Late Mesozoic–Cenozoic clay mineral successions of southern Iran and their palaeoclimatic implications

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ABSTRACT: Clay minerals of calcareous sedimentary rocks of southern Iran, part of the old Tethys area, were investigated in order to determine their origin and distribution, and to reconstruct the palaeoclimate of the area. Chemical analysis, X-ray diffraction, transmission electron microscopy, scanning electron microscopy, and thin-section studies were performed on the 16 major sedimentary rocks of the Fars and Kuhgiluyeh Boyerahmad Provinces.

Kaolinite, smectite, chlorite, illite, palygorskite and illite-smectite interstratified minerals were detected in the rocks studied. The results revealed that detrital input is possibly the main source of kaolinite, smectite, chlorite and illite, while in situ neoformation during the Tertiary shallow saline and alkaline environment could be the dominant cause of palygorskite occurrences in the sedimentary rocks.

The presence of a large amount of kaolinite in the Lower Cretaceous sediments and the absence or rare occurrence of chlorite, smectite, palygorskite and illite are in accordance with the warm and humid climate of that period. Smaller amounts of kaolinite and the occurrence of smectite in Upper Cretaceous sediments indicate the gradual shift from warm and humid to more seasonal climate. The occurrence of palygorskite and smectite and the disappearance of kaolinite in the late Palaeocene sediments indicate the increase in aridity which has probably continued to the present time.

KEYWORDS: clay minerals, palaeoclimate, sedimentary rocks, Iran.

Studies of the origin and the relative abundance of clay minerals can provide useful information on palaeoclimate, custasy, burial diagenesis, or reworking. Chamley (1998) and Bolle & Adatte (2001) provided convincing evidence that the presence of kaolinite, smectite, illite and chlorite in sediments of the Tethys area are the result of inheritance from soils and sediments subjected to a tropical or subtropical climate. The presence of kaolinite in Lower Cretaceous materials of Alava Block, Spain is also attributed to inheritance from soils developed on rocks in the source area (Sanguesa et al., 2000).

On the origin of palygorskite and sepiolite clay minerals, most evidence suggests that they have formed in perimarine environments where continental alkaline waters are concentrated by evaporation leading to solutions rich in Si and Mg which favour their formation (Pletsch et al., 1996).

According to Khormali & Abtahi (2003) the occurrence of kaolinite, illite and chlorite in soils of southern Iran is related mainly to their presence in the parent materials. Smectite, however, originated mainly from the transformation of illite and
palygorskite, and the distribution of palygorskite in the soils studied is related to its neoformation and/or inheritance from parent material.

Palaeoclimate studies based on the clay mineralogy of sediments have become a popular subject of research.

Illicite and chlorite are considered common by-products of weathering reactions with low hydrolysis typical of cool to temperate and/or dry climates (Li et al., 2000). Kaolinite is generally a by-product of highly hydrolytic weathering reactions in perennially warm humid climates and its formation requires a minimum temperature of 15°C. Kaolinite/smectite and smectite/illite ratios have been used as climatic indices by many researchers (Adatte et al., 2002; Fagel et al., 2003). The presence of abundant smectite is generally linked to transgressive seas and a warm climate with alternating humid and arid seasons (Adatte et al., 2002; Net et al., 2003). Dominance by palygorskite and sepiolite is related to more arid climate (Dixon & Weed, 1989).

Climatic evolution of the Tethys region was studied by Bolle & Adatte (2001). According to these authors, the abundance of kaolinite in the late Cretaceous and early Palaeocene sediments of coastal and continental areas of southern and southeastern Tethys margins indicates the presence of a warm and humid climate. Moreover the minimum soil temperature was at least 15°C during part of the year (Robert & Kennet, 1994). This climatic trend is also in agreement with the reports of Keller et al. (1998) and Adatte et al. (2002).

From the late Palaeocene to the early Eocene, the gradual disappearance of kaolinite in low latitudes was coincident with gradual increases in smectite, illite, chlorite, palygorskite and sepiolite, which indicates the progressive development of aridity and massive dryness and evaporation in the southeastern margins of Tethys (Robert & Chamley, 1991; Oberhansli, 1992; Bolle & Adatte, 2001).

