



## Geochemical Analysis of Early–Middle Jurassic Shales from Northern Iraq: Provenance, Tectonic Setting, and Paleoweathering Conditions

Farhad Ahmed Mohammad\*

Department of Earth Sciences and Petroleum, College of Science, Salahaddin University, Erbi, Kurdistan Region, Iraq. ORCID: <https://orcid.org/0009-0002-5350-9356>, E-mail: [farhad.mohammad@su.edu.krd](mailto:farhad.mohammad@su.edu.krd)

### Abstract

The Early–Middle Jurassic formations are regarded as important source rocks in the petroleum system of North Iraq. These formations contain papery shales between limestone and dolomite beds, and the major and trace elements of (early–middle) Jurassic shales in the Imbricated Zone, northern Iraq, were analyzed. In this study, the sediment provenance and tectonic setting were investigated, in addition to evaluating the conditions of paleoweathering in the source area. The elemental ratios in the Sehkanian and Sargelu shales, i.e.,  $\text{Al}_2\text{O}_3/\text{TiO}_2$ ,  $\text{Th}/\text{Sc}$ ,  $\text{La}/\text{Th}$ ,  $\text{Co}/\text{Th}$ ,  $(\text{Gd}/\text{Yb})_n$ ,  $\text{Eu}/\text{Eu}^*$ , and REE patterns, in addition to tectonic discrimination diagrams, indicated that they were derived from intermediate to felsic source rocks and deposited on an active collisional continental margin. REE patterns are characterized by significant LREE enrichment, negative Eu anomalies and relatively flat HREEs, which are typical of upper crustal rocks. The average  $\text{Th}/\text{Sc}$  ratios (0.52 and 0.67 for Sehkanian and Sargelu, respectively) of the studied samples are somewhat similar to those of upper crustal UCC 0.7 intermediate source rocks. The chemical index of alteration (CIA) (65 and 70 for Sehkanian and Sargelu, respectively) and the index of compositional variability (ICV) (1.02 and 1.46, respectively) represent immature compositions with the first cycle deposited in active tectonic settings. The  $\text{Al}_2\text{O}_3 - (\text{CaO}^* + \text{Na}_2\text{O}) - \text{K}_2\text{O}$  (A–CN–K) triangular diagram of the shale suggested a moderate intensity of alteration (Figure 5). Owing to carbonate dilution, source–rock composition, sediment recycling, diagenetic alteration and tectonic activity, the intensity of weathering is moderate for both formations but increases from early to Middle Jurassic.

### Keywords

*Sehkanian Formation; Source rocks; Barzewa; Elemental ratio; Sargelu Formation.*

Available Online: 10/09/2026

---

### Introduction

The Sehkanian and Sargelu Formations are among the most well-known formations in the Early–Middle Jurassic successions (Jassim and Goff, 2006) (Al-Ameri and Al-Nagshbandi, 2015). These two formations contain papery shales between limestone and dolomitic limestone beds (Rasool, R.H. et al., 2025); because these two formations are regarded as important source rocks in the petroleum system of northern Iraq, two sections of these formations were chosen for this study, which are near Barzewa Village (latitude: 38°S 0475516; longitude: 40°E 1633) NE Erbil Governor. Thicknesses of the two formations (85 m and 76 m) are shown in Figure 1.

In an attempt to explain the past formation conditions of the Sehkanian and Sargelu Formations (Early–Middle Jurassic), the major and trace elements in the shales were analyzed in the Barzewa area of the Imbricated Zone, North Iraq.

---

\*Corresponding Author: Farhad Ahmed Mohammad, E-mail: [farhad.mohammad@su.edu.krd](mailto:farhad.mohammad@su.edu.krd)

The geochemistry of siliciclastic rocks has been widely used to determine the source rock composition or provenance (Armstrong-Altrin et al., 2014, 2015a), (Zimmermann and Spalletti, 2009), weathering intensity (Srivastava et al., 2013; Zhang et al., 2013), diagenesis process (Zaid et al., 2015), and tectonic setting (Verma and Armstrong-Altrin, 2016). The  $\text{Al}_2\text{O}_3/\text{TiO}_2$  values, REE patterns and element ratios, Th/Sc, La/Th, La/Sc, Co/Th, (Gd/Yb)<sub>n</sub>, and Eu/Eu\*, were used to determine the source rocks of the Sehkanian and Sargelu Formations, while a binary diagram of  $\text{SiO}_2$  vs.  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  was used to explain the tectonic setting; likewise, the chemical index of alteration (CIA) was used to determine the intensity of weathering of the Sehkanian and Sargelu Formations in the Barzewa area.

