# Chapter 1

## Introduction

### *1.1. Introduction*

Most of Iran is arid or semi-arid with annual precipitation averaging about 240 mm or one-third of the world average (one-third of all precipitation in Iran occurs in the Caspian Sea region in the north). Iran's land surface covers 165 million hectares, more than half of which is not appropriate for cultivation. A total of 11.5 million hectares is under cultivation at any time, of which 3.5 million hectares were irrigated in 1987, and the rest watered by rain (U.S.Library of Congress, 1987). Only 10 percent of the country receives adequate rainfall for agriculture; most of this area is in western Iran. Seasonal rainfall intensifies the water shortage. The rainy season occurs between October and March, leaving the land parched for the remainder of the year. In most parts of the world with such conditions (e.g. Central Australia), there is no agriculture. Still, for most of its history, Iran has been primarily an agricultural economy. Animal husbandry was possible until recently only by nomadic pastoralism, the flocks moving at fixed seasons to new pastures, while crop farming was mainly dependent on the qanat system (U.S.Library of Congress, 1987).

Iran's rivers are characterized by seasonal variations in flow. The Karun River and other rivers passing through Khuzestan Province (in the southwest at the head of the Persian Gulf) carry water during periods of maximum flow that is ten times the amount borne in dry periods. Several of the government's dam projects are on these rivers (Figure 1.1). In numerous localities, there may be no precipitation until sudden storms, accompanied by heavy rains, dump almost the entire year's rainfall in a few days often causing floods and local damage. The runoffs are so rapid that they cannot be used for agricultural purposes (U.S.Library of Congress, 1987).

Water shortages are compounded by the unequal distribution of water. Near the Caspian Sea (north), rainfall averages about 1280 mm per year, but in the Central Plateau and in the lowlands to the south it seldom exceeds 100 mm to 120 mm, far below the 260 mm to 310 mm usually required for dry farming (U.S.Library of Congress, 1987).

Scarcities of water and of the means for making use of it have constrained agriculture since ancient times. To make use of the limited amounts of water, the Iranians centuries ago developed man-made underground water channels called *qanats* that are still in use. They are usually located at the foot of a mountain and are limited to sloping land. A qanat taps water that has seeped into the ground and channels it via straight tunnels in such a way to surface in proximity to village crops (U.S.Library of Congress, 1987). The main advantage of the *qanat* is that its underground location prevents most of the evaporation to which water carried in surface channels is subjected. In addition, the *qanat* is preferable to the modern power-operated deep wells because it draws upon underground water located far from the villages. The main disadvantages of the *qanat* are the costs of construction and maintenance and a lack of flexibility; the flow cannot be controlled, and water is lost when it is not being used to irrigate crops (U.S.Library of Congress, 1987). In the late 1980s, an estimated 60,000 *qanats* were in use, and new units were still being dug (although not in western Iran, where rainfall is adequate). To assist villagers, the government undertook a program to clean many *qanats* after the revolution in 1979. Qanat water is distributed in various ways: by turn, over specified periods; by division into shares; by damming; and by the opening of outlets through which the water flows to each plot of land. So important is the *qanat* system to the agricultural economy and so complex is the procedure for allocating water rights (which are inherited) that a large number of court cases regularly deal with adjudication of conflicting claims (U.S.Library of Congress, 1987).

Construction of large reservoir dams since World War II has made a major contribution to water management for both irrigation and industrial purposes. Dam construction has centered in the southwest of Iran in rivers flowing from the Zagros Mountains (e.g. Karun, Marun, Karkheh, Seymareh and Dez Rivers). The upper courses flow in parallel stretches before cutting through the surrounding mountains in extremely narrow gorges called *tangs* (U.S.Library of Congress, 1987). The terrain in Khuzestan provides good dam sites and government set up the Khuzestan Water and Power Authority in 1959 to manage natural resources in that province. All economic development plans emphasized the need to improve water supplies and reservoirs so as to improve crop production (U.S.Library of Congress, 1987). Large reservoirs were built throughout the country, beginning with the Second Development Plan with first dams built on the Karaj, Sefid (north), and Dez Rivers (southwest).

The first of the major dams had a significant impact on the Iranian economy. Completed in 1962, the Dez Dam on the Dez River was designed to irrigate the Khuzestan plain and to supply electricity to the province (U.S.Library of Congress, 1987). After several years of operation, the dam had achieved only a small part of its goals, and the government decided that the lands below the dam and other dams nearing completion required special administration. As a consequence, a law was passed in 1969 nationalizing irrigable lands downstream from dams. The lands below the Dez Dam were later leased to newly establish domestic and foreign companies that became known as agribusinesses (U.S.Library of Congress, 1987).

A sound foundation is one of the fundamental necessities in dam construction and critical geological phenomena have caused many problems in large dams.
One of the problems with regards to foundations is that water, due to high foundation permeability is lost through seepage, which is the case in the Asmari Formation in southwest Iran. Seepage depends on various parameters, such as foundation materials, geological and structural conditions of the area and also the hydraulic characteristics of the dam foundation. Due to complex local conditions, the need for more widespread and logical insight into the geology has increased and with it also to ensure the need for more extensive engineering and geological investigations of safety and stability, during the dam life. The permeability and porosity are important especially regarding the grouting and the assessment of the influence of weathering on foundation rocks also plays an important role.

Another common geological problem is overtopping due to a landslide in the reservoir that produce a tsunami which can rapidly wear away the land on either side of the dam (Hawker, 2000).
Thandaweswara (2012) listed dam failures depending on the type of dam and the causes of failure are classified as follows:

I. Hydraulic failures;
II. Piping and seepage through foundation and body of dam;
III. Overtopping and
IV. Stresses developed within the structure.

A study of dam failures in the world has indicated 40 percent of dam breaks are related to geological problems (Thandaweswara, 2012).
The following are some case histories regarding geological problems that caused failure and serious problems in dam construction;

a) *Malpasset* arch dam (France) was breached in 1959 due to a fault that was later found to be the cause of the disaster. The dam completely collapsed and produced an enormous dam break wave, or wall of water, 40 m high and moving 70 km per hour, destroying two villages and killing 450 people in the resulting flood (Bellier, 1967).

b) *Vajont* arch dam (Italy), one of the tallest dams (262 m) in the world caused overtopping of the dam in 1963 due to a landslide in the reservoir. This flood wave caused the deaths of 2000 people (Semenza, 1965).
c) *St. Francis* dam with a curved concrete gravity wall failed disastrously on its first full impoundment in 1928 killing about 450 people in the San Francisquito and Santa Clara River valleys because of unknown palaeo mega-slides on the left bank within the Pelona Schists. It was the biggest American civil engineering neglect in the twentieth century (Rogers, 1995).
d) *Teton* rockfill dam in the United States failed in 1976. Investigations into the cause placed blame on the permeable soil used in the core and on fissured rhyolite in the foundation that allowed water to seep under the dam (Arthur, 1977).
e) *Keban* a composite dam was built in 1974 on the Euphrates River in Turkey. The rockfill and concrete gravity structure rests on karstic marble and limestone. A crab cavity with a volume of 104 000 $m^3$ was detected during the construction in the foundation on the left flank (Ozbek, 1975).
f) *Hales Bar* dam was constructed on the Tennessee River on 1913. The Tennessee Valley Authority (TVA) spent two decades unsuccessful trying to fix a leakage problem in the foundation. Finally the TVA decided to replace the dam by building Nickajack Dam about 10 km downstream in 1968 (Tennessee Valley Authority, 1972).
g) *Lar* rockfill dam was built in 1981on a heavily faulted and fractured region of Damavand volcano region in the north of Iran. The fracturing increased the development of karst and sinkholes in the limestone below the dam in addition the acidic solutions that originated from the volcano accelerated the process of dissolution and development of karstic zones. The grouting operations continue for several decades and was unsuccessful untill recently (Uromeihy, 1999).

The responsibility of a geological engineer is to select the best dam location (site selection) and to give proper solutions for geological problems. By using technical information from different dam construction projects in the Zagros Range situated in the southwest of Iran, it has been attempted in this research, to evaluate the geological characteristics of the rock mass on dam site location for the construction of the dams (Koleini, 1997).

In general, the large dams and power plants that are situated in southwest Iran are on limestone, dolomitic limestone, marly limestone and marlstone belonging to the Oligo-Miocene rocks of the Asmari Formation and the engineering geological studies associated with the location of these dams present new engineering geological information on the Asmari Formation limestone of south-western Iran.