In high latitudes, a warm and humid climate was still present and in fact was the warmest period of the entire Cenozoic, referred to as the Late Palaeocene Thermal Maximum or LPTM, characterized by an abundance of kaolinite (Thomas, 1990; Kennet & Stott, 1991; Strouhal, 1993; Zachos et al., 1993; Lu & Keller, 1995; Pardo et al., 1999).

Khademi & Mermut (1998) found abundant authigenically formed palygorskite and sepiolite in the Oligo-Miocene lacustrine sediments of the post-Tethyan era in central Iran. Older formations, including Cretaceous limestones and sandstones and Jurassic shale contain only traces of detrital palygorskite and in contrast they are dominated by kaolinite.

Due to the lack of information on the clay mineralogy of sediments of southern Iran, the present study in the Fars and Kuhgiluyeh Boyerahmad Provinces, as a major part of Tethys area, might be helpful in understanding the origin and distribution of clay minerals in the geological sediments and the palaeoclimatic evolution of that part of the country.

**MATERIALS AND METHODS**

**Site description**

The study area, i.e. the Fars and Kohgiluyeh Boyerahmad Provinces are located in southern part of Iran, at 49°50'–55°38' longitude and 27°3'–31°42' latitude, covering areas of ~121,825 km² and 15,563 km², respectively (Fig. 1).

**Geological setting**

The study region is a part of the Zagros orogenic area (Fig. 1). Elevation varies from 500 m in the south to ~4500 m above sea level (a.s.l) in northwestern areas. According to Zahedi (1976), the Zagros area underwent a relatively moderate orogenic phase (attenuated Laramian phase) near the end of the Cretaceous and the beginning of the Eocene, characterized by folding, emergence and erosion. The Laramian movements were succeeded by a shallow marine transgression. A later regression of the sea eastwards resulted in the formation of intermontane lakes in the Middle Tertiary, which may have produced an environment conducive to the formation of fibrous clay minerals. Therefore the study area is part of the post-Tethyan Sea environment which is rich in evaporites (salts and gypsum) in most of the southern and southwestern parts.

The main geological formations of southern Iran, in chronological order, are shown in Figs 2 and 3. The brief descriptions of the geological formations are as follows:

- **Cambrian rock units.** The oldest recognizable rock unit is the evaporitic-volcanic Hormoz Formation in the salt plugs. It consists mainly of salt, anhydrite, dolomites, basic igneous rocks, red
Fig. 1. Map of the study areas: (1) Fars Province and (2) Kugiluyeh Buyerahmad Province.

siltstones, rhyolites, purple grey tuffaceous and micaceous sandstones and mudstones (James & Wynd, 1965; Stocklin, 1968).

Lower Cretaceous rock units. The Khami Group comprising the Dariyan, Gadvan, Fahlivan and Surmeh Formations are the main Lower Cretaceous rock units of the southern Iran. The Fahlivan Formation (Neocomian) is composed of massive and thick-bedded dolomitic limestones. Low-weathering, thin-bedded grey limestones and marlstones and Orbitolina limestones form the main rock types of the Gadvan (late Neocomian to Aptian) and Dariyan Formations (Aptian), respectively.

Mid- and Upper Cretaceous rock units. Bangestan limestone which has been referred to as the Mid-Cretaceous limestone, consists mainly of the Sarvak, Iram and Kazhdumi Formations. The Sarvak Formation (Albian to early Cenomanian and probably to Turonian) is composed of argillaceous limestone. The Gurpi-Pabdeh Formation (Santonian to Maastrichtian) consists mainly of marl and shale.

The Tarbur Formation (late Campanian-Maastrichtian) underlying the Sachun Formation (late Maastrichtian-early Eocene) consists of anhydrite limestones. The Sachun Formation (late Maastrichtian to early Eocene) consists of marlstones and limestones. The upper part is composed of massive gypsum, marls and ribs of dolomites.

Tertiary rock units. The Asmari Formation (Oligocene to early Miocene) is composed of well jointed limestones (Stocklin, 1968). The Asmari serves as a reservoir for most of the oil produced in southern Iran. Fossiliferous limestones are the main rock types found in the Jahrom Formation (Palaeocene to late Eocene). The Razak Formation (early Miocene) comprises silty marls. The Gachsaran Formation (early Miocene) is characterized by extreme mobility and evaporite sediments, with alternating layers of anhydrite and marl.