The different behaviors of the elements and chemical variations during the erosion and sedimentation stages may explain the sedimentary evolution and geological processes affecting siliciclastic sediments in addition to preserving the distribution of these elements; hence, the relationship between the source area and sedimentary basin can be determined.

The main purpose of this study is to identify the source rock characteristics, tectonic setting, and paleoweathering conditions by using major, trace, and rare earth element geochemistry of early–middle Jurassic formations exposed in the Barzewa area, Imbricated Zone, northern Iraq.



**Figure 1. Google Earth map showing the Barzewa area, which is located NE of Erbil Governorate, Kurdistan Region, Iraq.**

## 2. Geological setting

In the Early–Middle Jurassic, deposition occurred in restricted and deep water (Jassim and Goff, 2006). The Balambo–Tanjero Zone (BTZ) was a trough that developed along the plate boundary during the opening of the southern Neo-Tethys region during the Middle Jurassic. It extends from the Iranian border in the SE to the

Turkish border in the NW (Keshmiri et al., 2026). The zone may be completely overridden by the Northern Thrust Zone in northern Iraq and partly by units of the Zagros Suture in NE Iraq (Figure 2).

The BTZ is strongly folded and faulted, and the structures within the zone generally trend NW–SE, except in the area NW of the Greater Zab River, where the strike shifts in the E–W direction. Longitudinally, the BTZ can be subdivided into two belts. The NE belt is a depression with Paleogene clastics and forms a monocline dipping to the NE below the thrust sheets of the Zagros Suture (Jassim and Goff, 2006). The SW part (where Paleogene clastics are absent) is described by closely packed folds with several parallel or often obliquely (NNW–SSE) trending reverse faults or minor thrusts. This area was uplifted during the Tertiary and formed a ridge between the BTZ and the Zagros Suture. The study area is represented by two formations: Sehkanian and Sargelu, which belong to the Early–Middle Jurassic and are situated in the NE belt of the Balambo–Tanjero Zone in the Imbricated

Zone. These formations are widely exposed in the Imbricated Zone and somewhat in the High Folded Zone (Sissakian and Fouad, 2012). Table 1 shows brief lithological descriptions, thicknesses and ages of the Sehkanian and Sargelu formations.