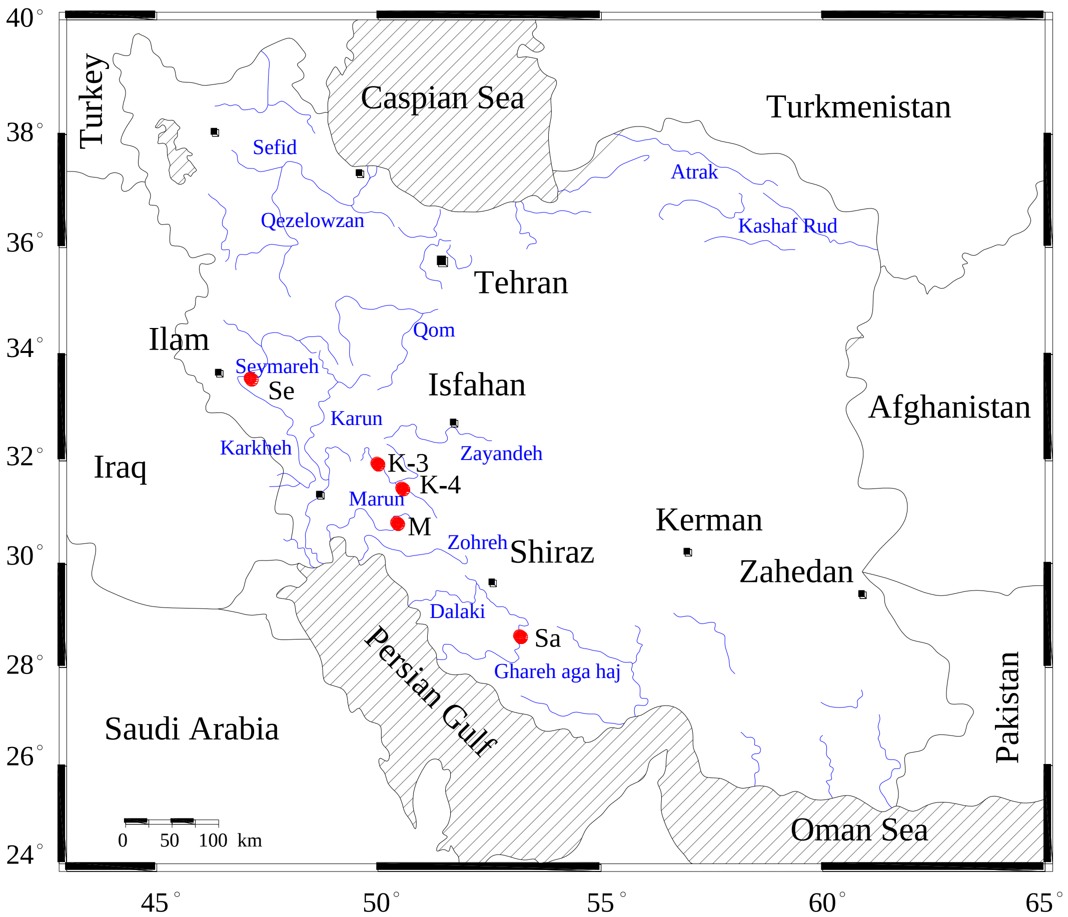


Figure 1.1. The map indicates some major rivers in Iran and dam localities in the Zagros region (research area). Salman Farsi dam (Sa), Marun dam (M), Karun-4 dam (K4), Karun-3 dam (K3), Seymareh dam (Se).

### *1.1.1. Aims of Thesis*

The dam construction projects that are considered in this research include the following:

1. *Karun-3 Dam (K-3)* and power plant (constructed) on the Karun River - about 28 km east of Izeh town at Khuzestan Province.
2. *Karun-4 Dam (K-4)* and power plant (under construction) on the Karun River -35 km west to southwest Lordegan town, 85 km southwest of Shahrekord City in Chahar Mahal Bakhtyari province.
3. *Marun Dam (M)* and power plant (constructed) on the Marun River-about 19 km northeast Behbahan City in Khuzestan Province.
4. *Seymareh Dam (Se)* and power plant (under construction) on the Seymareh River about 106 km southeast of Ilam City in Ilam Province.
5. *Salman Farsi (Sa)* or *Ghir Dam* and power plant (under construction) on the Ghareh-Aghaj River, about 140 km south of Shiraz City and 12 km north-east of Ghir in the Fars Province.

The aims and purpose of this research are the following:

- Investigate the engineering geological characteristics of the (Asmari) rock mass at the various construction sites including:

a) Determination of geological characteristics of dam locations.
b) Preparation of lithological columns and engineering geological sections along the dam axes.
c) Preparation of thin sections of rock samples for petrographical analysis.
d) Identification of hydrogeological characteristics of the dam locations, particularly porosity and permeability- also resultant grouting that will be needed at each site.
e) Characteristics and determination of rock mass classification along tunnels and slopes and the investigation of their stabilities by means of ordinary experimental method classifications.
f) Introduction of stabilization measures for tunnels and slopes.
g) Determination of net allowable pressure and cuttability classification of the Asmari Formation limestone.
h) Joint study (discontinuity survey).
i) Exposed foundation maps at each dam site.
j) Use of site bedrock as construction material in dams.

- Introduce an engineering geological model (rock material and rock mass properties and characteristics) for the Asmari Formation in the Zagros Region.

### *1.1.2. Previous Work*

The name Asmari Formation was introduced by Busk and Mayo (1918) and referred to a sedimentary sequence of Cretaceous-Eocene age. The Asmari Formation was also stratigraphically studied by Richardson (1924), Van Boecha, Lees et.al (1929). Lee (1933) revised the previous work and considered the Asmari Formation to be of Oligo-Miocene age.
The formation was studied in detail stratgraphically and formally defined by James and Wynd (1965). Adams and Bourgeois (1965) revised the biostratigraphy of the Formation in south-western Iran and various authors also discussed the Asmari Formation: Wells (1967), Sisler (1971), McCord (1974), Stonly (1975), Kalantari (1986, 1992) and Jalali (1987), National Iranian Oil Company (NIOC), Zahedinejhad, (1987), Seyrafian et al., (1996, 1998, 2002), Kimiagari, Vazirimoghadam and Taheri (2005).
All of the above concentrated basically on the stratigraphy of the Asmari Formation in the Zagros region.
The engineering geological reports on the Asmari Formation are from the:
Engineering geological investigations of various dam sites, located on the Asmari Formation in the south-western Iran, by Mahab Ghodss Consulting Engineers Company (MG. co.) dated 1984, 1986, 1993, 1996, 2003 (Ministry of Energy- Iran).

### *1.2. Geography of Iran*

Iran is situated in Southwest Asia, bordering the Gulf of Oman, the Persian Gulf (southern border), and the Caspian Sea, Armenia, Azerbaijan, Turkmenistan (northern border), Iraq, Turkey (western border) and Pakistan, Afghanistan (eastern border) between latitudes 25° and 39° north and longitudes 45°and 61° east. Iran is one of the world's most mountainous countries with high contrasting green oases (Figure 1.2).
With an area of 1 648 000 $km^2$, Iran ranks sixteenth in size among the countries of the world. Iran is about one-fifth the size of the continental United States, or larger than the combined area of the contiguous states of California, Arizona, Nevada, Oregon, Washington, and *Idaho*.

Iran's diagonal distance from Azerbaijan in the northwest to Baluchestan Sistan in the southeast is approximately 2 333 km (U.S.Library of Congress, 1987).

### *1.2.1. Topography*

Iran (Persia) consists of rugged mountainous rims surrounding high interior basins. The main mountain chain is the Zagros Mountains comprising a series of parallel ridges interspersed with plains that bisect the country from northwest to southeast (Figure 1.2).
Many peaks in the Zagros exceed 3 000 m above sea level, and in the south-central region of the country, there are at least five peaks that are over 4 000 m. As the Zagros continue into southeastern Iran, the average elevation of the peaks declines dramatically to under 1500 m (U.S.Library of Congress, 1987).

The narrow but high Alborz Mountains rim the Caspian Sea. Volcanic Mount Damavand (5 600 m), located in the centre of the Alborz range, is not only the country's highest peak but also the highest mountain on the Eurasian landmass west of the Hindu Kush.