The Mishan Formation (Middle Miocene), which underlies the Gachsaran Formation (early Miocene) contains ferruginous materials at its base. The Agha
Jari Formation (late Miocene to Pliocene), consists of sandstones and marlstones. The Bakhtyari Formation (late Pliocene to Pleistocene) comprises conglomerate, sandstone and gritstone.

Quaternary alluvial deposits. Quaternary deposits covered the surface of all of the alluvial fans. Their grading is different due to their distance from the older geological formations of the area.

Climate

Due to the geographic location of the Zagros mountain range, a major part of the rain-producing air masses enter the region from the west and the northwest, with relatively high levels of annual precipitation for those areas (800–1000 mm). Towards south and southeast, there is a smaller amount of rainfall. The mean annual precipitation for the study area is in the range of 100–1000 mm (MPB, 1994).

Sampling

Sixteen major geological strata were sampled for mineralogical, submicroscopic, thin-section and chemical studies (Fig. 3). Rocks belong to Lower Cretaceous (R15, R16), Upper Cretaceous (R11, R12, R13, R14), Palaeocene-Eocene (R9, R10), Oligo-Miocene (R6, R7, R8), Miocene (R4, R5), Miocene-Pliocene (R3) and Pliocene-Pleistocene (R1, R2).
Chemical and mineralogical analyses

The cation exchange capacity (CEC) of each clay was determined using sodium acetate (NaOAc) at a pH of 8.2 (Chapman, 1965). Removal of chemical cementing agents and separation of clay fractions were performed using the methods suggested by Mehra & Jackson (1960), Kittrick & Hope (1963) and Jackson (1975). Samples were ground and treated with sodium acetate (pH 5) to remove carbonates. The addition of 1 N sodium acetate was continued until no effervescence was observed with 1 N HCl (Jackson, 1975). The reaction was performed in a water bath at 80°C. The organic matter was oxidized by treating the carbonate-free soils with 30% H₂O₂, and digestion in a water bath. This treatment also dissolved MnO₂. Free Fe oxides were removed from the samples by the citrate dithionate method (Mehra & Jackson, 1960) and Fe was determined in the filtrated solution by means of atomic absorption.

Fe-free samples were centrifuged at 750 rpm for 5.4 min (RCF = 157 g, International IEC Centrifuge) and clay separates were removed. X-ray diffraction (XRD) studies were carried out using a Philips X-ray diffractometer with Cu-Kα radiation.

The 001 reflections were obtained following Mg saturation, ethylene glycol solvation and K saturation. The K-saturated samples were studied both after drying and heating at 330°C and 550°C for 4 h. To identify kaolinite in the presence of trioctahedral chlorite, samples were also treated with 1 N HCl at 80°C, overnight. The percentages of the clay minerals were estimated according to Johns et al. (1954). In this method, the major clay minerals ratio of X-ray peak areas in the glycol-treated samples is considered a semi-quantitative measure of their occurrences. Alkaline-earth carbonate (lime) was measured by acid neutralization and gypsum (CaSO₄·2H₂O) was determined by precipitation with acetone (Salinity Laboratory Staff, 1954).
Table 1. Thin-section description of some selected rock samples.