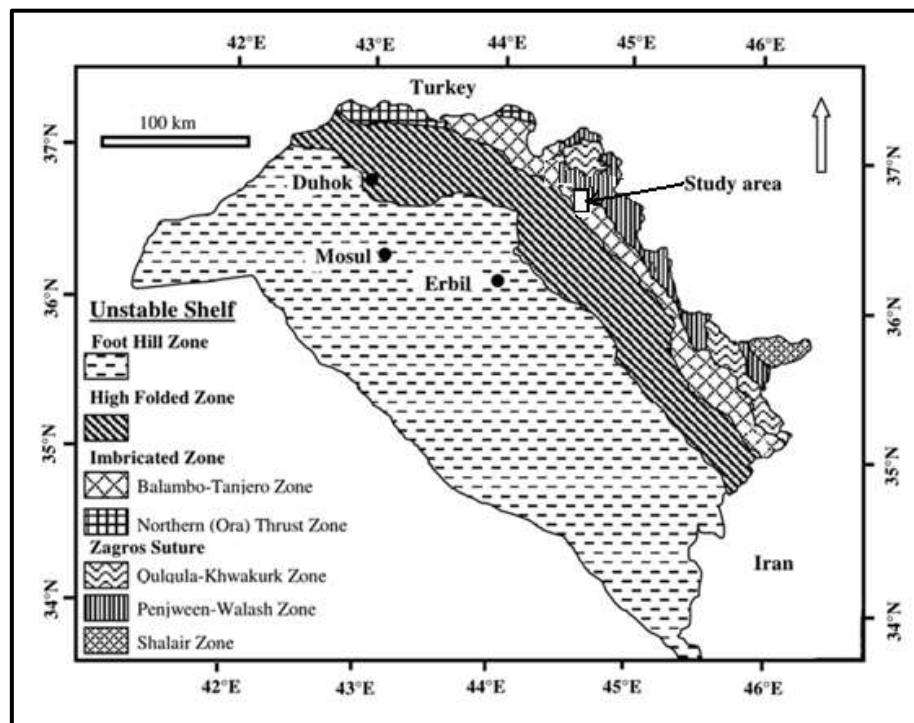


Figure 2. Location and structural map of the study area, Barzewa, North Iraq.

Table 1. Lithostratigraphic section for the Early–Middle Jurassic Formations, North Iraq

| Period   | Epoch  | Age           | Formations | Thickness (m) | Lithologic description                                                    |
|----------|--------|---------------|------------|---------------|---------------------------------------------------------------------------|
| Jurassic | Middle | Bathonian     | Sargelu    | 76            | Thin bedded, black, dolomitic limestones and gray to black, papery shales |
|          |        | Bajocian      |            |               |                                                                           |
|          | Early  | Pliensbachian | Sehkanian  | 85            | dolomitic limestones bedded and gray papery shales                        |
|          |        | Sinemurian    |            |               |                                                                           |

### 3. Sampling and analytical methods

Twenty-one (21) shale samples were collected from the Sehkanian and Sargelu formations (11 and 10, respectively) from the outcrop near Barzewa Village. Samples were taken from the bottom of the formation up to the top; because of the relatively scant shale in the Sehkanian Formation, 11 samples were taken randomly without a regular pattern; whenever foliated shale appeared between the dolomitic limestone layers, these 11 samples covered the overall thickness of the Sehkanian Formation, whereas owing to the abundant shale in the Sargelu Formation, 10 samples were taken in a regular pattern, with sample intervals every 7.5 m. The collected samples were washed thoroughly in distilled water to remove contamination. Representative rock samples were powdered and processed for their analyses (major, trace, and rare earth elements). Major oxides ( $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ ) were analyzed by X-ray fluorescence spectrometry (XRF) to determine the main oxides (Philips PW-1410 XRF spectrometer).

Trace and rare-earth elements were analyzed by using inductively coupled plasma–mass spectrometry (ICP–MS) at the ALS international laboratory in Spain (code ME-MS61r). The internationally recognized standard reference materials OREAS72B, SO-18 and OREAS45EA were used for reference. Repeated analyses of samples indicate

that the error for major elements is less than 2%, whereas the precision for other elements varies from 1 to 10%. On the basis of the abovementioned standards, The accuracy and precision of the analysis were within  $\pm 2\%$  for Zn, V, Zr, Y, La, Sm, Tb, Dy, Tm, Yb, and Lu;  $\pm 5\%$  for Ni, Mn, Cu, Cr, Co, and Eu; and  $\pm 10\%$  for Hf and Er. Comparisons between this study and the Post-Archean Australian Shale (PAAS) data of Taylor and McLennan (1985) were performed whenever possible. The REE contents were normalized to the chondrite values of Taylor and McLennan (1985). The normalized Eu anomaly ( $\text{Eu}/\text{Eu}^*$ ) is also a useful discriminator between samples and between plate-tectonic settings (McLennan, 1989;  $\text{Eu}/\text{Eu}^* = \text{Eu}_n / (\text{Sm}_n \times \text{Gdn})^{1/2}$ , where the subscript n refers to chondrite-normalized values).

