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

4-1 Motivation

Thermochronometric and stratigraphic data presented in Chapters 2 and 3 provide independent constraints on the timing and nature of the tectonic and topographic evolution of the Alborz Mountains. The nature of the methods is different, and both have their limitations. Thermochronometry dates the cooling of rocks within deforming domains, but does not always permit a robust identification of the cause of cooling. Further, thermochronometric findings strictly apply to the location of sampling alone, although the mechanisms driving cooling have characteristic length scales that permit some extrapolation of dates and rates. Finally, it is difficult to reconstruct a full geological history from thermochronometric data that by definition only provide a snap shot. Stratigraphy does offer a more continuous perspective on the geological history of a region, limited only by the availability of accommodation space at the time of deposition, and outcrop at present. However, many coarse clastic deposits, normally associated with mountain building, are difficult to date, and it may not be possible to pin their source area with much precision. Crucially, the two methods are complementary, each covering the weaknesses of the other, but have sufficient overlap to permit a rigorous testing of results and interpretations.

The thermochronometric and stratigraphic approaches have revealed a series of geological 'events' that appear to have shaped the Alborz Mountains. In this chapter the two sets of results are combined, firstly to find the matches and conflicts, and secondly to reconstruct the Cenozoic history of the region. This history is the result of tectonic forcing, notably the closure of the Neo-Tethys ocean and the collision of Arabia and Eurasia, and the effects of climate. In this chapter the elements of the geological history of the Alborz Mountains will be identified, verified, and explained.

4-2 Geological history of the Alborz Mountains

4-2-1 Late Cretaceous compression and emergence

Along the northern fringe of the Alborz Mountains, thermochronometric evidence has been found of a cooling phase likely in the latest Cretaceous Maastrichtian, although uncertainties permit a younger date. GOR1 and GOR2 in the easternmost Alborz have bulk AFT ages of 66.6 ± 8.9 Ma and 70.2 ± 17.5 Ma (with a main age component ~68 Ma), thermal modelling indicates that FIR2 was exhumed primarily during the Late Cretaceous, and the AFT age population of MOR has a 67 Ma trace. These ages have been obtained from sedimentary rocks, and are unlikely to reflect magmatic cooling.

Meanwhile, in the south flank of the Alborz Mountains, the stratigraphy has recorded marine deposition during the Maastrichtian, possibly lasting into Danian times of the Early Paleocene. The associated limestones are truncated by an erosional unconformity throughout the region, and the overlying Fajan conglomerates of indeterminate age signal a switch to clastic sediment supply from a nearby, subaerial terrain.

It is likely that the regional erosion phase recorded in the stratigraphy of the southern Alborz is equivalent to the cooling of the north Alborz recorded by AFT. If this is true, then the cooling was caused by erosional exhumation in northernmost Iran, and resulted in coarse clastic deposition further south. The apparent discrepancy of stratigraphic and thermochronometric ages of this event is accommodated within the uncertainties of the individual constraints, which do not allow a more precise dating of this event in the Alborz.

The Late Cretaceous-Early Paleocene unconformity reaches beyond the southern Alborz, and is found throughout the greater part of central Iran. It has been interpreted to reflect compression and uplift of the Iranian Plateau, including the Alborz (Berberian & King, 1981; Berberian, 1983; Ziegler, 2001), coeval with the closure of some small oceanic basins further south in Iran, now preserved as Late Cretaceous ophiolite complexes. A paleo-geotectonic map of the Alborz at this time is displayed in Figure 4.1.

This early phase of shortening across Iran substantially pre-dates initial Arabia-Eurasia collision (Brunet & Cloetingh, 2003). Instead, it is likely to reflect the relative movement of smaller plates within Neo-Tethys, which was undergoing N-S compression at the time.

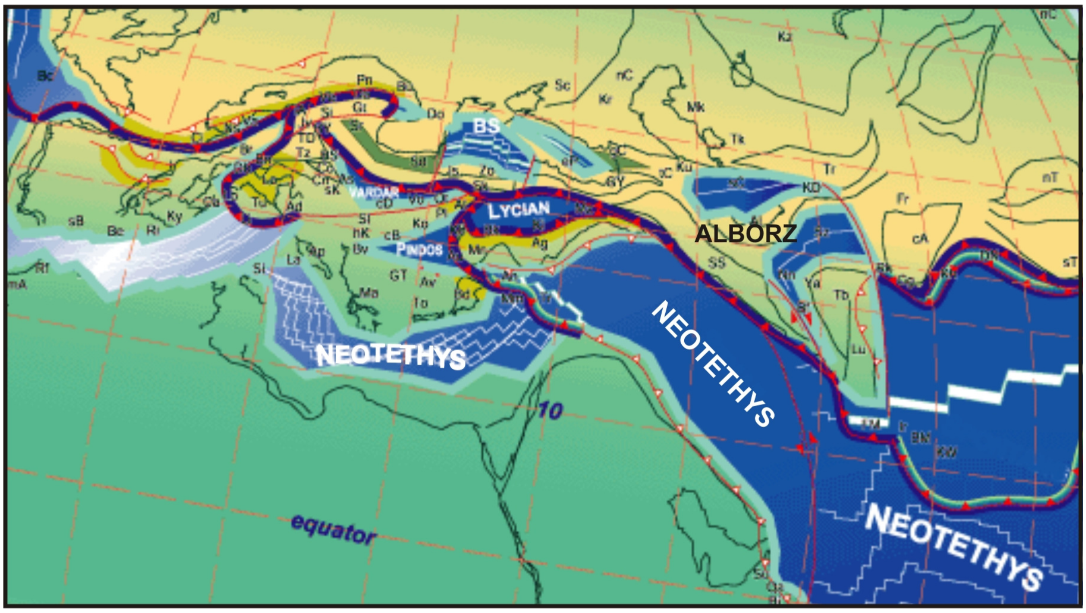


Fig. 4.1: Schematic paleo-geographic map of west-central Neo-Tethyan sea way in Maastrichtian (~69 Ma); red arrows indicate subduction zones and arc complexes in the sea way (Stampfli & Borel, 2003).

It is clear that a proto-Alborz Range had emerged by the Early Tertiary (*cf.*, Stocklin, 1968; Clark, 1975; Sussli, 1976). In fact, some workers have suggested that subaerial topography may have existed in the northern Alborz as early as the Middle Mesozoic (Sussli, 1976; Salehi Rad, 1979). This topographic barrier would have separated the South Caspian basin from central Iran, demarcating a boundary between the northern and southern domains of the Alborz (Stocklin, 1968). This boundary may have been located along the precursor of the North Alborz and South Talesh faults (Berberian & King, 1981) While the southern Alborz were transgressed after the Early Paleocene, the northern Alborz may have remained a land mass throughout the Paleogene (Sussli, 1976; Huber, 1977b).

4-2-2 Middle Eocene Magmatism

The stratigraphy of the southern Alborz reflects a return to marine conditions in the Paleocene, persisting throughout the Eocene. The deposits have a significant volcaniclastic component, from sources located within north Iran. The Middle Eocene was punctuated by the intrusion of plutons including the Tarom, Lavasan, and Qasr-e-Firuzeh intrusions with emplacement ages of 35-45 Ma. Magmatic activity appears to have been greatest in the western Alborz, and diminished toward the east.