<table>
<thead>
<tr>
<th>Rock</th>
<th>Geological formation</th>
<th>Thin section description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Bakhtiyari (Pliocene-Pleistocene) (Laar area)</td>
<td>Wackestone, 70% very fine-grained micrites, 30% small fossils, formed in a low-energy environment</td>
</tr>
<tr>
<td>R6</td>
<td>Razak (Miocene) (Sarvestan area)</td>
<td>Composed of clay and quartz grains</td>
</tr>
<tr>
<td>R8</td>
<td>Asmari (Oligocene-Miocene) (Laar area)</td>
<td>Floatstone, 20% large fossil fragments, 80% fine-grained matrix with high porosity</td>
</tr>
<tr>
<td>R9</td>
<td>Asmari-Jahrom (Eocene) (Sarvestan area)</td>
<td>Lime grainstone which is entirely composed of sparites up to 100 μm, formed in a high-energy environment</td>
</tr>
<tr>
<td>R11</td>
<td>Tarbur (Upper Cretaceous) (Zarghan area)</td>
<td>Rudstone, 50% large fossil fragments, 2 mm, and 50% coarse-grained sparites, formed in high-energy environment</td>
</tr>
<tr>
<td>R12</td>
<td>Gadvan (Upper Cretaceous) (Dehnaw area)</td>
<td>Grainstone, 98% pellets, 2% coarse-grained matrix, sparites, formed in a very-low energy environment</td>
</tr>
<tr>
<td>R13</td>
<td>Sarvak (Upper Cretaceous) (Takht Jameh Shid area)</td>
<td>Carbonate mudstone with &lt;10% allochons and is entirely composed of micritic calcite and the remains of animals, indicating a low-energy environment; carbonate tidal flats, lagoons, and restricted area</td>
</tr>
<tr>
<td>R16</td>
<td>Dariyan-Fahlisan (Lower Cretaceous) (Saadat Abad area)</td>
<td>Wackstone, 50% fossil fragment and 50% micrites, formed in a medium-energy environment, restricted area</td>
</tr>
</tbody>
</table>

Thin-section and submicroscopic studies (TEM and SEM)

Thin sections of ~10 cm² were prepared from rock samples using standard techniques. For transmission electron microscopy (TEM) studies, suspensions of 1:500 (g of dry clay/ml of water) were prepared from dried clay particles and 100 μl of the suspension were dried on 200-mesh formvar-coated Cu grids under a heat lamp for 25 min and examined using a LEO 906E transmission electron microscope. Small samples (~1 cm³) were studied by scanning electron microscopy (SEM). Rock samples were mounted on Al stubs using double-sided tape and carbon paste, then coated with Au and examined using a LEO SEM.

RESULTS AND DISCUSSIONS

As seen in Fig. 3, orogenic activity in Zagros near the end of Cretaceous and the beginning of Eocene resulted in outcrops of Cretaceous rocks mainly in northern parts of the study area with elevations of >3000 m a.s.l. This has resulted in retreatment of the Tethys Sea and the successive deposition of sediments toward the south, i.e. the Persian Gulf.

The sedimentary deposits throughout southern Iran are all calcareous. Table 1 summarizes the thin-section descriptions of some studied sediments. As seen, the rocks belong to the different types of calcareous sediments, with fossil inclusions. According to Table 2 all samples contain very small amounts of free Fe oxide, probably indicating weak weathering which occurred after their deposition. The maximum free Fe oxide in well drained soils of the Fars province was found to be around 1% in northwestern areas (Khormali & Aghta, 2003).

The sediments studied are highly calcareous (Table 2). The Gachsaran (R5) and Agha Jari Formations (R3) also include evaporite sediments. The gypsum content of those sediments is 74.7% and 3.4%, respectively. The soils formed adjacent to these formations are highly gypsic with low suitability for crop production. Figure 4 presents the SEM image of hemibipyramidal and subhedral gypsum in the Gachsaran Formation (R5).

The type and relative abundance of clay minerals in the studied rocks are presented in Table 2 and Fig. 5. Chlorite, illite, smectite, palygorskite, kaolinite and interstratified illite-smectite are the
Table 2. Clay mineralogy (%) and some chemical properties of the studied rock samples.