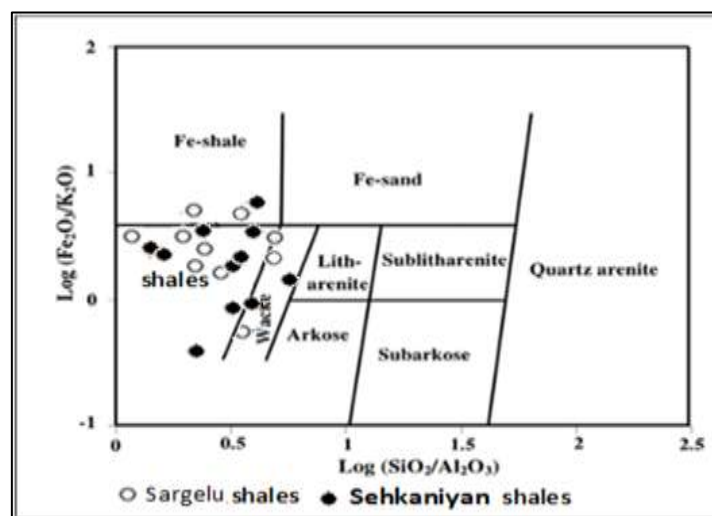
#### **Ethical Considerations**

No human subjects, animal experiments, or other personal confidential information was used in this study. Thus, ethical approval was unnecessary. All methods and procedures used in this study comply with institutional, national, and international guidelines and regulations applicable to the field of research. The authors affirm that there are no ethical conflicts or issues associated with this work.

## **4. Results**

### **4.1. Major Elements**

Table 2 presents the major element data for the studied shales. The contents of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  in the Sehkaniyan and Sargelu shales are moderate and nearly similar. Several elements ( $0.775^{**}$ ,  $0.529^*$  and  $0.696^*$   $\text{Al}_2\text{O}_3$ ) are clearly positively correlated with  $\text{K}_2\text{O}$ . The average  $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$  ratios for the Sehkaniyan and Sargelu shales are 0.25 and 0.26, respectively (Table 2). This ratio can be employed to predict the original composition of ancient sediments (Cox and Lowe, 1995). The Early–Middle Jurassic shales have high  $\text{CaO}$  contents that are significantly correlated with the LOI ( $0.645^*$ ) (Table 3). The  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratios (2.96 and 0.82 for Sehkaniyan and Sargelu, respectively) are clearly lower than those of the UCC (4.34), and the  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  ratios (37 and 34.37 for Sehkaniyan and Sargelu, respectively) are higher than the UCC ratio (0.87; Taylor and McLennan, 1985; Condie, 1993). The  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios of the investigated sediments (72.8 and 68.60 for Sehkaniyan and Sargelu, respectively) are higher than the ratio of PAAS (19.0; Taylor and McLennan, 1985). Titanium is concentrated mainly in phyllosilicates (Condie et al., 1992), is immobile relative to other elements during several sedimentary processes and may strongly represent source rocks (McLennan et al., 1993). The Early–Middle Jurassic shales have lower  $\text{TiO}_2$  concentrations for Sehkaniyan and Sargelu (0.39 and 0.296, respectively) than the PAAS (0.99) (Taylor and McLennan, 1985). Compared with the PAAS, the Sehkaniyan and Sargelu shales are characterized by higher  $\text{P}_2\text{O}_5$  contents and are significantly positively correlated with redox-sensitive elements (Co  $0.481^*$ , V  $0.398$ , and U  $0.461^*$ ). To characterize the type of the present rock samples, a diagram of  $\log \text{SiO}_2/\text{Al}_2\text{O}_3$  vs.  $\log \text{Fe}_2\text{O}_3/\text{K}_2\text{O}$  following Herron (1988) is used. The samples are classified as shale, wacke and Fe-shale for the Sehkaniyan and Sargelu Formations, as shown in Figure 3.



**Figure 3. Chemical Classification of sedimentary rocks from Early–Middle Jurassic Formations in northern Iraq on the basis of major element composition (Herron, 1988)**

