 1975).

The oldest marginal conglomerate of the Ng1 subunit, referred to as the first accumulation phase, consist largely of clasts derived from Karaj Formation volcanics and, to a lesser extent from older formations (Stocklin & Eftekhar-Nezhad, 1969; Annells *et al.*, 1975); this implies that a substantial topographic relief had developed within Karaj volcanics, in Late Oligocene-Early Miocene time, soon after their deposition.

<u>The Middle subunit (Ng2)</u>:

From lateral correlation with calcareous beds the base of Ng2 is inferred to be of Early Miocene age, and the subunit as a whole is thought to have formed within the Miocene (Clarck *et al.*, 1975). In many places, it rests unconformably rests on the older subunit, but a disconformity has been found in the central part of the Qezel Owzan basin in the west Alborz (Annelles *et al.*, 1975; Clark *et al.*, 1975) (Fig. 3.1 for the location). Some volcanic beds unconformably top the subunit (Clark *et al.*, 1975). The only geochronological constraint on the volcanic activity and the timing of the unconformity is a 40Ar/39Ar date for a micro-diorite dike that intruded into a lacustrine-fan conglomerate at 8.74±0.15 (Guest *et al.*, 2006a).

Subunit Ng2 consists of terrestrial sedimentary beds, mainly silty-sandy-conglomerates, with gypsiferous marls, and local intercalations of tuffs and agglomerates. Volcanic strata are reported form basins in the NW Alborz (Stocklin & Eftekhar-Nezhad, 1969; Annells *et al.*, 1975; Clark *et al.*, 1975).

The conglomeratic sequence of Ng2 is referred to as the second accumulation phase. It is the most conspicuous fill of the intramontane basins, and consists of fragments mainly of Paleogene and occasionally older formations (Stocklin & Eftekhar-Nezhad, 1969; Annells *et al.*, 1975; Clark *et al.*, 1975).

<u>The Upper subunit (Ng3)</u>:

This subunit is assigned a Pliocene-Early Pleistocene age, based on bio-stratigraphy (Annells *et al.*, 1975). It lies unconformably on gently folded sediments of older subunits Ng1 and Ng2. Bedding in Ng3 is commonly gently tilted, and less folded and faulted than the underlying strata; and has not been cut by the faults that affected the older subunits (Stocklin & Eftekhar-Nezhad, 1969; Clark *et al.*, 1975). This implies that basins within the Alborz were deformed before subunit Ng3 was deposited.

Coarse sediments of the Ng3 subunit, referred to as the youngest accumulation phase, crop out in the Shah Rud basin. They consist of poorly sorted breccia with sand and silt interbeds conformably overlying gypsiferous mudstones (Annells *et al.*, 1975). Further to the west, Ng3 sediments, mainly sandstone, breccia and conglomerate, rest unconformably on older strata with sub-horizontal, Pleistocene travertine deposits on top. In some outcrops this non-marine limestone reaches a thickness up to 10 m (Clarck *et al.*, 1975).

The Miocene-Pliocene strata of the Hezardareh Formation (Rieben, 1955) in the south Alborz are equivalent to subunit Ng3 in intramontane basins. It is composed mainly of conglomerates, with minor intercalations of sandstones and mudstones (Stocklin, 1972). A thick sequence of alluvial-fluvial conglomerates dominates the foothills of the southern Alborz along its entire length (Rieben, 1955). They are composed of tuffs, eroded from the Karaj Formation, and shed from the rising Alborz. The Hezardareh Formation was folded in the Late Pliocene and/or Pleistocene, and it is overlain uncomfortably by subhorizontal, alluvial formations of Quaternary age (Stocklin, 1972). Dating of the Hezardareh Formation is problematic. An Upper Pliocene age has been reported by Rieben (1966) from a core sample collected in south Tehran, where there is a gradual transition with underlying sediments of the Upper Red Formation. In the absence of clear criteria it is difficult to date the conglomerates in other places.