AFT cooling ages of samples from granitoid plutons in the western Alborz peak at 39.1±2.7 Ma. There is close agreement between these ages and the emplacement ages determined by U/Pb and 40Ar/39Ar dating, implying that the AFT ages are for magmatic cooling.

Eocene magmatism was paired with transtension and subsidence across the southern Alborz. This created the accommodation space for several kilometres of Karaj Formation deposits. The thickness of this formation appears to decrease abruptly along the main divide of the Alborz mountains, and thermochronometric data from the northern Alborz indicates that a thick cover of Cenozoic sediments has not existed there at any time. It is likely that the paleo-high of the north Alborz was bounded to the south by an array of normal faults, aligned with the present Kandavan Fault system.

Eocene extension and magmatism reached beyond north Iran, affecting much of the region now occupied by the Pontides, Caucasus, Talesh and Iran Plateau. This region was located in the back arc of an active margin further south, where Neo-Tethys ocean crust was being subducted towards the north (Berberian & King, 1981). Vincent *et al.* (2005) have attributed the high rates of extension and magmatism in the Middle Eocene to rollback of the subducting slab. A reconstruction of the Mid-Eocene of the paleo-geographic situation of the Alborz is displayed in Figure 4.2.

4-2-3 Eocene-Oligocene Boundary: collision, compression and mountain building

The next peak of AFT ages is 31.7 ±1.3 Ma, coinciding approximately with the Eo-Oligocene boundary. Samples in this cluster are from pre-Tertiary (meta)sedimentary rocks and Tertiary granitoids, scattered throughout the Alborz. Although magmatic activity persisted through the Eocene and into the Neogene, there is no evidence of a pronounced pulse at this time.

In the southern Alborz, Eocene marine and marginal marine deposits of the Karaj and Kond Formations terminate in an erosional unconformity, overlain by a basal conglomerate, continental red beds of the Lower Red Formation, and subaerial volcanics. This is clear evidence of emergence of the Alborz, and substantial subaerial erosion, the timing of which is now constrained by AFT to around 32 Ma. Cooling of the rock mass at this time was caused by erosional exhumation.

The intensity and geographic extent of erosion in the Alborz around the Eocene-Oligocene transition, and the coarse nature of the associated sediments indicate the formation of subaerial topography with significant local relief. It is unlikely that this could have been caused by a eustatic sea level drop alone; implying that active uplift of the Alborz was the likely driver of erosion. The area affected by uplift may have coincided largely with the domain of Maastrichtian and Danian uplift in north Iran, but the modern Alborz Mountains originated around 32 Ma, and have been a topographic feature ever since.

The switch from transtension to compression in the Alborz around 32 Ma has a broader significance. It may have been caused by the onset of collision along the Bitlis-Zagros suture in the Turkish-Iranian Plateau (*e.g.*, Hessami *et al.*, 2001; Haq & Al-Qahtani, 2005; Vincent *et al.*, 2005; Agard *et al.*, 2008), after the last substantial piece of oceanic plate separating Arabia from Eurasia had been subducted (Allen & Armstrong, 2008). After collision, convergence between the two plates will have resulted in compressional deformation of the continental lithosphere, involving folding and thrusting and the construction of mountain belts. Another effect of collision was the segmentation of the Neo-Tethyan sea way. Figure 4.3 shows a map of the west-central Neo-Tethys in the Early Oligocene, when the Alborz Mountains started exhuming.

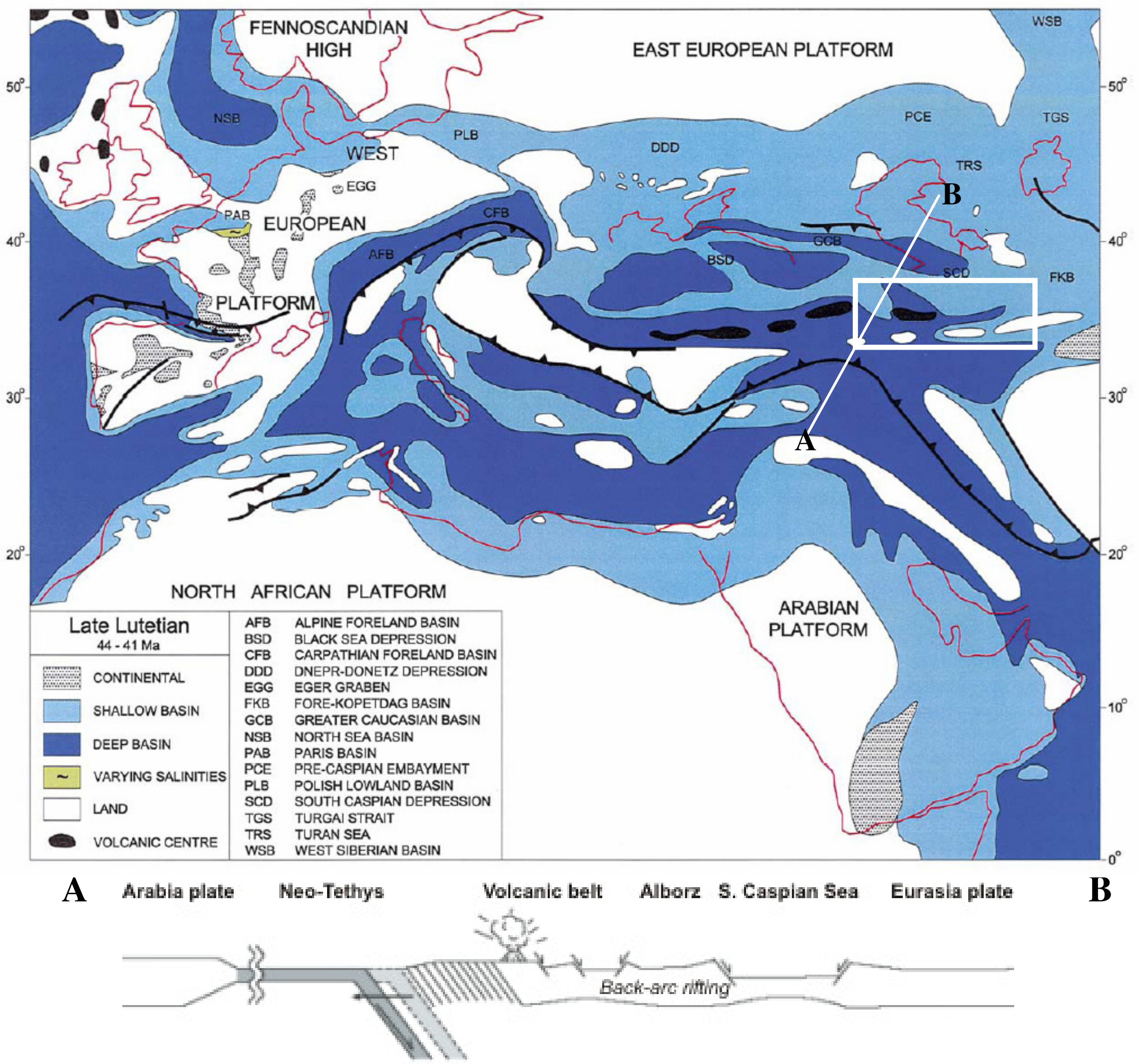


Fig. 4.2: Schematic paleo-geographic map of west-central Neo-Tethyan sea way and the geological cross section along the A-B (white line) in the Mid-Eocene (~44-41 Ma). The Alborz area is located in a white box in south of SCD (after: Meulenkamp & Sissingh, 2003). The cross section, showing the inferred rollback of the Neo-Tethyan subduction hinge-line and the consequent magmatism and extension (after: Vincent *et al.*, 2005).