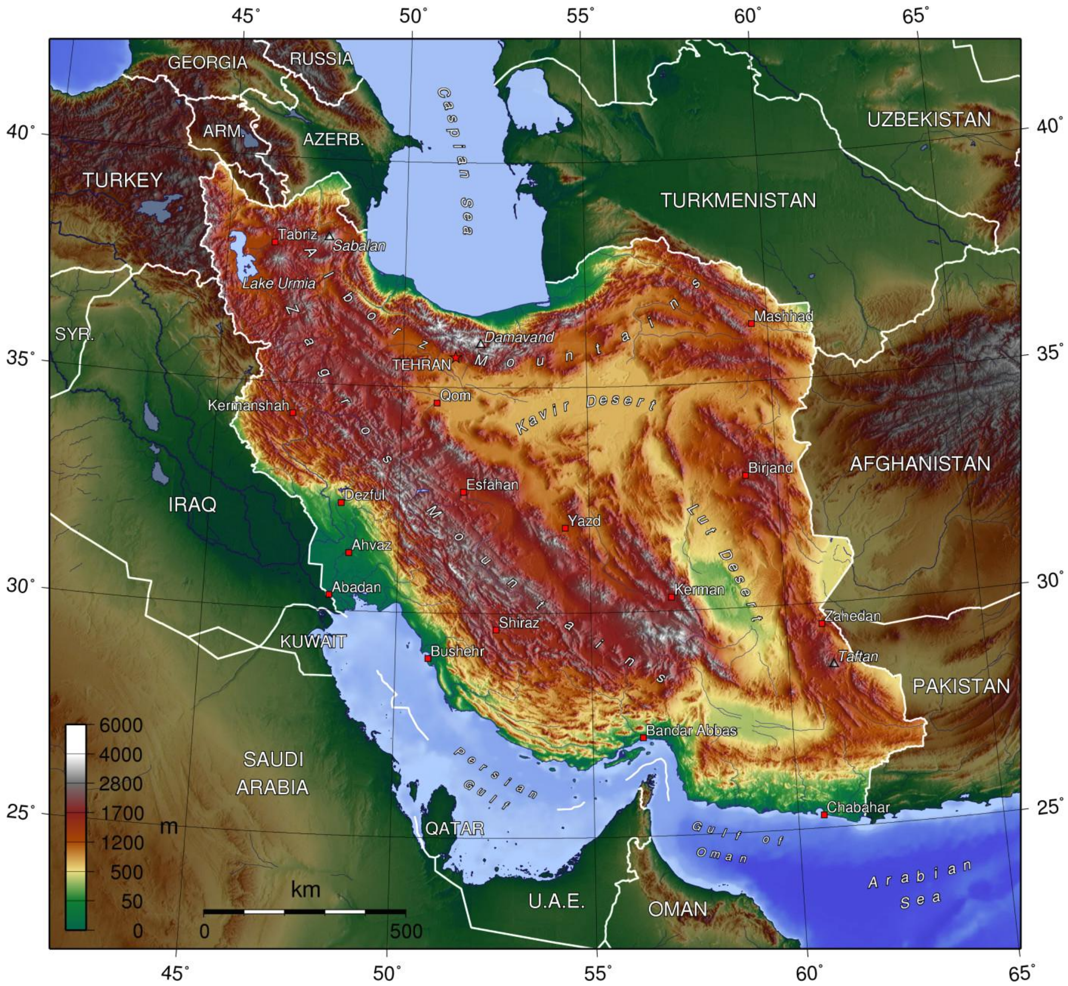


Figure 1.2. The topographic map of Iran (Iran topo en.jpg, 2006).

The Alborz represents a north branch of the Alpine-Himalayan orogenic system and runs for a distance of 960 km separating the Caspian Lowland from the Central Iran *Plateau*. The centre of Iran consists of several closed basins that are collectively referred to as the Central Plateau. The average elevation of this plateau is about 900 m, but several of the mountains that tower over the plateau exceed 3 000 m. The eastern part of the plateau is covered by two salt deserts, the Dasht-e Kavir (Namak) and the Dasht-e Lut. Except for some scattered oases, these deserts are uninhabited (U.S.Library of Congress, 1987).

The two mountain ranges of Iran provide for a variety of climates, though most of Iran is dry. Of the small rivers and streams, the only one that is navigable is the Karun, which shallow-draft boats can negotiate from Khorramshahr to Ahwaz, a distance of about 180 kilometres. Several other permanent rivers and streams also drain into the Persian Gulf, while a number of small rivers that originate in the northwestern Zagros or Alborz drain into the Caspian Sea. On the Central Plateau, numerous rivers, most of which have dry beds for the greater part of the year, form from snow melting in the mountains during the spring and flow through permanent channels, draining eventually into salt lakes that also tend to dry up during the summer months (U.S.Library of Congress, 1987).

### *1.2.2. Climate and Water Resources*

The climate of Iran is one of great extremes due to its geographic location and varied topography. The summer is extremely hot with temperatures in the interior rising possibly higher than anywhere else in the world; certainly over 55°C has been recorded. In winter, however, the great altitude of much of the country and its continental situation result in far lower temperatures than one would expect to find in a country in such low latitudes. Tempratures of - 30°C can be recorded in the north-west and - 20°C is common in many places such as west and centre (U.S.Library of Congress, 1987).
Iran can be divided into the following major river basins: the Central Plateau in the middle, the Lake Urumiyeh basin in the northwest, the Persian Gulf and the Gulf of Oman in the south-southwest, Lake Hamoun basin in the east, Kara-Kum basin in the northwest and the Caspian Sea basin in the north. (Ministry of Energy, 1992).
The rainfall characteristics of the above basins are summarized in Table 1.1.

All of these basins, except the Persian Gulf and Gulf of Oman, are interior basins. The Karun River, with a total length of 890 km, occurs in the southwest of the country. The few streams that empty into the Central Plateau dissipate into the saline marshes. All streams are seasonal and variable with spring floods causing enormous damage, while there is little water flow in summer when most streams disappear. Water is however stored naturally underground, finding its outlet in subterranean water canals (qanats) and springs and is also tapped by wells (Ministry of Energy, 1992).

Table 1.1. Rainfall in the major basins in Iran (Bureau of Operation and Maintenance of Dams and Irrigation Networks, 1995).

| Basin | Total area (km²) | As % of total area | Rainfall (mm/y) | Rainfall (km/y) | As % of total rainfall |
|---|---|---|---|---|---|
| Central Plateau | 832 000 | 51 | 165 | 138 | 33 |
| Persian Gulf and Gulf of Oman | 431 000 | 26 | 366 | 158 | 38 |
| Caspian Sea | 178 000 | 11 | 430 | 77 | 19 |
| Lake Hamoun and Kara-Kum | 150 000 | 9 | 142 | 21 | 5 |
| Lake Urumiyeh | 57 000 | 3 | 370 | 21 | 5 |
| Total | 1 648 000 | 100 | 252 | 415 | 100 |

Internal renewable water resources are estimated at 128.5 km$^3$/year. Surface runoff represents a total of 97.3 km$^3$/year, of which 5.4 km$^3$/year comes from drainage of the aquifers, and groundwater recharge is estimated at about 49.3 km$^3$/year, of which 12.7 km$^3$/year is obtained from infiltration in riverbeds. Iran receives 6.7 km$^3$/year of surface water from Pakistan and some water from Afghanistan through the Helmand River. The flow of the Arax River, at the border with Azerbaijan, is estimated at 4.63 km$^3$/year. The surface runoff to the sea and to other countries is estimated at 55.9 km$^3$/year. The total safe yield of groundwater (including non-renewable water or unknown groundwater inflow from other countries) has been estimated at 49.3 km³/year (Ministry of Energy, 1992).

The Zagros serves as the main origin of the rivers running into the Persian Gulf and Oman sea watersheds. Among all these rivers, the major ones are: Arvand Rud, Gamasb, Karun, Rajah, Zaal and Marun join and form Jarahi, Seymareh, Qareh Aqhaj, Zohreh, Dalaki, Mend, Shur, Minab, Mehran and Naband (Figure 1.1).
The major rivers running into the Caspian Sea (north) from Iranian shorelines flow from the northern Alborz attitudes like: Aras, Sefid Rud, Chalus, Haraz, Sehezar, Babol, Talar, Tajan, Gorgan, Atrak, Qarasu and Neka. Zayandeh Rud flow through central Iran. Halil Rud and Bampur occur in the southeast of Iran (Ministry of Energy, 1992).

### *1.3. Geology of Iran*

#### *1.3.1. Structural Units*

Fundamental differences in crustal character and in age of basement consolidation allow three major structural units to be distinguished, separated from each other by an ophiolite-bearing suture. Other criteria such as structural style, age and intensity of deformation, age and nature of magmatism, are used to subdivide these major zones into smaller elements (Figure 1.3). The three major units and their main constituents (Berberian and King, 1961) are as follows:

1. A crystalline basement consolidated during the Precambrian and a platform-type Palaeozoic development forms the basement of the Zagros Fold Belt.
2. The central unit is interpreted as an assemblage of marginal Gondwana fragments that were united with the mother-continent and separated from the northern (Eurasian) continent in the Palaeozoic, but detached from Gondwana and attached to Eurasia in the Mesozoic, and finally rejoined by Gondwanic Afro-Arabia in the Late Cretaceous. It comprises Central Iran and the Alborz.
3. The northern unit is sharply separated from the central unit by the north Iran Suture. It is characterized by continental crust including remnants of more or less cratonized former (Palaeozoic) oceanic crust that seems to reflect a Palaeotethys. This northern unit represents a marginal strip of the Hercynian realm of Central Asia-broadly overlapped by the Alpine realm. It was deformed and largely consolidated by strong early Kimmeridjian folding and a Late Alpine folding (Stocklin, 1977). The northern unit comprises the South Caspian Depression and the Kopet Dagh Range.