3-4-2-3 Quaternary Deposits

In many places along the southern edge of the Alborz Mountains, deposition of coarse clastic sediments on river beds, alluvial fans and talus slopes has continued in the Quaternary. At its southern fringe, the piedmont area grades into the evaporate plains of Iran's high interior, and its easy to see the Tertiary facies described above reflected in the modern environment. Inside the mountain belt, Quaternary deposition has been associated with volcanic activity, faulting, and slope failure.

Early Quaternary volcanic rocks have been identified in several places in the central and southern Alborz, notably around Damavand volcano in the central Alborz. Mount Damavand is a composite cone of > 400 km^3 of trachy-andesitic lavas and pyroclastic material, with a summit elevation of 5,600 m asl. Its volcanism is thought to be related to decompression melting (Davidson *et al.*, 2004). Eruptions have occurred since 1.8 Ma and as recently as 7 Ka (Davidson *et al.*, 2004). Volcanic rocks associated with the Damavand eruptive centre are observed in small patches up to 40-50 km from the current volcano (Davidson *et al.*, 2004; Geological Survey of Iran, 1987; 1988). In many cases these deposits are separated from their source by important erosional topography.

The most recent volcanic activity in the western Alborz occurred slightly earlier in the Late Pliocene (2.86 ± 0.83 Ma), based on 40Ar/39Ar dates of andesitic lava flows (Guest *et al.*, 2006c). These flows rest on undeformed, subhorizontal alluvial and fluvial sedimentary rocks, some of which may be Quaternary in age (Annells *et al.*, 1975; Geological Survey of Iran, 1975; 1997; 1998b; 2005).

Landslide deposits, dammed lake fills, volcanics, and travertine and loess deposits are present locally within the Quaternary of the southern Alborz. As in the north Alborz, many of the large landslides may have originated under Pleistocene wet conditions. They dammed rivers and produced lake basins. Landslides have also been caused by recent large earthquakes in the mountain belt (Davies *et al.*, 1972; Clark *et al.*, 1975; Annells *et al.*, 1975; Sussli, 1976). Deposits of fluvially re-worked loess of the Pleistocene age have been described in the flank of the lower Sefid Rud valley (Stocklin & Eftekhar-Nezhad, 1969).

3-5 Stratigraphic events

The stratigraphic record of the Alborz Mountains reflects as series of tectonic developments and events, together with their geomorphic consequences. The stratigraphic record can be summarized as follows (see Plate 3.1):

1) An erosional unconformity at the base of the Cenozoic sequence may be related to compressional deformation of north Iran. The unconformity is present throughout the Alborz, but only in the south flank of the mountain belt can its formation be pinned to the Latest Cretaceous-Paleocene.

2) During the Eocene (55-34 Ma), extension caused subsidence of the southern Alborz, while the northern Alborz probably remained a geographic high. Extension was paired with widespread, submarine volcanism, and the deposition of a thick sequence of volcanics and volcani-clastic sediments in the southern Alborz.

3) Around the Eocene-Oligocene boundary (34 Ma), deposition ended. The southern Alborz region emerged above sea level, and wide-spread erosion occurred. This was accompanied by subaerial volcanism, and the deposition of sediments in subaerial environments. The Alborz Mountains were established as a topographic feature.

4) Erosion diminished in the Early Miocene (after 23 Ma), and a regional transgression flooded central Iran and the southern fringe of the Alborz Mountains.

5) In the Middle Miocene marine deposition ceased, and subaerial erosion of the southern Alborz was renewed. A thick sequence of continental red beds was deposited along the southern edge of the mountain belt, but along the northern fringe, deposition occurred in a marine environment. In the interior of the mountain belt distributed volcanism occurred.

6) Neogene erosion of the Alborz Mountains was pulsed. Miocene deposits are topped by an erosional unconformity, and deposition renewed in the Pliocene. On both sides of the mountain belt this latest phase of deposition resulted in subaerial deposits, signalling emergence of the northern Alborz at this time. The two depositional domains were separated, by now, by a substantial and coherent mountain belt. Volcanic activity has shifted within the last few My from the west of the mountain belt to the centre-east.

In the next chapter, this stratigraphic record will be paired with the thermochronometric data presented in Chapter 2.

Rezaeian M., 2008, Coupled tectonics, erosion and climate in the Alborz Mountains, Iran. PhD thesis, University of Cambridge; 219 p.