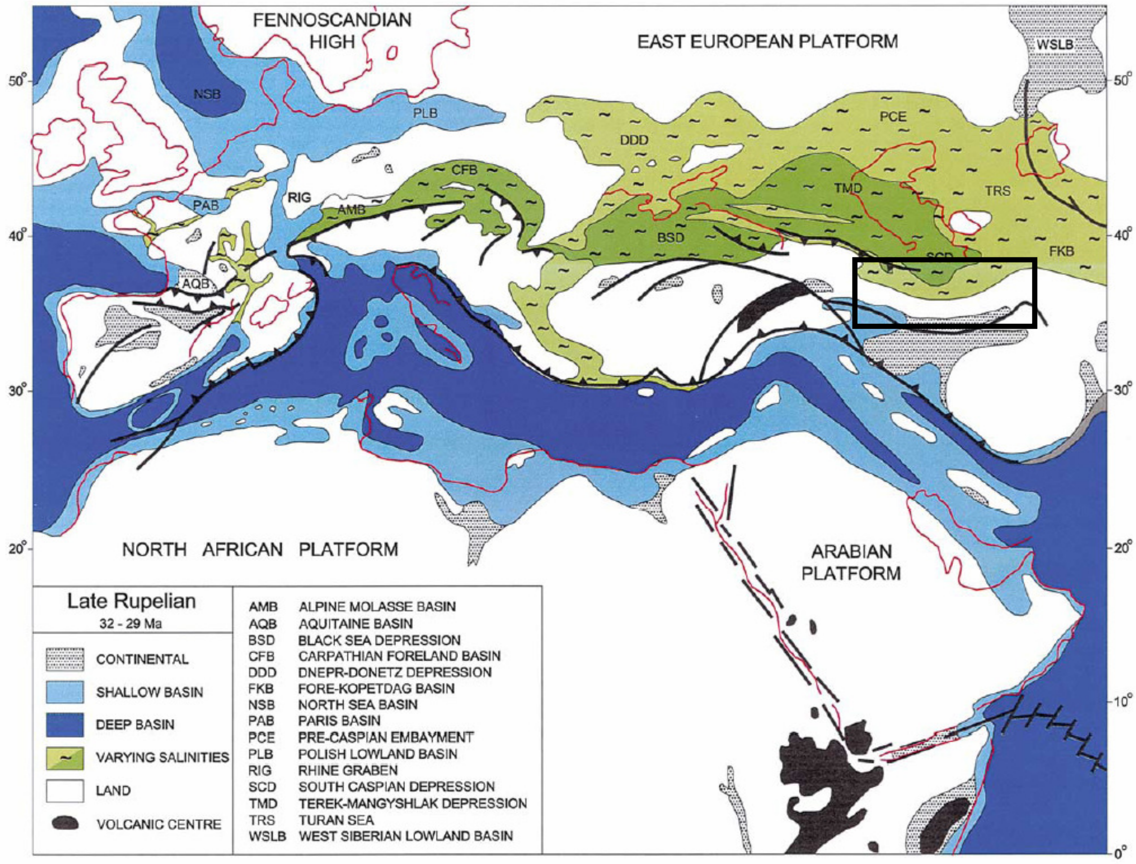


Fig. 4.3: Schematic paleo-geographic map of west-central Neo-Tethyan sea way in the Early Oligocene (~32-29 Ma). The Alborz area located in a black box in south of SCD (Meulenkamp & Sissingh, 2003).

4-2-4 Middle Miocene: accelerated erosion

Paucity of Late Oligocene and early Miocene AFT ages indicates that exhumation of the Alborz Mountains may have slowed down after the initial phase of mountain building. On the southern fringes of the mountain belt, and further south in the Iranian interior, a shallow marine carbonate shelf (Qom Formation) formed with limited clastic input from surrounding highs.

In the Middle Miocene, the northern edge of the Qom shelf became subaerially exposed, eroded, and covered by basal conglomerates of the Upper Red Formation shooting far out into the basin. The source of these conglomerates was located in the Alborz Mountains, where intramontane basins formed and filled with lacustrine, evaporitic and terrestrial deposits.

Rapid exhumation of the Alborz Mountains at this time is captured by a strong cluster of AFT ages at 15.78±0.58 Ma, located mainly in the south flank of the central Alborz, and along the main divide of the central and western part of the mountain belt.

The northern edge of the mountain belt was defined by the North Alborz Fault. Across this boundary, red marls were deposited in a subsiding basin, reflecting deep weathering and soil erosion further south.

There is no evidence that the rate of convergence between Arabia and Eurasia has varied significantly within the Miocene (McQuarrie *et al.*, 2003) (Fig. 4.4). Thus, subdued erosion of the Alborz during the Early Miocene, and subsidence and transgression of the Iranian interior can not be attributed to an overall tectonic slow down. Instead, these events must be explained within the context of sustained shortening across the Turkish-Iranian Plateau.

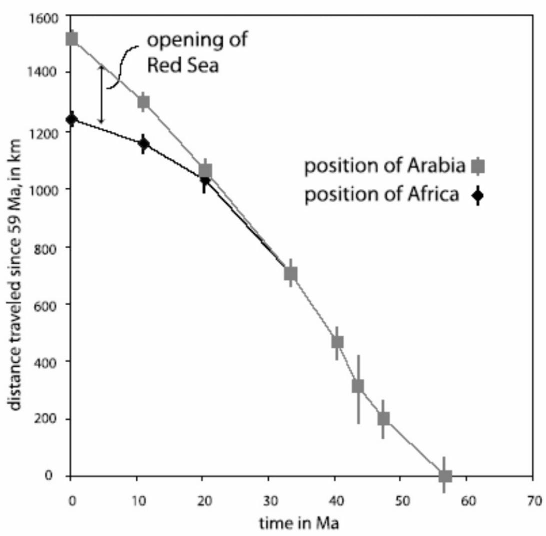


Fig. 4.4: Motion of Arabia and Africa relative to Eurasia since 56 Ma, indicating separation of Arabia from Africa and associated extension in Red sea initiated in Early Miocene (~20 Ma) (McQuarrie *et al.*, 2003).

Distinct phases of mountain building may be due entirely to internal restructuring as mass accumulates within the deforming domain, rather than to varying external conditions (*e.g.*, Toussaint *et al.*, 2004). Alternatively, active deformation may have relocated within the broad domain affected by Arabia-Eurasia convergence, which extends from the central Caspian Apsheron sill to the Zagros suture (Fig. 1.4 & 1.6). However, neither explanation accounts for the transgression of central Iran, which must have involved active subsidence. It is possible that this was related to the rotation and putative break off of the subducted Neo-Tethian slab after collision, involving patterns of mantle flow that could give rise to localised uplift as well as subsidence (*cf.*, Davies & von Blanckenburg, 1995; Regard *et al.*, 2003, 2008). A tomographic study has yielded tentative evidence for the presence of a detached slab fragment below Turkey in the Late Miocene (Faccenna *et al.*, 2006), but it did not reach into Iran. Although a significant amount of Neo-Tethyan lithosphere must have been subducted under Iran, its fate remains unknown.