##### *1.3.1.1. Zagros*

In the simply folded belt of the Zagros Mountains, a sequence of Precambrian to Pliocene shelf sediments about 8-10 km thick has undergone folding from Miocene to Recent. The Zagros Mountains trend southeast through northeast Iraq to southwest Iran. They are the topographic expression of an orogenic event that continues to the present time. The sediments have been folded into a series of huge anticlines and synclines. The folding has taken place since the Miocene and is reflected in the topography, which is dominated by anticlinal mountains and synclinal valleys. The anticlinal oil traps of Iran and northeast Iraq are in this belt. The Zagros Orogenic Belt is bounded to the southwest by the stable platform of *Arabia*, where shelf sediments laterally equivalent to those in the simply folded belt are virtually undeformed and overlie the metamorphic rocks of the Arabian Shield (Geological Survey of Iran, 2006).

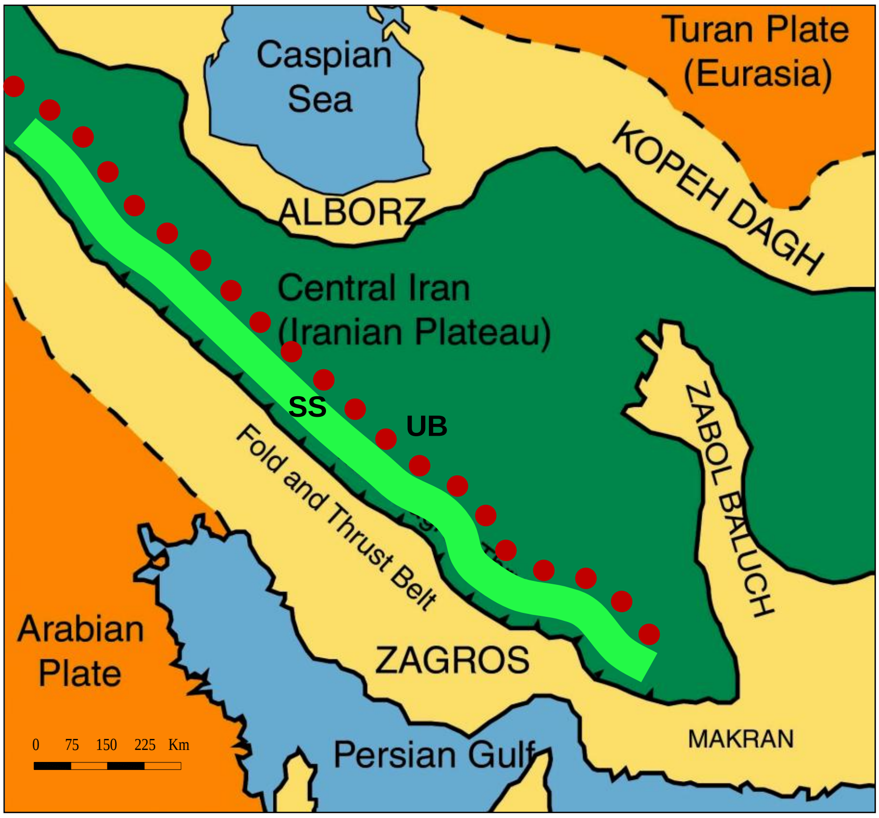


Figure 1.3. The main structural units of Iran (after Berberian and King, 1961).

### *1.3.1.2. Zagros Thrust Zone*

The folded belt passes northeastward without a sharp boundary into a narrow zone of thrusting bounded on the northeast by the main Zagros Thrust line (Figure1.3). In this zone, older Mesozoic rocks and the Palaeozoic platform cover were thrust southwestward in several schuppen-like slices on the younger Mesozoic and Tertiary rocks of the folded belt. The thrust zone represents the deepest part of the Zagros Basin in Mesozoic and early Tertiary time (Geological Survey of Iran, 2006).

### *1.3.1.3. Sanandaj – Sirjan Metamorphic Belt (SS)*

The Sanandaj-Sirjan Zone was first recognized as a separate linear structural element by Stocklin (1968). The zone lies between the main Zagros Thrust in the southwest and the Urumiyeh-Bazman volcanic belt in the northeast. The ranges occupy a northwest trending belt in which the Zagros structural grain is overprinted on the typical Central Iran structural framework. Characteristic features include the consistent Zagros trend of the zone as a whole, the nearly complete lack of Tertiary volcanics and the poor development of Tertiary formations in general. Part of the zone is characterized by Palaeozoic volcanism and Hercynian or Early Kimmeridjian metamorphism (Geological Survey of Iran, 2006).

### *1.3.1.4. Urumiyeh–Bazman Volcanic Belt (UB)*

This volcanic belt runs parallel to the Sanandaj-Sirjan Zone to the northeast, and owes its existence to the widespread and intensive volcanic activity, which developed on the Iranian plate from the Upper Cretaceous to Recent time. The Urumiyeh-Bazman volcanic belt is supposed to have resulted from the collision of the Arabian and Central Iranian continental plate margins. It is represented by sub-alkaline volcanics that vary in composition from basaltic through andesitic to rhyolitic composition (Geological Survey of Iran, 2006)

### *1.3.1.5. Central –East Iran Micro Plate*

Central Iran, in a broad sense, comprises the whole area between the north and south Iranian ranges. Within the Iranian plate the central east Iran microplate is bordered by the Great Kavir Fault in the north by the *Nain-Baft Fault* in the west and southwest and by the *Harirud Fault* in the east. It is surrounded by the Upper Cretaceous to Lower Eocene ophiolite and ophiolitic melange. The microplate consists of different structural components; the Lut Block, Kerman-Tabas Block, Yazd Block and Anarak-Khur Bloc (Geological Survey of Iran, 2006).

### *1.3.1.6. Makran and Zabol –Baluch Zone, Southeast Iran*

Makran and Zabol-Baluch in the southeast of Iran are post-Cretaceous flysch-molasse belts, which join together in southeast Iran and continue to the Pakistan Baluchestan Range. The flysch sediments were deposited on the Upper Cretaceous ophiolites (Geological Survey of Iran, 2006).

### *1.3.1.7. Alborz*

The Alborz Mountains form a gently sinuous east-west range across northern Iran south of the Caspian Sea, and constitute the northern part of the *Alpine-Himalayan* Orogeny in western Asia. The Alborz Range in north Iran is stratigraphically and structurally related to Central Iran (Geological Survey of Iran, 2006).

### *1.3.1.8. Kopet-Dagh*

The northeast active fold belt of Iran, the Kopet Dagh, is formed on the Hercynian metamorphosed basement on the south-western margin of the Turan Platform. The belt is composed of about 10 km of Mesozoic and Tertiary sediments (mostly carbonates) and, like the Zagros, was folded into long linear northwest-southeast trending folds during the last phase of the Alpine Orogen, in Plio-Pleistocene time (Geological Survey of Iran, 2006).

## *1.3.2. Stratigraphy of Iran*

### *1.3.2.1. Precambrian Basement*

The consolidation of the Iranian basement by metamorphism, partial granitization and partly by intense folding took place in the Late Precambrian (Figure 1.4). This event has been attributed to the 'Baikalian' or Pan-African Orogeny. Isotopic data of Iranian basement rocks give ages between 600 and 1 100 Ma (Geological Survey of Iran, 2006).

A similar range of isotopic data has been obtained for Arabian Shield rocks. An important post-Pan-African magmatism is documented by the widespread Doran Granite, which cuts the Upper Precambrian rocks and is covered by Lower Cambrian sediments. Late Precambrian postorogenic volcanics, mainly alkali rhyolite, rhyolite tuff and basic dykes are known in the Eocambrian formations. The basement is exposed only in limited parts of the platform area. It consists of low-grade (greenschist facies) metamorphosed, fine-caustic sediments (Geological Survey of Iran, 2006).

#### *1.3.2.2. Palaeozoic Platform*

The platform deposits are well developed in the main and south Alborz Range, in the greater part of central and east Iran as well as in southwest Iran. The north Iran Suture marks the northern termination of the platform regime of the Arabian-Iranian Plate. The Pan-African Orogeny in Iran was followed by a long period of tectonic calm during most of the interval from the Infracambrian to the middle Triassic (Geological Survey of Iran, 2006).
The rock sequence deposited during this time displays all the characteristics of a platform cover. It indicates an epicontinental environment with alternating shallow-marine, lagoonal and continental deposits (Figure 1.4). The thickness of the whole sequence is between 3 000 m and 4 000 m and increases up to 8 000 m in the region of Tabas in east Iran (Stocklin, 1965; Ruttner et al., 1968).