| Sampl.n                        | Sehkaniyan |       |           |       |           |       |           |       |           |        |           |            |       |
|--------------------------------|------------|-------|-----------|-------|-----------|-------|-----------|-------|-----------|--------|-----------|------------|-------|
|                                | She1       | She2  | She 3     | She4  | She 5     | She6  | She7      | She8  | She 9     | She1 0 | She 11    | Av.        | PAA S |
| SiO <sub>2</sub>               | 12.6       | 11.12 | 12.1<br>1 | 10.7  | 12.8      | 11.16 | 14.1<br>4 | 13.11 | 10.1<br>4 | 11.14  | 13.1<br>1 | 12.02      | 62.4  |
| Al <sub>2</sub> O <sub>3</sub> | 26.46      | 24.86 | 30.8<br>8 | 25.42 | 25.4<br>2 | 32.42 | 28.6<br>2 | 28.44 | 32.3<br>6 | 29.11  | 28.4<br>6 | 28.40      | 18.78 |
| Fe <sub>2</sub> O <sub>3</sub> | 1.14       | 2.8   | 3.2       | 2.6   | 1.8       | 2.82  | 3.4       | 1.8   | 3.4       | 2.4    | 2.6       | 2.67       | 7.18  |
| CaO                            | 24.4       | 22.2  | 21.2      | 16.6  | 23.2      | 22.4  | 22.6      | 18.6  | 20.1<br>6 | 23.8   | 24.1<br>2 | 21.75      | 1.29  |
| MgO                            | 2.66       | 2.96  | 3.76      | 4.22  | 0.68      | 1.44  | 4.36      | 2.18  | 3.34      | 0.74   | 2.34      | 2.60       | 2.19  |
| Na <sub>2</sub> O <sub>3</sub> | 0.06       | 0.04  | 0.04      | 0.02  | 0.03      | 0.06  | 0.02      | 0.06  | 0.04      | 0.02   | 0.04      | 0.04       | 1.19  |
| K <sub>2</sub> O               | 1.58       | 1.78  | 1.68      | 1.28  | 2.36      | 1.46  | 1.24      | 0.96  | 2.34      | 3.16   | 1.72      | 1.48       | 3.68  |
| TiO <sub>2</sub>               | 0.66       | 0.45  | 0.36      | 0.26  | 0.32      | 0.38  | 0.44      | 0.38  | 0.36      | 0.26   | 0.46      | 0.39       | 0.99  |
| P <sub>2</sub> O <sub>5</sub>  | 0.18       | 0.14  | 0.17      | 0.08  | 0.21      | 0.32  | 0.16      | 0.28  | 0.31      | 0.08   | 0.16      | 0.19       | 0.16  |
| LOI                            | 36.21      | 34.42 | 32.4      | 38.24 | 32.4      | 30.8  | 31.3<br>6 | 36.42 | 32.4<br>2 | 33.22  | 35.4<br>2 | 33.94      | 6     |
| Total                          | 99.47      | 99.77 | 99.4<br>1 | 99.84 | 99.2<br>2 | 99.26 | 99.3<br>2 | 99.98 | 99.8<br>7 | 99.93  | 99.4<br>8 | 99.59      |       |
| As                             | 35.9       | 44.6  | 16.8      | 12.2  | 29.6      | 26.8  | 28.8      | 24.3  | 24.6      | 14.8   | 36.8      | 26.84      |       |
| Ba                             | 68         | 86    | 64        | 48    | 56        | 64    | 76        | 88    | 68        | 72     | 66        | 68.73      | 650   |
| Cd                             | 0.44       | 7.22  | 12.4      | 8.24  | 6.8       | 11.6  | 16.1<br>8 | 7.28  | 6.44      | 12.16  | 14.2      | 9.36       |       |
| Co                             | 4.6        | 28.4  | 10.2      | 8.2   | 12.6      | 6.4   | 8.6       | 28.4  | 6.4       | 14.3   | 8.68      | 12.43      | 23    |
| Cr                             | 52         | 44    | 68        | 54    | 44        | 72    | 38        | 42    | 76        | 116    | 74        | 61.82      | 110   |
| Cs                             | 23         | 20.5  | 6.5       | 1.68  | 1.24      | 12    | 4.46      | 10.6  | 4.46      | 14.4   | 18.6      | 10.68      | 15    |
| Cu                             | 34.2       | 68.4  | 114       | 42.6  | 82.8      | 26.2  | 38.2<br>2 | 32.22 | 52.8      | 52.60  | 48.7<br>8 | 53.89      | 50    |
| Hf                             | 4.4        | 4.6   | 1.6       | 0.8   | 1.4       | 6.8   | 7.4       | 8.42  | 1.68      | 6.46   | 5.68      | 4.3        | 5     |
| Li                             | 32.2       | 28.4  | 12.2      | 10.6  | 14.4<br>6 | 46.4  | 36.2      | 8.46  | 10.4<br>4 | 12.64  | 34.4      | 22.4       |       |
| Mn                             | 134        | 84    | 52        | 56    | 132       | 88    | 112       | 132   | 114       | 44     | 76        | 93.1       | 850   |
| Mo                             | 33.4       | 62.6  | 236       | 364   | 368       | 358   | 46.3<br>2 | 66.7  | 312       | 232    | 78.4      | 196.1<br>3 |       |
| Nb                             | 10.6       | 9.8   | 6.34      | 8.8   | 6.4       | 12.33 | 10.3<br>4 | 10.68 | 8.44      | 6.2    | 6.8       | 8.79       | 19    |
| Ni                             | 32         | 346   | 416       | 324   | 378       | 268   | 362       | 314   | 276       | 82     | 76        | 261.2<br>7 | 55    |
| P                              | 320        | 360   | 710       | 530   | 570       | 890   | 1230      | 1300  | 634       | 1440   | 860       | 804        | 350   |
| Pb                             | 11.4       | 19.3  | 6.8       | 7.7   | 5.34      | 7.42  | 8.26      | 9.42  | 4.16      | 12.3   | 14.2      | 9.66       | 20    |
| Sb                             | 3.16       | 2.78  | 16.8      | 14.2  | 3.86      | 8.4   | 5.16      | 6.46  | 3.44      | 8.4    | 12.8      | 7.77       |       |
| Sc                             | 10.6       | 6.36  | 9.6       | 8.7   | 8.6       | 5.2   | 10.3      | 8.7   | 6.12      | 4.6    | 7.71      | 7.86       | 16    |
| Sr                             | 106        | 127   | 390       | 382   | 472       | 468   | 740       | 432   | 268       | 216    | 98.2      | 336.2<br>9 | 200   |
| Th                             | 8.6        | 7.4   | 5.4       | 3.4   | 11.6      | 14.6  | 10.8      | 4.6   | 8.23      | 6.22   | 8.46      | 8.21       | 14.6  |