Irrespective of the direct cause of renewed erosion and exhumation of the Alborz around 16 Ma, it is thought to be around this time that the ocean basin remnants to the north of the Turkish-Iranian Plateau had become fully isolated from the larger Neo-Tethyan fragments further south, and the Caspian Sea was identified, for the first time, as a separate entity. Moreover, from this time the proto-Mediterranean region to the west and the proto-Arabian Sea to east have had separate and distinct paleo-biological populations, indicating that hydrological connectivity between these basins no longer existed. The location of the Alborz in the west-central Neo-Tethyan sea way in the Early and Late Miocene is displayed in Figure 4.5.

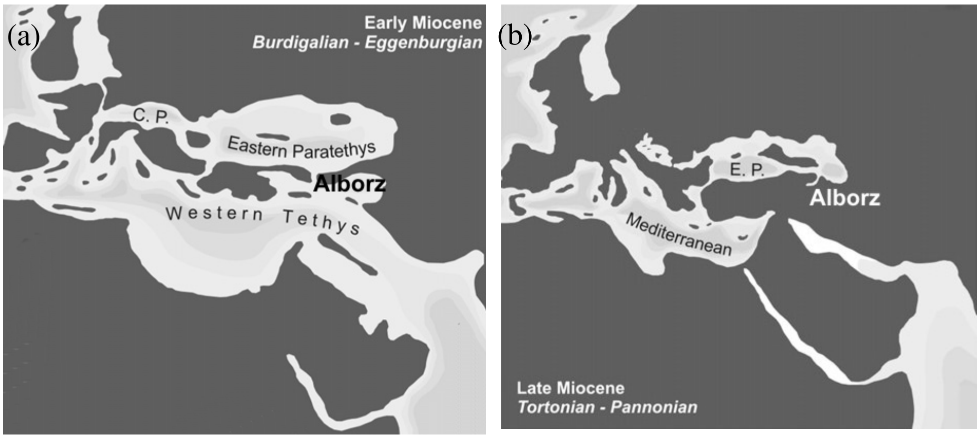


Fig. 4.5: Schematic paleo-geographic maps of west-central Neo-Tethyan sea way in (a) the Early and (b) Late Miocene. The marginal sea of Para-Tethys consists of western, central and eastern segments located in the northern part of Tethys. The present day Black Sea and the Caspian Sea are remains of the eastern Para-Tethys (Vasiliev *et al.,* 2004; Harzhauser & Piller, 2007).

4-2-5 Plio-Pleistocene: accelerated erosion, again

The absence of a substantial number of AFT ages younger than 12 Ma is due entirely to the relatively slow pace of shortening and exhumation across the Alborz Mountains. However, the ultra-low temperature thermochronometer AHeFT has revealed a distinct cooling phase around 4.4 ± 0.04 Ma, which appears to be separated from the earlier, Middle Miocene cooling phase by a period of slower exhumation.

This latest phase of rapid exhumational cooling is recorded in the stratigraphy as an erosional unconformity at the top of the Upper Red Formation in the southern Alborz, and the Red Marls in the northern Alborz. Above this unconformity, a km thick sequence of coarse Hezardareh conglomerates signal intensified erosion of a steep topography in the south flank of the mountain belt, while the coarsening of deposits is even more profound along the northern edge of the Alborz, where conglomeratic Brown Beds were deposited. There, this most recent phase of erosional exhumation has been accompanied by an outward migration of the deformation front, manifest in the (re)activation of the Khazar Fault. Geological units between the current deformation front and the North Alborz Fault were a part of South Caspian rigid block until this structural reorganization, and have not been uplifted and exhumed enough for their apatite fission tracks to be reset.

Again, there does not appear to be a direct tectonic cause of intensified erosion of the Alborz Mountains in the Pliocene-Pleistocene. Instead, this increase appears to be part of a global pattern, which will be discussed in more detail in the next section.

4-3 Synchronous Erosion of Mountain Belts along the Eurasian Margin

The Alborz Mountains are a central link in a long chain of mountain belts along the active, southern margin of Eurasia. From the Pyrenees in the west to the Himalayas in the east these mountain belts have formed because of the closure of the Neo-Tethys Ocean and subsequent continent-continent collision during the Cenozoic. Two mountain belts have received special attention. They are the Alps and the Himalayas. The stratigraphic and exhumational histories of these mountain belts have been documented in considerable detail. In this section, published Alpine and Himalayan records will be compared with the Cenozoic history of the Alborz Mountains as established in this thesis.

Perhaps the most authoritative and complete reconstruction of the erosion of the Alps is due to Kuhlemann *et al.* (2002), who have calculated the sediment flux from the mountain belt in km^3 /my from the stratigraphy of surrounding basins (Fig. 4.6). The same approach has been used by Clift (2006) to estimate Cenozoic erosional fluxes from rivers in east Asia with headwaters in the Himalayas (Fig. 4.7).

Unfortunately, there are insufficient constraints on the fill rates and total volumes of sediment in basins around the Alborz for this method to be practical. The alternative is to compare the probability distributions of thermochronometric ages. However, orogen-wide compilations of cooling ages were not available for the Alps and Himalayas at the time of writing, although Vernon and colleagues (2008) have produced relevant maps for the Alps. Kuhlemann *et al.* (2006) have revealed synchronised peaks of exhumation rate and volume estimates of the Eastern and Western Alpine-derived sediments in the Mid-Miocene. A full literature review is beyond the scope of this thesis. A direct comparison of equivalent data sets for these three mountain belts is therefore not possible. Instead, the thermochronometric record of exhumation of the Alborz has been juxtaposed with the stratigraphic records of the Alps and Himalayas. Whilst the Alpine record is widely used and proven to be robust, its Himalayan counterpart is less complete and open to debate. For example, Clift has not included the Bengal Fan in his flux estimates, and there are many sediment traps and sources between the Himalayas and the basins he has studied. Strictly speaking, Clift's record is not for the Himalayas, but for large river basins in east Asia that happen to get much of their sediment from that mountain belt.