#### *1.3.2.2.1. Precambrian–Cambrian Boundary*

The Precambrian-Cambrian boundary is now known from many places in Iran, notably in Alborz, near Kerman. The Lower Dolomite Member of the Soltanieh Formation contains an assemblage of phosphatic tubes and other poorly preserved remains. The succeeding Lower Shale Member bears macroscopic algae (Hamdi et al., 1989).

#### *1.3.2.2.2. Infracambrian –Ordovician*

Infracambrian rock units in Iran were deposited over large areas after the Pan-African tectonic phase. These movements gently folded and uplifted Precambrian fine clastic, flysch-type sediments (Kahar Formation, Morad Series and Shorm Beds) along Pan-African trends and caused epeirogenic uplifting, and emergence of lowland areas in west Iran, in east Central Iran and probably also in East Iran. In central Iran and northwest Iran, the Eocambrian rock units are mainly shallow water shelf platform carbonates, which interfinger towards the northern Iran Suture with brown, fine-grained sandstone-shale sequences defined as the Bayandor Formation. The carbonates are stromatolitic dolomites of the lower parts of the Soltanieh Formation (Geological Survey of Iran, 2006).

#### *1.3.2.2.3. Silurian to Lower Devonian*

Early Caledonian tectonic movements resulted in an uplifting of west and south Iran and caused emergence of the southern Caspian and central Alborz area, which were temporarily linked to the west Iranian land platform. The pre-Zagros swell emerged with a large low land area in southwest Iran and remained free of marine ingressions in Silurian-early Devonian time. Central and northwest Central Iran was depositional areas in the Silurian-early Devonian time. In east central Iran, basalts are at the base of the *Niur Formation*, a predominantly shallow water platform limestone and dolomite sequence (Weddige, 1984). This marine fossiliferous facies, which laterally interfingers with fine clastics and sandstones, is only developed in east central Iran to a thickness of about 500 m (Geological Survey of Iran, 2006).

#### *1.3.2.2.4. Middle Devonian to Carboniferous*

##### *1.3.2.2.4.1. Alborz*

Marine deposits of Devonian age are known in the Maku area (northwest Iran). They consist of dolomite with some intercalations of sandstone and quartzite and are called the *Muli Formation* (Alavi Naini and Bolourchi, 1973). The thickness of the Muli Formation is 1 250 m and metamorphic rocks unconformably underlie it. In central Alborz, the Upper Palaeozoic sedimentary cycle began with the transgression of the sandy Jeirud Formation (Upper Devonian). The Guired Formation consists in its lower part of sandstone, shale, sandy limestones and several phosphatic layers, followed by sandstones (Alavi Naini and Bolourchi, 1973). Lower Carboniferous of Central Alborz is made up of dark Limestone with subordinate marl intercalations in the lower part (*Mobark Formation*). Formation is about 450 m thick and disconformably overlies the Jeirud Formation. In east Alborz the *Khosh Yelagh Formation* transgressed with a basal conglomerate on the *Padeha Formation*. The *Khosh Yelagh Formation* consists of shale, limestone, sandstone and basic volcanics (Geological Survey of Iran, 2006).

##### *1.3.2.2.4.2. Central Iran*

In east Central Iran the cycle of middle Devonian to late Carboniferous marine sediments reaches a thickness of 1 500 to 2 000 m and was defined as the Ozbak Kuh Group (Ruttner, Nabavi and Hajian, 1968; Stocklin, Eftekharnezhad and-Hushmandzadeh, 1965). It consists of the Sibzar Dolomite at the base (100 m thick), the Bahram Formation (300-500 m thick of late Devonian age) and the Shishtu Formation (300-400 m thick, of alternating marls, shale and limestone of the late Devonian to early carboniferous age); the cycle terminates with the Sardar Formation (shales, sandstones and sandy limestone) of the late Visean to late Carboniferous age (Geological Survey of Iran, 2006).

##### *1.3.2.2.4.3. Zagros Area*

The Devonian is nowhere present in the southwest of Iran. The Carboniferous sandstone is very consistent, being present beneath the Permian limestone wherever the base of this limestone is exposed (Setudehnia, 1972). This Carboniferous sandstone is disconformably underlain by Cambrian sediments in the Kuh-e-Dinar, Zard–Kuh and Oshtoran–Kuh areas. Ordovician and Silurian sediments in the Kuh-e-Surmeh and Gahkum-Faraghan areas also disconformably underlie it respectively. The upper boundary of the Carboniferous with the Permian is not clear. These two units are often combined and referred to as Permo-Carboniferous (Geological Survey of Iran, 2006).

#### *1.3.2.2.5. Permian Sedimentary Cycle*

Over wide areas in northwest Iran and in the main Alborz Range, a red-clastic shallow marine transgressive phase, the *Dorud Formation*, indicates Permian sedimentation. The Dorud Formation interfingers towards the eastern Alborz with shelf carbonates and towards central Iran it changes into a thinner, basal quartz sandstone member (Geological Survey of Iran, 2006).

### *1.3.2.2.6. Permian –Triassic Boundary*

The lowermost Triassic, as well as a continuous section between the Permian and Triassic, is so far only known from Julfa (northwest Iran) and Abadeh (west central Iran). At Julfa the dark, brachiopod-bearing limestone of Guadalupian age is conformably overlain by 33 m of shales, marls and thin limestones of whitish gray and purple color; these are the Julfa Beds (Stepanov et al, 1969), which contain a peculiar Late Permian fauna and correlate in minute detail with the stratotype of the Dzhulfian (Geological Survey of Iran, 2006).

### *1.3.2.3. Mesozoic*

In the geological history of Iran, the Mesozoic Era is of greater significance, since many important geological events occurred during this era. The tectonic and palaeogeographic evolution of Iran during the Mesozoic was controlled by the geodynamic interaction of the Eurasian continental margin and the Tethyan oceanic belt (Geological Survey of Iran, 2006).

### *1.3.2.3.1. Lower and Middle Triassic Sedimentary Cycle*

The cycle of platform sedimentation began with the Permian transgression, continued into the Triassic and ended in late Middle Triassic. The Lower and Middle Triassic facies on the Iranian and on the Turanian Plates are significantly different. In contrast to the carbonate platform sedimentation on the Iranian Plate, geosynclinal sediments were deposited on the southern part of the Turan Plate (east Kopet Dagh and south Caspian area) and in the Nakhlak area in Central Iran. This Triassic facies has the following characteristics; besides the carbonate rocks, the sequence consists of marine and non-marine clastic sediments and volcanic rocks (tuff and lava) are abundant; the thickness of the sequence reaches 1 000-3 000 m indicating strong subsidence of the basin. In Iran this facies type appears only in few localities such as Aghdarband in east Kopet Dagh (Ruttner, 1993), in Talesh area in the west Alborz (Davies et al., 1972) and at Nakhlak north of Anarak in Central Iran (Davoudzadeh and Seyedemami, 1972).

The Zagros depositional area was separated from the central Iran realm by the opening of Neotethys in Late Palaeozoic or in Early Triassic time. The Zagros Triassic epicontinental basin was filled with carbonates, evaporites and the Dashtak basal red shale of Khaneh Kat Formation. The thickness of the Khaneh Kat Formation is 400 m or more (James and Wynd, 1965).

### *1.3.2.3.2. Upper Triassic to Middle Jurassic Sedimentary Cycle*

The time interval from Late Triassic to Middle Jurassic was in fact a cycle of sedimentation between two tectonic events of the Early Kimmerian movements and the mid-Jurassic event. As a result of the Early Kimmerian tectonics, most parts of Iran were split into a horst and graben mosaic. Synsedimentary fault tectonics caused the formation of troughs that developed during the deposition of the Shemshak Formation in central and east Alborz and in north Kerman (Geological Survey of Iran, 2006). During the Late Triassic to Middle Jurassic, these troughs were filled with 3 000- 4 000 m of sediments. These basins were temporarily connected with the open shallow part of the Tethys. The alternation of subcontinental coal-bearing facies with plant remains and marine carbonates in the sequences indicate four transgressive–regressive macro cycles. They are represented accordingly by Upper Triassic, Lower, Middle and Upper Jurassic sediments (Geological Survey of Iran, 2006).