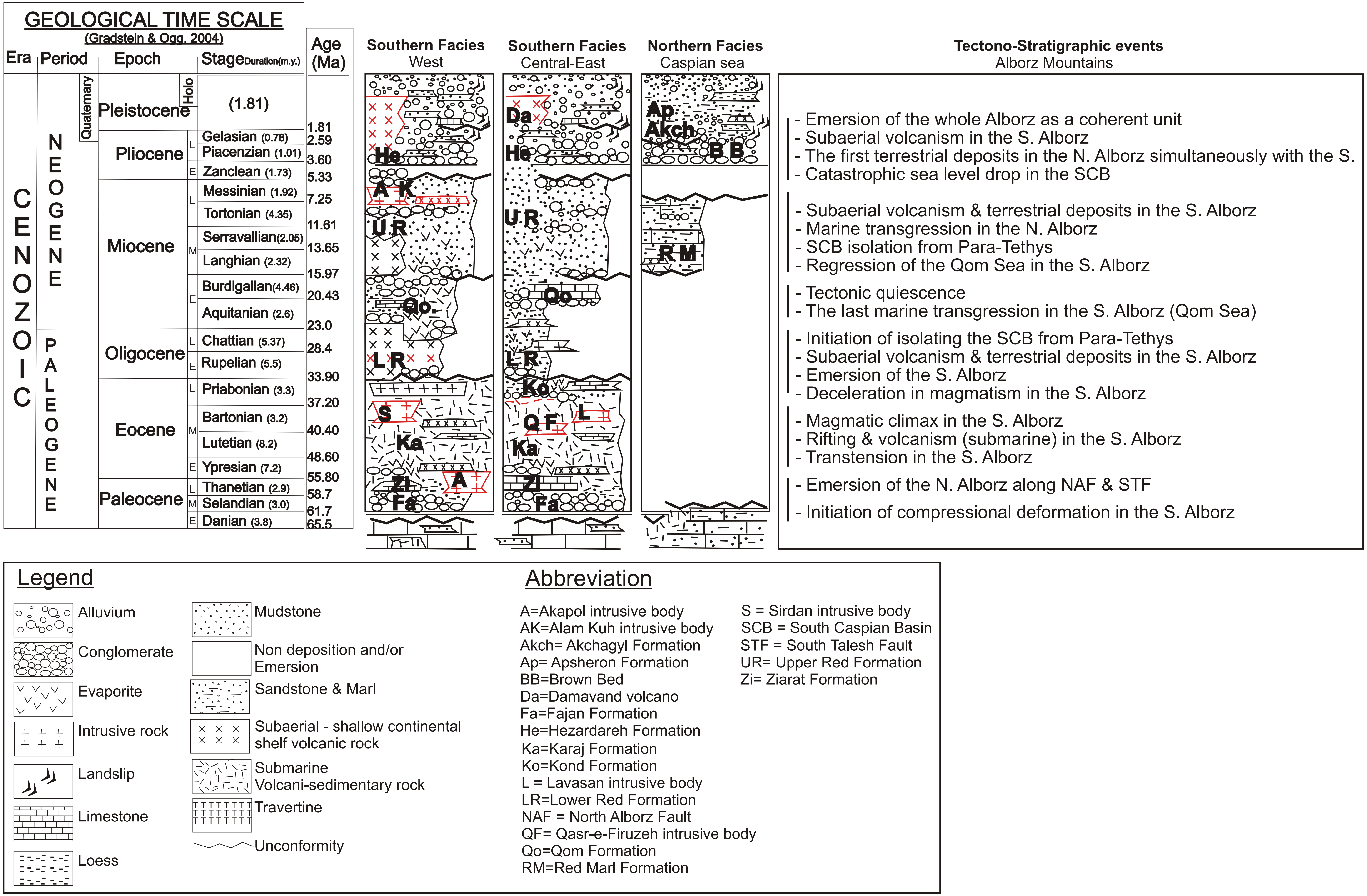

Plate 3.1: Generalised stratigraphic units summarised in main three tectono-stratigraphic collumns in the Alborz Mountains. Units with radiometric dates have been spotted in red.