It appears that three main phases of erosional exhumation are shared between the Alps, the Alborz, and the Himalayas/east Asia

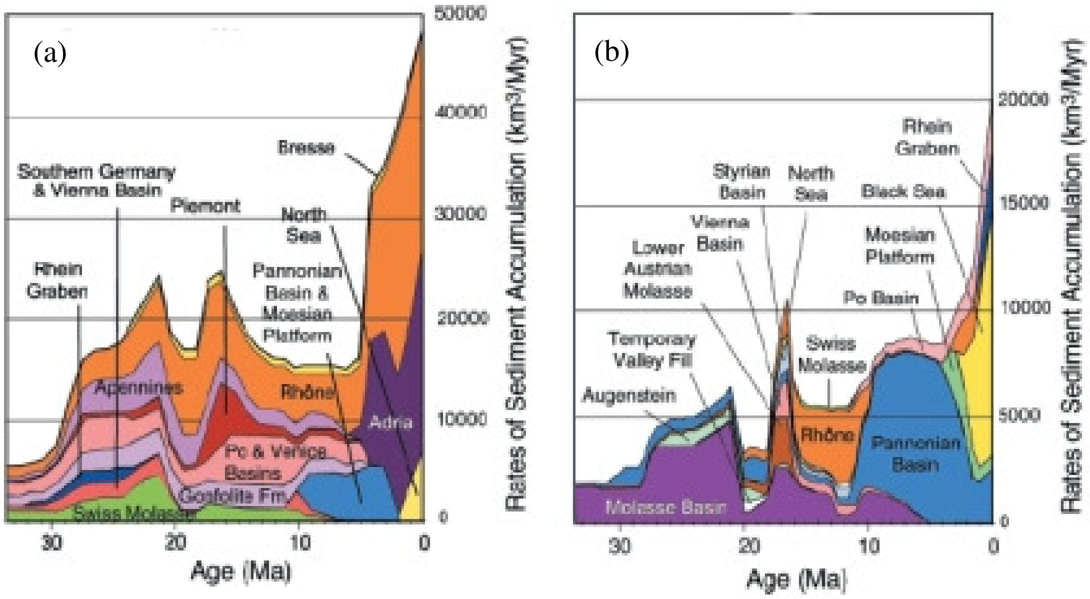


Fig. 4.6: Sediment budgets for (a) western Alps, and (b) eastern Alps summed by considering the basins in which the eroded material was deposited (Kuhlemann *et al*., 2002; redrawn by Molnar, 2004)

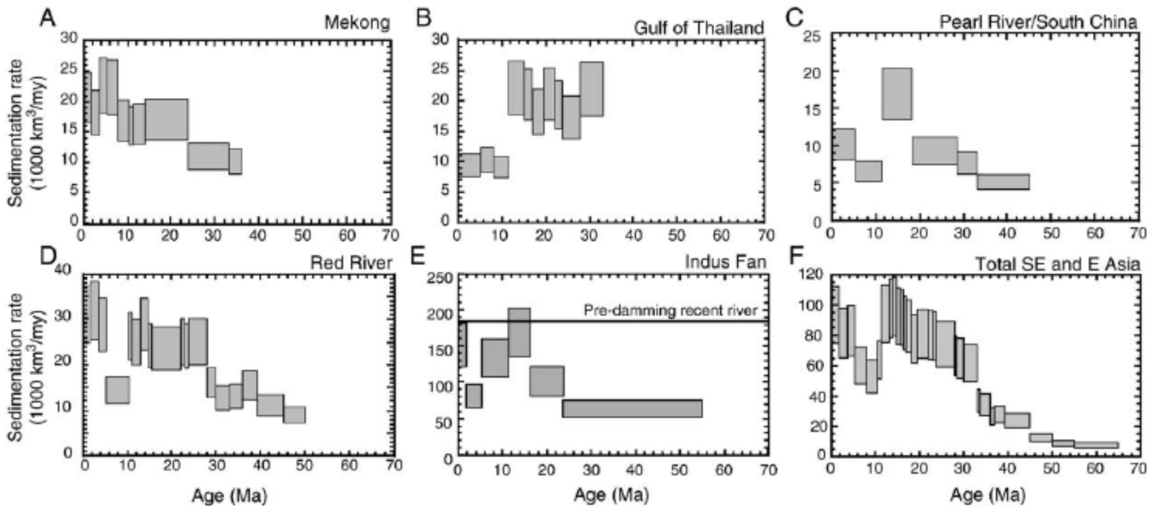


Fig. 4.7: Sediment budgets for five major basin systems of Asia (A) Mekong/Nam Con Son Basin, (B) Gulf of Thailand/Pattani, Malay, West Natuna Basins, (C) South China margin/Pearl River Mouth Basin, (D) Red River/Yinggehai-Song Hong Basin, (E) Indus Fan, and (F) the integrated sediment budget for all these basins, representing the net flux of material from Asia into the marginal seas (Clift, 2006).

4-3-1 Late Eocene-Early Oligocene

After a period of magmatic activity and sporadic erosion, the first phase of mountain building and erosional exhumation occurred in the Alborz ~32 Ma.

In the Alps, initiation of the North and South Alpine Foreland Basins (NAFB and SAFB) is constrained by the Rupelian (33.9-28.4 Ma) molasse (Schlunegger, 1999), whilst inside the orogen a major phase of thrusting was accompanied by wide spread, high pressure metamorphism (Schmid *et al*., 1996).

Initiation of erosion and exhumation of the Alps in the Early Oligocene has been attributed to the pop up of a central domain between pro- and retro-thrusts (Sinclair & Allen, 1992).

Onset of mountain building in the Himalayas significantly predates orogenesis in the Alps and Alborz, but Clift (2006) has found a doubling of the total sediment flux from east Asia around 32 Ma (Fig. 4.7). At first glance this is a striking coincidence with findings further west, but many individual basins in southeast Asia do not have a strong signal at 32 Ma. The exception is the Gulf of Thailand and Pearl river in south China (Fig. 4.7b & c), where the sedimentary record starts at this time, and this is the principal component of the jump in sediment flux at the Eocene-Oligocene boundary.

4-3-2 Middle Miocene

Oligocene and Early Miocene sedimentation trends in the Alps and east Asia follow remarkably similar patterns, climbing gradually to a subdued peak at 22-20 Ma, before dipping. This pattern is not shared with the Alborz Mountains, where erosional fluxes appear to have been limited throughout the period. However, all three regions share the next event, which is the Middle Miocene erosion maximum. In the Alborz Mountains, this maximum is dated at 15.78±0.58 Ma. In the Alps a brief but pronounced maximum occurred around 18-16 Ma, while in east Asia, sediment flux peaked around 16 Ma in three separate, major basins of the Indus, Red and Pearl rivers. The Mekong basin had a lesser flux peak (4.7a). Sparser data from elsewhere suggest that sedimentation rates may have increased globally at ~15 Ma (Molnar, 2004).

4-3-3 Pliocene-Quaternary

Globally, and corrected for preservation potential, the sediment flux from continents into the oceans has been three times greater in the last five million years than at any other time in the Cenozoic (Hay *et al*., 1988; Zhang *et al*., 2001). This is mirrored in each of the three mountain regions. In the Alborz Mountains, AHeFT cooling ages cluster around 4.4 ± 0.04 Ma, indicating that exhumation rates increased in the Middle Pliocene and have remained high since then. In the Alps, sediment supply rates to peri-Alpine basins have soared since ~6 Ma. Sediment fluxes from east Asia may have dipped to Oligocene levels in the Late Miocene, but since climbed back to Middle Miocene peak values, driven principally by high transport rates in the Indus, Mekong and Red River.