<table>
<thead>
<tr>
<th>Sample rock</th>
<th>Geological formation</th>
<th>Age*</th>
<th>CCE</th>
<th>Gyp</th>
<th>Fe₂O₃</th>
<th>Chl</th>
<th>Ill</th>
<th>Sm</th>
<th>Pal</th>
<th>Kao</th>
<th>Ill-Sm</th>
<th>CEC (mEq/100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Bakhtyari</td>
<td>P 98.8 n.d.**</td>
<td>0.03</td>
<td>20</td>
<td>25</td>
<td>15</td>
<td>40</td>
<td>n.d.</td>
<td>n.d.</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2 Bakhtyari</td>
<td>P 95.3 n.d.</td>
<td>0.08</td>
<td>20</td>
<td>30</td>
<td>15</td>
<td>35</td>
<td>n.d.</td>
<td>n.d.</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3 Agha Jari</td>
<td>MP 68.5 3.4</td>
<td>0.1</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>25</td>
<td>n.d.</td>
<td>n.d.</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4 Mishan</td>
<td>M 78.8 n.d.</td>
<td>0.2</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>n.d.</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5 Gachsaran</td>
<td>M 20.3 74.7</td>
<td>0.09</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>n.d.</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R6 Razak</td>
<td>OM 93 n.d.</td>
<td>0.03</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>n.d.</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7 Asmari</td>
<td>OM 97 n.d.</td>
<td>0.02</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>55</td>
<td>n.d.</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8 Asmari-Jahrom</td>
<td>E 95.2 n.d.</td>
<td>0.01</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>n.d.</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R10 Pabdeh</td>
<td>E 98.2 n.d.</td>
<td>0.3</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>n.d.</td>
<td>20</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R11 Tarbur</td>
<td>UCr 97.5 n.d.</td>
<td>0.03</td>
<td>15</td>
<td>15</td>
<td>25</td>
<td>n.d.</td>
<td>45</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R12 Gadvan</td>
<td>UCr 96.8 n.d.</td>
<td>0.01</td>
<td>15</td>
<td>20</td>
<td>15</td>
<td>n.d.</td>
<td>45</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R13 Sarvak</td>
<td>UCr 97.8 n.d.</td>
<td>0.04</td>
<td>10</td>
<td>15</td>
<td>5</td>
<td>n.d.</td>
<td>60</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R14 Sarvak</td>
<td>UCr 98 n.d.</td>
<td>0.07</td>
<td>15</td>
<td>15</td>
<td>10</td>
<td>n.d.</td>
<td>60</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R15 Bangestan</td>
<td>LCr 94 n.d.</td>
<td>0.07</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>n.d.</td>
<td>70</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16 Dariyan</td>
<td>LCr 96.9 n.d.</td>
<td>0.2</td>
<td>n.d.</td>
<td>5</td>
<td>n.d.</td>
<td>95</td>
<td>n.d.</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* P: Pliocene-Pleistocene; MP: Miocene-Pliocene; M: Miocene; OM: Oligocene-Miocene; E: Eocene; UCr Upper and Mid-Cretaceous; LCr: Lower Cretaceous
**n.d.: not detected; CCE: Alkaline Earth Carbonate; Gyp: Gypsum; Chl: Chlorite; Ill: Illite; Sm: Smectite; Pal: Palygorskite; Kao: Kaolinite; Ill-Sm:

major clay minerals. The relative abundances of the clay minerals are in accordance with their CEC values (Table 2).

As seen, kaolinite is present only in Cretaceous sedimentary rocks and are more prevalent in the Lower rather than Upper Cretaceous. Smectite is absent from the Lower Cretaceous rocks and appears in the Upper Cretaceous, late Paleocene and all other Tertiary and Quaternary rocks. Unlike kaolinite, palygorskite occurs only in Eocene and all other younger sediments and is absent from Cretaceous and late Paleocene rocks. The greatest abundance of this fibrous clay mineral is observed in the Oligo-Miocene sample (R8). Illite and chlorite are present in almost all rocks. A small amount of interstratified illite-smectite is seen in some samples.

**Origin of clay minerals in rocks**

Clay minerals present in the sedimentary rocks can be inherited or neformed. Inherited clay minerals provide information about the lithology and topography of the source area and about the

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**Fig. 4.** SEM image of the (a) hemibipyramidal, and (b) subhedral gypsum in Gachsaran Formation (R5).
climatic conditions prevailing during the time in which weathering and erosion take place. Neoformed clay minerals can give information about the physical and chemical conditions in the sedimentary environment (early diagenesis) and/or about the burial and thermal history of sediments (burial diagenesis).

According to Chamley (1998) the Tertiary limestone deposits of the Tethys area in the Arabian Peninsula are no more than 1500 m thick, indicating that sediments have not suffered deep burial diagenesis. The following evidence reported by Bolle & Adatte (2001) and Chamley (1998) were also found for southern Iran: (1) the almost constant but variable presence of smectite; (2) the co-existence of smectite with much kaolinite in the Upper Cretaceous and early Palaeocene samples and with palygorskite in other samples; and (3) the scarcity of mixed-layer illite-smectite. According to these findings, the distributions of the clay minerals in different sediments of southern Iran could indicate an inherited (detrital) origin for kaolinite, smectite, illite and chlorite.