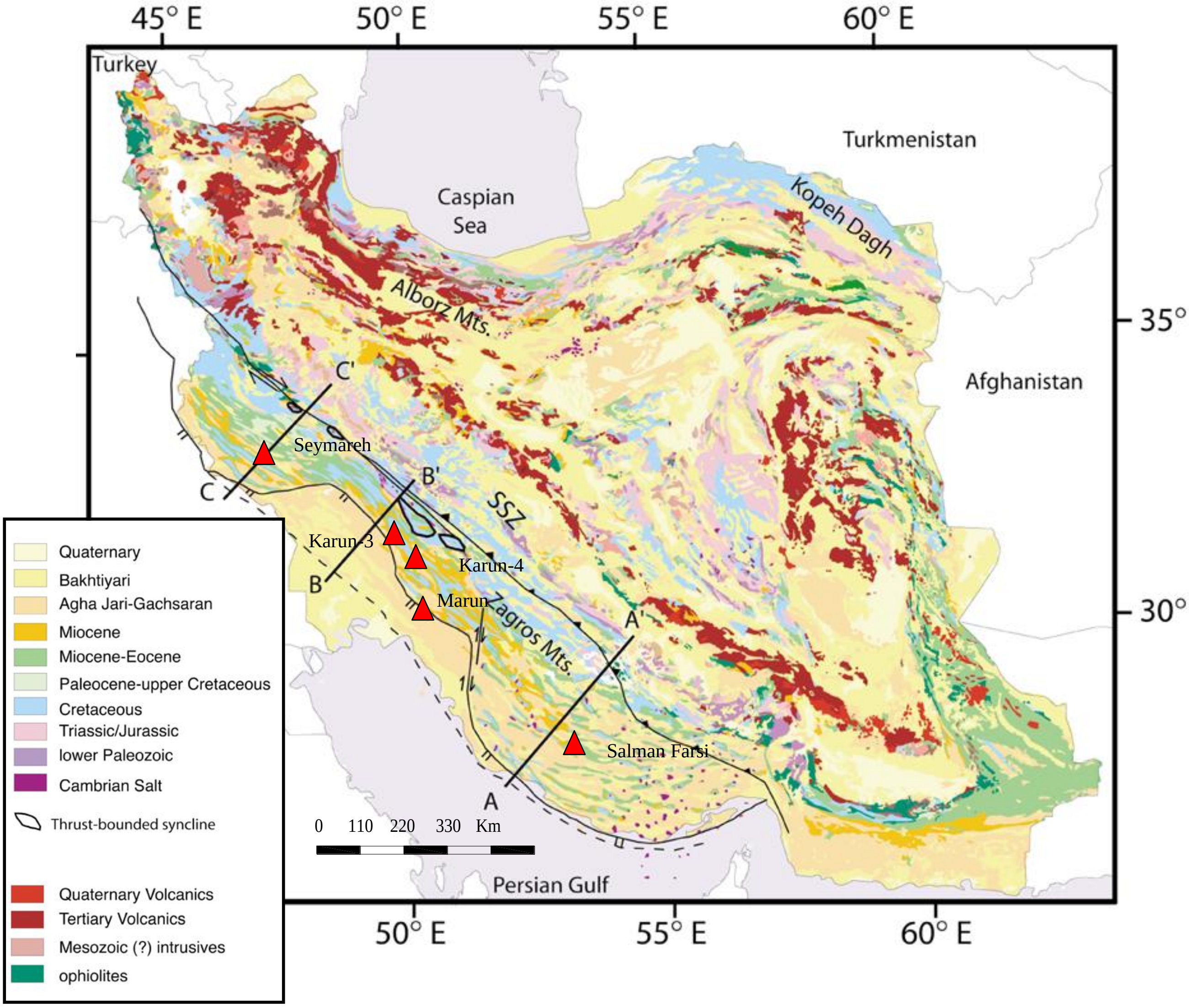


Figure 1.4. Geological map of Iran, SSZ represent the Sanandaj-Sirjan Zone (after Pollastro et al., 1997). The dam localities in Zagros region are presented by red triangle.

#### *1.3.2.3.3. Middle and Upper Cretaceous*

The Late Kimmerian and early Alpine relief were peneplaned and partly covered by red clastic debris. In the Barremmian and Aptian a shallow sea transgressed extensively over almost the whole of Iranian territory and uniform Orbitolina Limestone was deposited everywhere. Some higher areas in east Iran, on the Lut Block, Shotori Horst and west of Kerman remained emerged or else were stripped again after the Austrian movements (Cenomanian-Turonian) (Geological Survey of Iran, 2006).

Turonian and Coniacian sediments are missing in many parts of northern and central Iran. In north central and east Alborz the Cretaceous sediments mainly represent deep shelf and neritic facies. Southwest and south Iran were not much affected by the early Alpine movements and remained as an epicontinental sea. A slight regression is only indicated by the Late Jurassic-Early Neocomian evaporites towards the Arabian Platform (Geological Survey of Iran, 2006).

The Albian to Cenomanian rock units of the Zagros area are represented by the *Bangestan Group*. During this period, the massive, neritic wackestones and packstones of the *Sarvak Formation* were spread over Kajhdomi. A pelagic facies indicating deeper water is developed in the eastern Interior Fars and along a furrow, extending from northeastern Fars through the Bakhtyari to central Lorestan (James and Wynd, 1965).

### *1.3.2.4. Tertiary*

Regional folding in Late Cretaceous-Palaeocene time produced a regional unconformity at the base of the Tertiary throughout the greater part of north central and eastern Iran. Marine areas remined in Palaeocene time in flysch troughs and subsiding shelf areas in east Iran, in landward Makran (southeast Iran), in parts of the Urumiyeh-Hamadan Zone and in the Zagros Miogeosyncline (Geological Survey of Iran, 2006).

#### *1.3.2.4.1. Palaeogene (excluding Upper Oligocene)*

In the northern Alborz area, middle Alpine movements caused emersion only in late Palaeocene time. Here Maastrichtian-Danian marine-neritic sedimentation continued into the Palaeocene. In the Kopetdagh (northeastern Iran), the middle Alpine movements caused regression, and red beds and lagoonal deposition of the Pestehligh Formation were deposited in Early Palaeocene time (Afshar-Harb, 1979). Shortly afterwards during the Upper Palaeocene, the Kopet Dagh Foredeep extended to the south and marine shelf conditions returned, where the Chehel Kaman Limestone (300 m to 400 m thick) was deposited Davoudzadeh, 1969). The northern part of the Alborz and the southern Caspian coastal areas remained a landmass, throughout the Eocene. This land area was fringed by reefal limestones in the westernTalesh (southwestern Caspian area) through most of the Eocene and by lagoonal evaporite deposits in the west-central Alborz area during the Early Eocene time.

During the Lutetian stage, flysch troughs continued to subside along the zone between Zagros and Central Iran, along the Great Kavir Fault, in the east Iranian *Baluch* and landward *Makran Range* and along the Hamadan-Urumiyeh Zone. In the area N of Nain, more than 3 000 m of Middle Eocene fine-clastic flysch sediments) Akhoreh Formation) were accumulated with a fauna of Nummulites partschi and N. burdigaleinsis (Davoudzadeh, 1969).

#### *1.3.2.4.2. Upper Oligocene to Lower Miocene*

Northern Iran was already separated from central and north-western Iran by the rising Qara Dagh (northwest Iran), Alborz and Kopet Dagh ranges. Eastern Iran was essentially a continental area, with temporary brackish and marine embayments only along the eastern Alborz Foredeep and in the Jazmurian Depression (southeast Iran). The *Qom Sea* in central and northwest Iran and the Asmari Sea in southern and south-western Iran may have been connected by sea lanes in the Kermanshah area and possibly in north *Kurdistan*. Temporary sea connections may have also existed between the Oligocene Makran Flysch trough in southeastern Iran and the Jazmurian Platform, but evidence of these channels was eroded in late Alpine thrusting and uplifting of the Zagros and Zendan (southeastern Iran) ranges (Geological Survey of Iran, 2006).

The Qom Sea started to cover north-western and central Iran from the southwest during Middle Oligocene time. The north and east shorelines up to the foot of the Alborz Range and to the east of the Dasht-e-Kavir were reached by the sea only in early Miocene time. Starting with a basal sandy calcarenite, with reworked Eocene volcanic pebbles, the marine area was somewhat irregularly covered in three cycles of marl, limestone and evaporite deposition in thickness up to 1 500 m (Geological Survey of Iran, 2006).

Shallow-water bioclastic and reef detrital yellow-cream weathered limestones 100 to 250 m thick (in some areas increasing to 500 m) uniformly cover the platform areas on the northeast side of the Zagros Range, in the Esfahan-Sirjan Depression, at the foot of the Alborz Range and on shoal areas inside the Central Basin, which were only later flooded by the sea. Some more basinal areas are filled with dark, partly bituminous marls and shales (Sarajeh and Talkheh anticlines 100 km south of Tehran) of thickness 750 to 1 000 m. The fauna in the lower part of the Qom Formation indicate Chattian to lower Aquitanian stages (Huber, 1979). The bryozoan's limestones, marls, shales and anhydrite of the middle part contain fauna of the late Aquitanian Stage. The upper part of the Qom Formation is of Burdigalian age and can reach 500 m in thickness. This cycle is terminated by regression and deposition of anhydrite and salt of Lower Miocene upper evaporite (Geological Survey of Iran, 2006).