The erosional histories of the Alps, Alborz and Himalayas/east Asia show a significant degree of synchrony, when considered at the regional level. In particular, it appears that there is much overlap between times of enhanced erosion and exhumation of the Alborz Mountains and the Alpine and Himalayan main stays of the Neo-Tethyan belt. Although all three mountain areas are located along the active southern margin of Eurasia, they are the products of convergence and collision with three separate plates. Whilst tectonic processes have driven mountain building, it is unlikely that the choreography of African, Arabian and Indian plate motion has produced the apparent synchrony of exhumation along the entire active margin. Moreover, even within individual mountain belts, variations in the rate of erosional exhumation do not necessarily coincide with changes in tectonic forcing (section 4-2). In contrast, climate has undergone a series of strong, global changes, capable of affecting the style and rate of surface processes simultaneously in different locations. Have these changes played a role in the pulsed erosion and exhumation of mountain belts along the Eurasian margin?

4-4 Tectonics, Global Climate and Erosion

Plate tectonics and global climate are interrelated; however, specific cause-and-effect relationships and the relative importance of different processes are controversial. The continent-ocean configuration and the flow of air through vertical uplift are set up by plate tectonics. Opening and closing of ocean gateways change the global circulation of water, and reorganize ocean heat transport and air-sea interactions. Mountain building can change air flow in the atmosphere as a result of the relations between air temperature, pressure, and water vapour pressure; but tectonics can also affect the net atmospheric water balance by changing the proportion of oceans located within the tropics and subtropics versus higher latitudes. Similarly, mountain building and plateau uplift affect the climate by blocking and deflecting the flow of air, changing the regional radiation balance and enhancing seasonality, which may ultimately result in an increase of the global contrast between high- and low-pressure systems. Moreover, increased efficiency of silicate weathering caused by tectonically driven erosion can change the alkalinity and major element content of the oceans to affect atmospheric CO2 levels, presumably on longer timescales. Also, volcanic activity and metamorphic outgassing in response to plate tectonic processes is the major long-term source for CO2 (*e.g.*, Raymo *et al.*, 1988; Molnar & England, 1990; Raymo & Ruddiman, 1992; Hay, 1996; Lyle *et al.*, 2008).

A multitude of investigations of past climate oscillations in Cenozoic is providing a growing pool of high resolution paleo-climate records in global scale, in which uncertainties in dating most of marine records are < 2 Myr. Nevertheless, little information on the Cenozoic evolution of spatial patterns of climate on the continents is yet available, due to the lack of constraints on the timing and magnitude of terrestrial events. Moreover, the links between climate and erosion are complex. The following discussion is, therefore, exploratory in nature.

The Cenozoic is characterized by a stepped, long-term fall in global sea levels and temperature following the demise of the greenhouse world in the Eocene. This broad pattern is overlain by the effects of diachronous mountain building, high-frequency and high-amplitude changes in polar glaciation and the repeated development of continental icesheets in sub-polar areas of the northern and southern hemisphere.

Since the mid-1970s (Kennett & Shackleton, 1976), oxygen isotope records harvested from benthic foraminifera have been used to document the combined evolution of global ice volume and deep-sea temperatures. From these records, three episodes of rapid cooling and eustatic sea level change have been identified: the Eocene/Oligocene transition, Middle Miocene, and the Plio-Pleistocene (Zachos *et al.*, 2001; Miller *et al.*, 2005) (Plate 4.1). Superficially, there is a remarkable coincidence of global climate change and enhanced erosion and exhumation in active Eurasian mountain belts.

The Eocene-Oligocene transition (*ca.,* 34 Ma) was the most profound oceanographic and climatic change of the past 50 My. It represents the transition from a "greenhouse" world to the present-day "icehouse" world. A rapid 1.5 per mil $\delta^{18}O$ increase around 34 Ma has been recorded throughout the Atlantic, Pacific, Indian, and Southern Oceans. It is interpretated to signal the onset of permanent Antarctic ice sheets, and may have been accompanied by a eustatic sea level drop of as much as 100-125 m (Tripati *et al.*, 2005).

At this time, global atmospheric temperatures fell dramatically. In continental North America, for example, mean annual temperatures may have dropped by 8.2 ± 3.1°C within 400,000 years (Eldrett *et al.*, 2007). Although Clift *et al.* (2006) have speculated about a strengthening of the Asian monsoon around 33 Ma, the Asian continental interior underwent a marked aridification around this time, recorded in the demise of playa environments, an increase of arid-adapted plant taxa, and an abrupt faunal turnover from large Eocene species to small Oligocene species dominated by rodents (Dupont-Nivet *et al.*, 2007). The faunal turnover is a global phenomenon, known as the Grand Coupure (Stehlen, 1910), which has been linked specifically with lowering of winter temperatures (Ivany *et al.*, 2000). This lowering and its importance are perhaps best illustrated in a study by Mosbrugger *et al.* (2005), using pollen records to quantify changes of mean annual temperature (MAT), warmest month mean temperature (WMM) and coldest month mean temperature (CMM) in central Europe, north of the Alps. In this region, MAT dropped by an estimated 3°C through the Eocene-Oligocene transition, and WMM by less, but CMM decreased by about 8°C (Fig. 4.8).

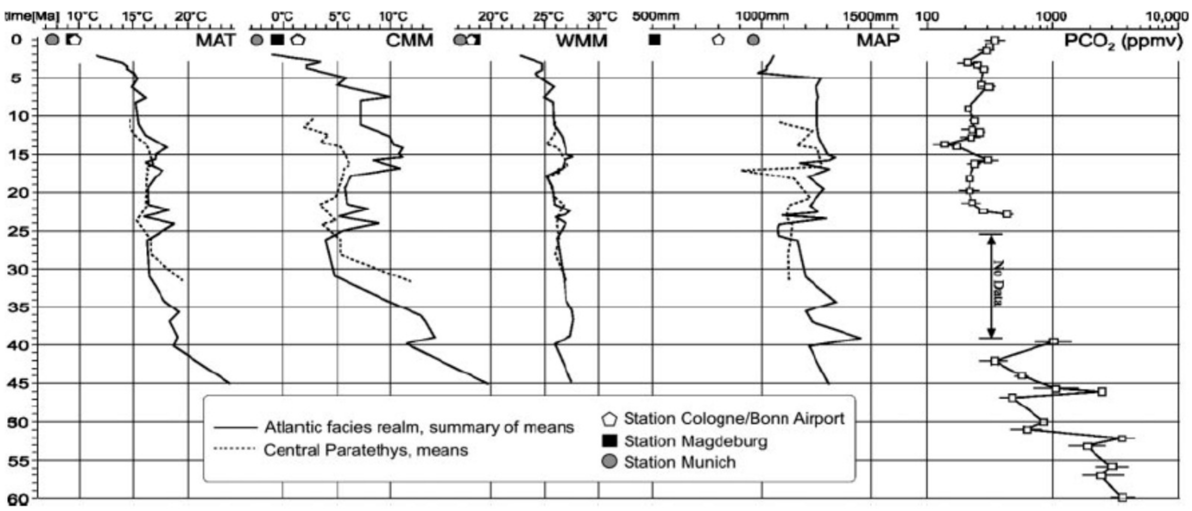


Fig. 4.8: Climate records for the Atlantic realm (northeast and northwest Germany) and the Para-Tethys. All of the continental curves are tentatively interpolated, using the means of coexistence intervals. Present climate data for the different regions are indicated by CMM = cold month mean; MAP = mean annual precipitation; MAT = mean annual temperature; WMM = warm month mean (Mosbrugger *et al.*, 2005**).**

The ensamble of changes has been attributed to the progressive narrowing of the Neo-Tethys sea way (Allen & Armstrong, 2008) at low latitude and the establishment and strengthening of circum-Antarctic sea water flow, while the attendant lowering of the calcite compensation depth indicates a reduction of atmospheric CO2 concentrations at this time (*e.g*., Shackleton & Kennett, 1975; 1976; Miller *et al.*, 1987; Zachos *et al*., 2001; Coxall *et al*., 2005; Scher and Martin, 2006; Miller *et al*., 2008).