According to the present study, detrital input is probably the dominant factor responsible for the presence of large amounts of kaolinite in Cretaceous rocks, which was developed under tropical soils, characterized by warm, humid climates, well drained areas with high precipitation and accelerated leaching of the parent rocks. The presence of kaolinite in the studied soils of arid and semi-arid regions of the study area is attributed to its inheritance from surrounding parent rocks (Khormali & Abtahi, 2003). The greater occurrence of kaolinite was observed in pedons adjacent to the Cretaceous outcrops. There was no (or only traces of) kaolinite detected in soils of the southern parts of the study area where Cretaceous sediments are almost absent.

Chlorite, illite and associated quartz and feldspar typically constitute terrigenous species (Chamley, 1998). These clay minerals generally develop in areas of steep relief where active mechanical erosion limits soil formation, particularly during periods of enhanced tectonic activity (Millot, 1970; Chamley, 1998).

The presence of palygorskite and sepiolite in Tertiary sediments of the southern margin of Tethys has been related to their authigenic formation in shallow saline and alkaline environment (Robert & Chamley, 1991; Hillier, 1995; Charisi & Schmitz, 1995; Pletsch et al., 1996).

As seen in Fig. 6, the presence of large amounts of highly crystalline elongated palygorskite as confirmed by a sharp peak in the XRD patterns, may be an indication of in situ neoformation during the Tertiary shallow saline and alkaline environment. Shallow water and high temperature increase the pH and consequently enhance Si solubility. These conditions seem to have been provided in the area during the Tertiary, whereas the absence or rare occurrence of this clay mineral in Cretaceous deep-sea sediments probably indicate the lack of those conditions at that time (Fig. 7). Hexagonal kaolinite dominates the clay mineral portion of these sediments.

Khadem & Mermut (1998) examined the textural relations of palygorskite in the Oligo-Miocene
limestone and suggested that this mineral was formed authigenically as it enmeshes calcite crystals and sprouts out from their surfaces. Interestingly, the same geological formations in different regions of southern Iran also show the same clay mineralogical pattern (e.g. R1 and R2, R7 and R8 or R13 and R14) which could indicate the presence of a similar palaeoclimate in different areas, during their deposition.

Fig. 6. TEM image (a) and XRD patterns (b) of the carbonate-free clay fraction showing highly crystallized palygorskite in an Oligo-Miocene rock sample (R8).

No smectite was detected in Lower Cretaceous sediments, probably due to the warm and humid environment of that period which was suitable for the formation of kaolinite (Fig. 7). The occurrence of smectite in Upper Cretaceous and early Palaeocene might be an indication of a gradual shift of the warm and humid climate to more seasonal and increasing aridity. The presence of 10–30% of smectite and 20–40% of palygorskite in Eocene and younger sediments indicates their
stability under the arid climate which was dominant from the beginning of Tertiary in this region (Fig. 8).

It has been shown that the southern margin of the Tethys corresponded to a relatively stable period, with no hydrothermal or volcanic activity (Oberhansli, 1992; Charisi & Schmitz, 1995). Thus, smectite appears to be mostly of detrital origin and can issue from soils developed under a warm to temperate climate characterized by alternating humid and dry seasons.

Mixed-layer illite-smectite is also detected in Eocene-Oligocene sediments reflecting the presence of seasonal climates and an increase of aridity. Climatic conditions might have allowed their formation in poorly drained soils and their subsequent inheritance in the sediments (as confirmed by Deconinck & Chamley, 1995). Table 3 summarizes the most likely origins of the clay minerals in the parent rocks of southern Iran. Neoformation is the most likely dominant process in the formation of palygorskite. Other clay minerals seem to be mainly detrital.

Reconstruction of the palaeoclimate of southern Iran

The climatic evolution of the Tethys in southern Iran, as inferred from clay mineralogy of parent rocks of the study area, is shown in Fig. 9. It is evident that southern Iran had almost the same climatic trend as reported by Bolle & Adatte (2001) for southeastern Tethys. The presence of much kaolinite and the absence or rare occurrence of chlorite, smectite, palygorskite and illite in the Lower Cretaceous sediments is in accordance with a warm and humid climate during that period. However, smaller amounts of kaolinite and the occurrence of smectite in the Upper Cretaceous sediments indicate a gradual shift from a warm and humid to a more seasonal climate.