In the South Caspian area, The Neogene rock units start only in Vindobonian time with the deposition of red beds on eroded Palaeocene and Upper Cretaceous strata. These Vindobonian-Sarmatian units have thickness ranging from 600 to 800 m in the exposures of the Mazanderan foothills. In the East Mazanderan embayment, they give way to clastic continental beds, which also cover the marine sequence of the Mazanderan plain, nearly 2000 m thick. Towards the Caspian Sea, the continental beds interfinger with fine-clastic marine Pliocene rock units and rapidly increase in thickness to more than 3 000 m. In the Gorgan embayment, this part of the Neogene's sequence is represented by brown clays, marls and siltstones of the Chelecken Formation (Geological Survey of Iran, 2006).

In the Kopet Dagh, the intermountain valleys of the Atrak and Kashafrud were filled with partly coarse clastics and contain chalk and freshwater limestones of temporary lakes. In the northern Kopet Dagh foredeep, the Neogene clastic sequence has more than 2000 m thickness in the Darreh Gaz area. No marine Neogene units are recorded in the central and east Iranian Kopet Dagh (Geological Survey of Iran, 2006).

#### *1.3.2.4.3. Neogene Basin*

##### *1.3.2.4.3.1. Central Iran*

With dimensions of 700 km west to east and 500 km from north to south, the Central Basin covers the Great Kavir Desert and Draya-e-Namak Playa and has an irregular triangle shape. It covers an area of more than 150 000 km. In the eastern part, basal red beds and conglomerates of a continental red-bed sequence may be partly time equivalents of the Qom Formation. To the north, the Central Basin is limited by the Central Alborz Range and to the southwest by the Urumiyeh-Bazman volcanic range. The coarse clastics of these marginal troughs interfinger basin ward with mudstones and evaporites. Great thicknesses (more than 600 m) of these softer more mobile sediments were recorded in the northern Kavir area and in the southern Siah Kuh and Qom-Saveh area, whereas the more stable, incipient horst areas of Eocene volcanic rocks were covered only with 1 000-2 000 m of Neogene clastics. In the interior part of the Central Basin, the Neogene sequence starts with evaporites (upper evaporites), because they cover and seal the Qom limestone reservoir in the Qom and Semnan areas (Huber, 1979). This first evaporite cycle has a thickness of up to 800 m and consists of rock salt, soft red salt-clay, green shale and gypsum beds in several repeated cycles. Some papery weathering bituminous calcareous shale (50 cm thick) is also interbedded and terminates the cyclothems (Geological Survey of Iran, 2006).

The bulk of the Upper Red formation is formed by thickly bedded gray–brown calcareous sandstones and red-brown mudstones with few intercalations of thin, fetid pyritic limestones lenses and green shale beds of playa and mudflat type containing ostracods and occasionally miliolids and gastropods. This part has a thickness of 2 000-4 000 m (Geological Survey of Iran, 2006).

### *1.3.2.4.3.2. Lut Basin*

With dimensions of 400 km north-south and 200 km east-west, the Lut Basin subsided in the late middle Alpine tectonic phase on a basement of Eocene andesitic lava flows, mainly along the western Lut (Nayband-Lakar Kuh) and eastern Lut fault systems. The northern part of the Lut Block was covered by several andesitic, dacitic and rhyolitic lava flows, which poured out partly from fissure volcanoes along tensional faults, and were partly spread, together with tuffs and ashes, from eruption centres, which were later plugged by porphyry masses, while the central Lut was covered by silt and salty mud sheets of a few hundred metres thick. The marginal trough zones along the western and eastern Lut fault system were filled with several thousand metres of red beds and conglomerates mainly in two cycles of deposition, separated by a late Alpine unconformity.

The Lut Formation (Bobek, 1969) comprises the loess-like deposition, which has been shaped into the fantastic Lut towns (by wind erosion): smaller erosional features of similar type were identified by Dresch (1968) in the *Yardages* of Central Asian deserts.

The formation probably represents lake deposits and consists of unfolded poorly consolidated, bedded, yellowish silt with minor amounts of clayey, calcareous and gypsiferous material (Geological Survey of Iran, 2006).

### *1.3.2.4.3.3. Makran and Baluchistan (Southeast Iran)*

The late Middle Miocene saw a general regional uplift and total disappearance of the flysch trough from this area. The elimination of the flysch trough may have been related more to the intense tectonic deformation accompanying the vigorous onset of subduction offshore (in the present Indian Ocean) during the late Middle Miocene rather than simple passive filling up of the basin.

The southern platform sea was a shelf extending out from the land without the intervention of a deep trough, and was now covered by coarse terrigenous detritus supplied by the newly uplifted landmass to the north. Not only the Eocene flysch was being reworked, but also the Oligocene-Miocene and Miocene flysch (Geological Survey of Iran, 2006). It is clear that the synclinal basins were tectonically controlled. They appear as a linear chain on Landsat imagery. The immense thickness of sediments (5 000 m or more) must mean that deposition was in a tectonically controlled subsiding basin. The intervening areas were probably the site of continuous sequences, but thinned out in the anticlinal zone, where there was little or no subsidence. These intervening zones have now been largely removed by erosion (Geological Survey of Iran, 2006).

### *1.3.2.4.3.4. Zagros*

Southwest of the Zagros Main Thrust, the Neogene period is represented by the Fars Group and Bakhtyari Formation. From the gradually rising Zagros Range, red clastic conglomerates, sands and mudstones of the Razak Formation filled the basin from northeast to southwest by lower Miocene time (Geological Survey of Iran, 2006). From Late Oligocene to Early Miocene time, the Asmari Sea receded from the Zagros Basin on the Fars platform and no important evaporite section was deposited. The evaporation products of these lagoons and the relict sea patches are the gypsum, anhydrite and salt beds of the Gachsaran Formation. Dendritina rangi and Miogypisna Fars Group deposition ended with the Agha Jari Formation, a mudstone and sandstone of sequence of continental nature, 3000 m thick in the type section (Figure1.5) (Geological Survey of Iran, 2006).

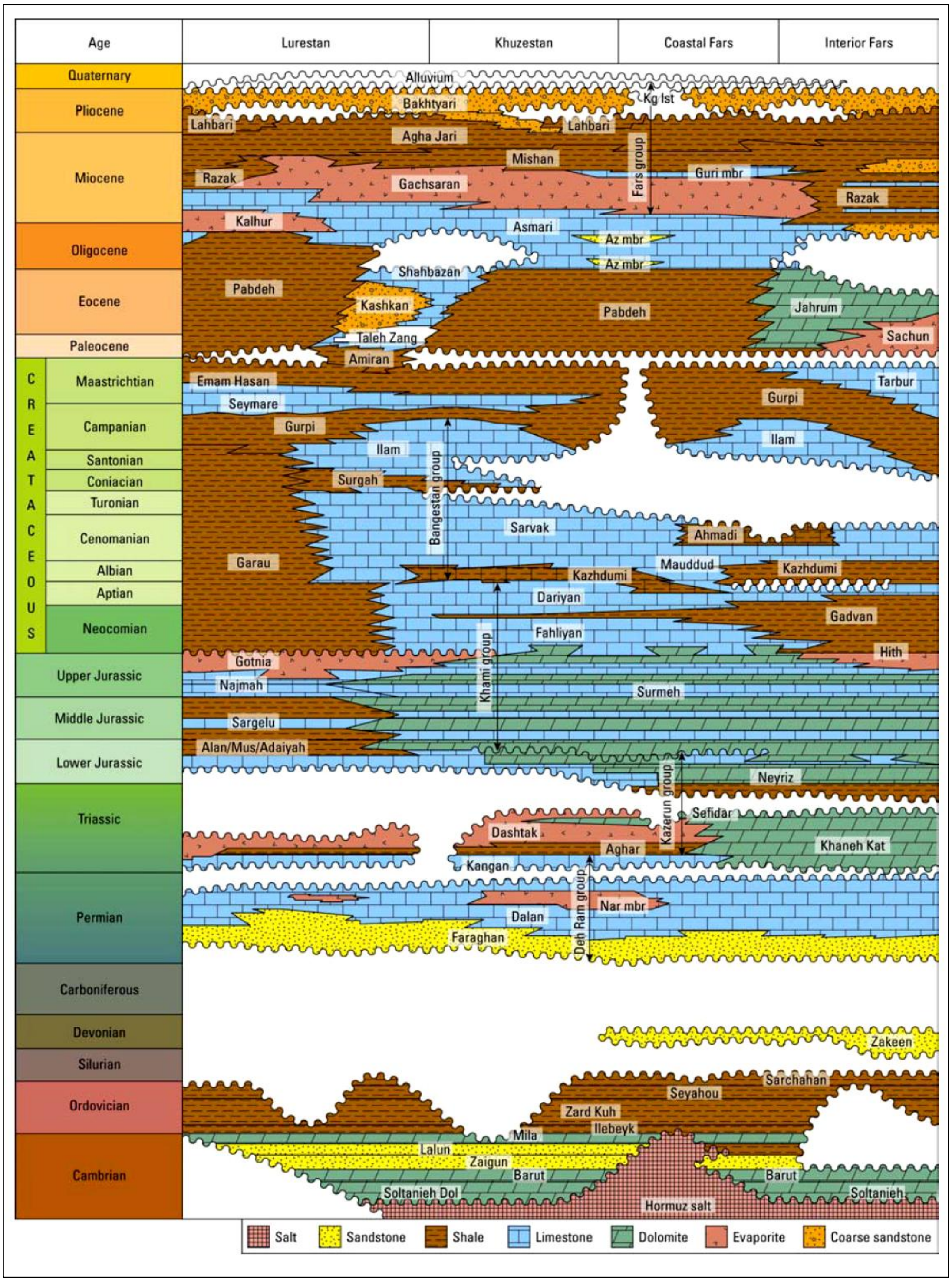


Figure 1.5. Stratigraphic nomenclature of rock units and age relationships in the Zagros basin (after Rezaie and Nogole-Sadat, 2004).