It is clear that the eustatic sea level drop around 34 Ma will have caused exposure of erodible continental shelf deposits, and may have resulted in a wave of erosion migrating inland from coast lines. However, it is unlikely that this has driven substantial exhumation of the internal parts of mountain belts. Changes in the variability, seasonality and extremes of precipitation and temperature are more likely drivers of this exhumation. The grand change of global climate at the Eocene-Oligocene boundary has undoubtedly been accompanied by shifts in attributes of climate that affected continental erosion. There is an indication that increased seasonality and substantially colder winters were a key feature of the climate change. However, these shifts have not yet been quantified in the detail required for a robust, mechanistic explanation of synchronous exhumation of mountain belts around the epoch boundary.

It should be noted that increases in the sediment flux from east Asia and the Alps, and exhumation of the Alborz Mountains may post-date the Eocene-Oligocene transition by a few My. This could be due to the landscape response time to climate forcing, or to the gradual establishment of a more erosive set of climate conditions within the Oligocene.

Following the cooling and rapid expansion of Antarctic continental ice sheets in the earliest Oligocene, deep sea $\delta^{18}O$ values remained relatively high (>2.5‰), indicating permanence of an ice sheet with a mass as great as half that of the present-day ice sheet and ocean bottom water temperatures of ~4°C. These conditions persisted throughout the Oligocene, after which a warming trend reduced the extent of Antarctic ice. This warming trend culminated in the Middle Miocene climate optimum (MMCO), 17-15 Ma, and was followed by gradual cooling and reestablishment of a major ice sheet on Antarctica by 10 Ma (Zachos *et al.*, 2001; Miller *et al.*, 2005). Globally, sedimentation rates increased at ~15 Ma, approximately when oxygen isotopes in benthic foraminifera imply high-latitude cooling and expansion of the Antarctic ice sheet (Molnar, 2004). However, peaks of erosion and exhumation in the Alps and Alborz and likely the Himalaya/east Asia predate the global cooling, coinciding, instead, with the MMCO.

In central Europe, the MMCO had slightly elevated MAT and WMM compared to the preceeding period, while CMM had increased by approximately 5°C, reaching Eocene levels in places (Mosbrugger *et al.*, 2005). It is possible that mean annual precipitation had also increased to a Neogene maximum by the Middle Miocene, but ectothermic vertebrate systematics indicate that the period 16.3- 15.7 Ma had a marked increase of the seasonality of precipitation with long dry seasons (Böhme, 2003). This effect has been attributed to the tectonic closure of Para-Tethyan basins.

By 16 Ma, the main Neo-Thethys seaway had also been closed and Arabia and Iran were joint together. The timing of this event is constrained by the separation of the marine faunal communities of the Mediterranean Sea and the Indo-Pacific Ocean (Schuster & Wielandt, 1999; Harzhauser *et al.*, 2002; 2008). It is likely that the water vapour flux from the south into the interior of Iran diminished as a result, and this may have caused aridification in the Alborz at a time when conditions elsewhere were more humid.

However, it must be kept in mind that at present, the dominant air flow into the Alborz is from the north and west. If this was also the case in the Middle Miocene, then reduction of sea surface area to the south will have been of little consequence.

In east Asia, climate records from the South China Sea show a shift to a wetter climate prior to 15 Ma (Jia *et al.*, 2003), possibly associated with a strengthening of the summer monsoon. This is also reflected in the clay mineral statistics of deposits in the Pearl River basin, where a shift from wet, hematite-dominated weathering, to dryer, goethite-dominated weathering occurred shortly after 15 Ma. Sediment fluxes in east Asia decreased markedly after the MMCO, indicating that precipitation was a primary control on erosion in the Miocene (Clift, 2006). This finding applies also to the European Alps, but can be confirmed nor denied for the Alborz Mountains.

Mean $\delta^{18}O$ values continued to rise gently through the Late Miocene until the Early Pliocene (6 Ma), indicating gradual cooling and limited ice sheet expansion on west Antarctica and in the Arctic. The Early Pliocene was marked by a subtle warming trend until about 3.6-3.2 Ma, when $\delta^{18}O$ again increased reflecting the onset of substantial northern hemisphere glaciation, in response to closure or opening seaways, and the consolidation of full icehouse thermohaline circulation in the Atlantic Ocean. From then, ice sheet volume, sea level, and atmospheric temperatures have fluctuated significantly on time scales of orbital forcing (23 kyr, 41 kyr, 100 kyr and 400 kyr) (*cf.*, Zachos *et al.*, 2001; Lyle *et al*., 2008).