Adatte et al. (2002) investigated the clay mineralogy of Cretaceous-Tertiary sediments in Tunisia and suggested that the climate across the Cretaceous-Tertiary transition alternated between warm and humid periods and drier periods with increasing seasonality. According to those authors, high kaolinite/smectite ratios, the small chlorite content and very scarce mica indicate an overall warm and humid climate from the Maestrichtian Zone to the Lower Palaeocene Zone while a decrease in the kaolinite/smectite ratio corresponds to generally increased smectite during transgressive intervals under more seasonal conditions.

The disappearance of kaolinite and the presence of some palygorskite and smectite in the late Palaeocene sediments indicate the increase in aridity. This absence of kaolinite shows that southern Iran might have not experienced the LPTM period with its characteristic warm and
Table 3. Most likely origin of clay minerals in the studied parent rocks of southern Iran.

<table>
<thead>
<tr>
<th>Clay mineral</th>
<th>Detrital (inherited)</th>
<th>Diagenesis</th>
<th>In situ neoformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>+++</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Smectite</td>
<td>+++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Palygorskite</td>
<td>−</td>
<td>−</td>
<td>+++</td>
</tr>
<tr>
<td>Illite</td>
<td>+++</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Chlorite</td>
<td>+++</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

+++: Major importance  ++: Moderate importance  +: Minor importance  −: No importance

humid climate which is also reported for coastal areas of the Arabian Peninsula (Bolle, 1999).

The same results were also reported for the Tethyan Sea environment of central Iran (Khademi & Mermut, 1998). Based on their studies, authigenically formed palygorskite and sepiolite is predominant in the lacustrine sediments of the post-Tethyan era (Oligo-Miocene epoch). Older formations, including Cretaceous limestones and sandstones and Jurassic shale contain only traces of detrital palygorskite and in contrast they are dominated by kaolinite.

The results of the sulphur isotope geochemistry of gypsiferous Aridisols of central Iran strongly support the hypothesis that the central Iran was cut off from the Tethys seaway at the end of the

Fig. 9. Climatic evolution of the Tethys area of southern Iran based on the clay mineralogy of the studied parent rocks. (K: Kaolinite; P: Palygorskite; S: Smectite; I: Illite; C: Chlorite; M-S: Mica-smectite; * after Krinsley (1970)).
Mesozoic era, and as a result, the Lower Cretaceous sulphate has controlled the sulphur geochemistry of the younger sediments (Khademi et al., 1997).

The maximum amount of palygorskite (65%) detected in the studied sediments of the Oligo-Miocene confirms the presence of the former shallow lakes, a suitable environment for the formation of fibrous clay minerals (Fig. 9). Through volcanic activity during the Tertiary, thermal waters charged with dissolved Si for the formation of palygorskite and sepiolite. The associated dolomitic sediments in the study area, as reported by Ghazban et al. (1994) probably provided enough Mg for this process.

The period of aridity continues to the present time (Fig. 9). There are some fluctuations, however, in the late Pleistocene as reported by Krinsley (1970) with a predominance of cold and arid climate. A late Quaternary period in Australia was also believed to have a more arid climate which was affected by glacial cycles (Hesse et al., 2004).

**CONCLUSIONS**

Detrital input is probably the main factor responsible for the presence of large amounts of kaolinite in Cretaceous rocks. Chlorite, illite and smectite are also believed to be mainly of detrital origin. In situ neoformation during the Tertiary shallow saline and alkaline environment is the main source of palygorskite in sedimentary rocks. The climatic evolution of the Tethys in southern Iran, as shown by the clay mineralogy of the parent rocks of the Fars and Kohgiluyeh Buyerahmad Provinces reveal that the presence of a large amount of kaolinite in the Lower Cretaceous and the absence or rare occurrence of chlorite, smectite, palygorskite and illite are in accordance with a warm and humid climate during that period. However, smaller amounts of kaolinite and the occurrence of smectite in the Upper Cretaceous indicate the gradual shift from a warm and humid to a more seasonal climate. The disappearance of kaolinite and the presence of some palygorskite and smectite in the late Palaeocene sediments indicate the increase in aridity which continues to the present time.

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