### *1.4. Zagros Structure*

Various schemes exist for the subdivision of the Zagros (Stocklin 1968; Falcon 1974; Alavi and Mahdavi, 1994; Berberian 1995). It is subdivided into two main zones, divided by major faults and/or abrupt changes in geomorphology. The original Arabia-Eurasia Zagros suture is also known as the Main Zagros Reverse Fault. Part of this fault zone is active in a right-lateral sense, where it is known as the Main Recent Fault (Berberian, 1995). To the southwest, the High Zagros (HZ) Thrust Belt contains highly imbricated slices of the Arabian margin and fragments of Cretaceous ophiolites in the southeastern Zagros, it splays off another discontinuous series of faults for which Berberian (1995) used the term 'Zagros Foredeep Fault, to refer to a blind 'master' thrust that causes uplift along the Zagros foreland. This zone is up to 80 km wide and forms the topographically highest part of the Zagros, with summits over 4 000 m above sea level. The High Zagros Thrust Belt overthrusts the second main structural zone, the Simple Folded Zone (also known as the Simple Fold Belt, or Simply Folded Belt) to the southwest along the High Zagros Fault spectacular 'whale-back' anticlines of the Simple Folded Zone (deformed sedimentary cover of the Arabian plate, exposing a Mesozoic-Cenozoic mixed carbonate-clastic succession (Figures 1.6, and 1.7). Resistant units such as the Oligo-Miocene Asmari Limestone and the Cretaceous Bangestan Group produce the characteristic whaleback geomorphology (Alavi and Mahdavi, 1994; Berberian 1995).

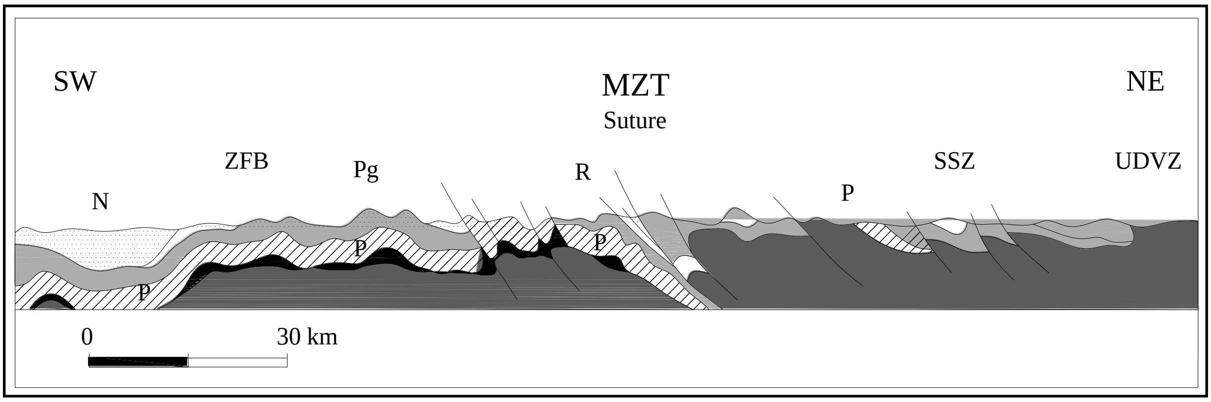


Figure 1.6. A generalized cross-section through the Zagros Mountains. Note the location of the MZRF or Main Zagros Thrust (MZT) and the folding within the Zagros fold Belt (ZFB) Sediment ages are labeled as follows; Neogene (N), Palaeogene (Pg), and Palaeozoic (P). Also shown are radiolarites near suture zone (R), the Sanandaj-Sirjan Zone (SSZ), and the Urumiyeh Dokhtar volcanic zone (UDVZ) (after Stocklin, 1968).

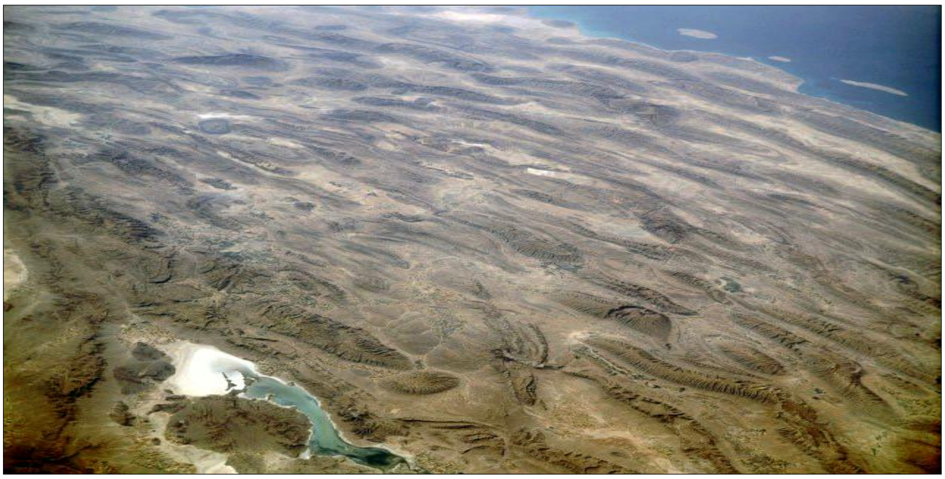

Figure 1.7. An oblique satellite image of the Zagros Mountain range (Earthobservatory.nasa.gov., 1992).

### *1.5. Seismicity in the Zagros Folded Belt*

In general, the recent seismicity of Iran according to the International Institute of Earthquake Engineering and Seismology (IIEES, 2004) shows the high inhomogeneity and seismic activity scattering of the Iranian plateau. Also, the Zagros Folded Belt shows a high number of earthquakes and no earthquakes larger than Ms = 7.0 have been experienced during the 20th century, but shocks of magnitude over Ms = 7.0 have occurred in central and eastern Iran (Figure 1.8).

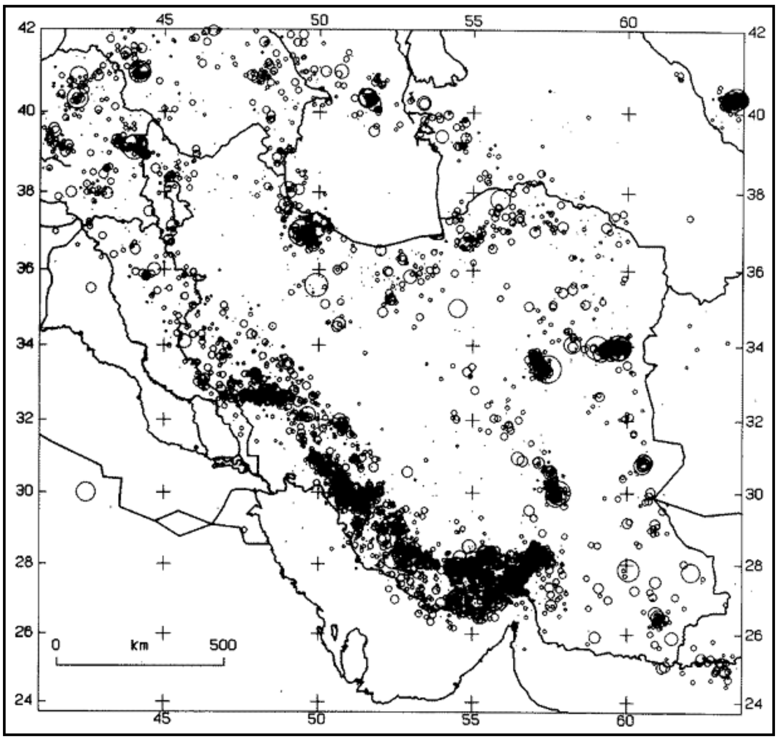


Figure 1.8. Seismicity map of Iran. It shows the high inhomogeneity and seismic activity dispersion of the Iranian Plateau (after International Institute of Earthquake Engineering and Seismology-IIEES, 2004).