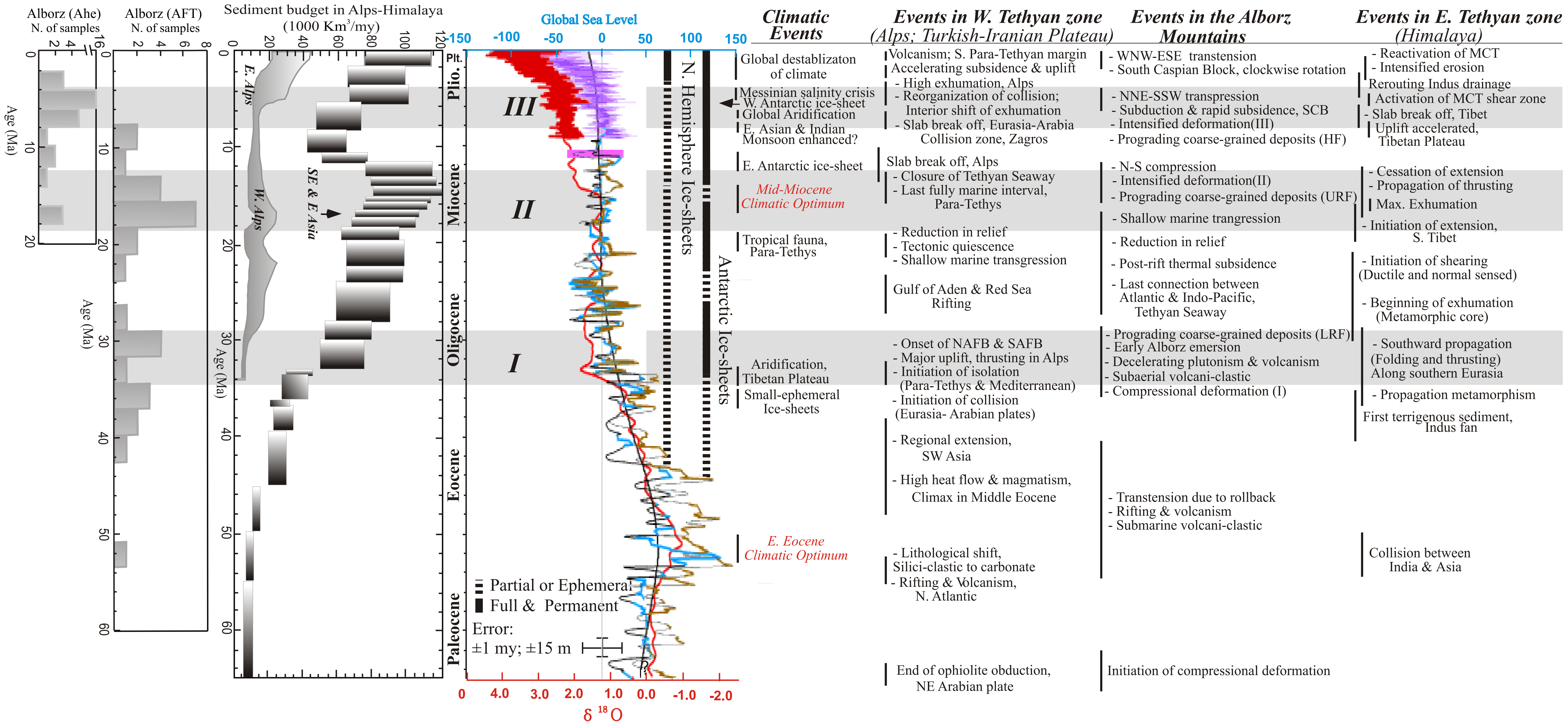
Paired with these developments was a global expansion of C4 vegetation in the Early Pliocene (4-8 Ma), manifest in the replacement of mixed needle-leaf and broad-leaf forests by grasslands, signalling an increased seasonality of precipitation and atmospheric temperatures (Manabe & Broccoli, 1990; Cerling *et al.*, 1997; Ramstein *et al.*, 1997; Ma *et al.*, 1998; Ivany *et al.*, 2000; An *et al.*, 2001; Guo *et al.*, 2002; Jia *et al*., 2003; Molnar, 2005; Dupont-Nivet, 2007). Conditions generally became more arid, as reflected in a shift to arid-adapted faunal assemblages (Cerling *et al.*, 1997; Pagani *et al.*, 1999; Lyle *et al*., 2008). Since the Late Pliocene conditions have oscillated between glacials with strong seasonal variability and very cold winters, and interglacials with less seasonal variability and milder winter temperatures. Glaciers are thought to be effective erosive agents (Hallet *et al.*, 1996), while physical weathering in periglacial environments is also held responsible for high Quaternary erosion rates.

Notably, the global increase in continental erosion, seen in each of the three mountain belts discussed here, started before the Late Pliocene. It is evident that glacial and periglacial processes have driven rapid erosion of the Alps and Himalayas during the Quaternary. But it may have been the shift to C4 vegetation, and an increased frequency of erosive rainstorms and floods that caused increased erosion in the warmer period before the onset of climate oscillation. Increased erosion of the Alborz Mountains from the Middle Pliocene must be seen in this context, with the caveat that evidence of glacial processes is limited to the highest portions of the mountain belt.

4-5 Conclusion

Three main phases of erosional exhumation of the Alborz Mountains during the Neogene have coincided approximately with enhanced erosion in the Alps and Himalayas/east Asia (Plate 4.1). Although long-term mountain building and exhumation in each of these mountain belts is driven by compression and collision along the active, southern margin of Eurasia, it is unlikely that synchrony of erosion in three separate orogens is due to tectonic forcing. Global climate changes may have been a more likely driver. Each of the erosion phases was associated with special climate conditions. Rapid erosion around the Eocene-Oligocene boundary followed the first dramatic deterioration of the Cenozoic climate, with especially fierce drops in winter temperatures. Rapid erosion also occurred during the Middle Miocene climate optimum, with warm, humid conditions and enhanced monsoonal activity. Finally, erosion rates increased again when the climate became dryer and more seasonal in the Early Pliocene, and during the subsequent oscillations of Late Pliocene and Quaternary glacials and interglacials. From this, it is clear that there has not been a single, repeating cause of enhanced erosion along Eurasia's active margin. Instead, lower winter temperatures, increased aridity, increased storminess and flooding, increased precipitation, increased glaciation, and a change from forest to grassland have all contributed at times to the erosional exhumation of mountain belts. It is likely that this complexity has applied to the Alborz as much as to the Alps and Himalayas.

Given the multitude of possible climatic and climate-related controls on erosion rate, it may not be a surprise that the exhumation pattern across the Alborz conflicts with expectations based on the pattern of precipitation. In geodynamic models, erosion is often set as a function of the local precipitation, and the discharge from upslope. Following this reasoning, the north flank of the Alborz, which has consistently received water vapour from the adjacent Caspian basin, would be expected to have been the focus of exhumation. Thermochronometric and stratigraphic data presented in this thesis conflict with this expectation, and indicate instead that erosional exhumation was located in the drier interior and south flank of the mountain belt. Past climatic conditions are not known in sufficient detail to explain this. In the next chapters, short-term observations will be used to uncover the key controls on the erosion of the Alborz Mountains.



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

Plate 4.1: Reconcile exhumation pulses in the Alborz with global cooling and sediment discharge in Alps-Himalayan orogen. Sea level curve in blue (*Miller et al., 2005*), in brown (*Kominz et al., 2008*). Red oxygen isotopic curve (*Miller et al., 2005*). Depositional phases in Alps (*Kuhlemann et al., 2002*), in Himlaya (*Clift, 2006*). AFT, AHe, HF, LRF, MCT, NAFB, SABF, SCB, and URF stand for Apaptite Fission Track, Apatite U-Th/He, Hezardareh Formation, Lower Red Formation, Main Central Thrust, North Alpine Foreland Basin, South Alpine Foreland Basin, South Caspian Basin, and Upper Red Formation. Three phases of regional compressional deformation (*I, II, III*) are displayed.
Climatic and geo-tectonic events summerized from: *Allen et al., 2002, 2003, 2004; Argard et al., 2008; Axen et al., 2001; Ballato et al., 2008 ; Berberian & Berberian, 1981; Cerling et al., 1997; Clift & Blusztajn, 2005; De Celles et al., 2000; Dupont-Nivet et al., 2007; Egger et al., 2002; Golonka, 2004; Guest et al., 2007; Haq & Al-Qahtani, 2005; Harangi et al., 2007; Harrison et al., 1997; Harzhauser & Piller, 2007; Hessami et al., 2001; Hsu et al., 1973; Huntington et al., 2006; Jackson et al., 2002; Kempf & Pfiffner, 2004; Kuhlemann et al., 2002; Lyle et al., 2008; Moran et al. 2006; Najman, 2006; Oczlon, 2006; Popov et al., 2006; Qiang et al., 2001; Reynolds et al., 1998; Ritz et al., 2006; Rogl, 1999; Schlunegger, 1999; Schmid et al., 1996; Schulz et al., 2005; Sinclair & Allen, 1992; Smith-Rouch, 2006; Szulc et al., 2006; Thomas, 2008; Tripati et al., 2008; Vincent et al., 2005; White et al., 2002; White, 2002; Willett et al, 2006; Williams et al., 2004; Williams et al., 2001; Zachos et al., 2001; Zheng et al., 2004.*