|                                                    |      |      |           |      |      |      |      |      |      |       |      |            |      |
|----------------------------------------------------|------|------|-----------|------|------|------|------|------|------|-------|------|------------|------|
| <b>U</b>                                           | 8.4  | 16.4 | 21.1<br>4 | 32.6 | 34.2 | 16.4 | 24.5 | 36.2 | 14.2 | 52.4  | 22.6 | 25.37      | 3.1  |
| <b>V</b>                                           | 420  | 183  | 384       | 463  | 182  | 560  | 386  | 580  | 168  | 296   | 334  | 359.6<br>4 | 150  |
| <b>Y</b>                                           | 9.6  | 9.8  | 8.8       | 10.6 | 13.8 | 24.6 | 32.8 | 32.2 | 20.2 | 24.8  | 18.4 | 18.69      | 27   |
| <b>Zn</b>                                          | 446  | 54   | 120       | 362  | 264  | 188  | 143  | 95   | 73   | 245   | 334  | 211.2<br>7 | 85   |
| <b>Zr</b>                                          | 78.4 | 34.4 | 23        | 54.2 | 17.3 | 64.6 | 74.4 | 85.4 | 52.6 | 21.2  | 42.6 | 49.83      | 210  |
| <b>SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub></b> | 0.23 | 0.45 | 0.2       | 0.4  | 0.5  | 0.25 | 0.25 | 0.39 | 0.16 | 0.25  | 0.15 | 0.29       | 3.3  |
| <b>K<sub>2</sub>O/Al<sub>2</sub>O<sub>3</sub></b>  | 0.26 | 0.33 | 0.32      | 0.25 | 0.25 | 0.23 | 0.23 | 0.32 | 0.17 | 0.24  | 0.16 | 0.25       |      |
| <b>K<sub>2</sub>O/Na<sub>2</sub>O</b>              | 26.3 | 19.5 | 17        | 64   | 78.7 | 7.7  | 62   | 11   | 58.5 | 158   | 43   | 37         | 3.1  |
| <b>Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub></b> | 40.1 | 55.2 | 85.8      | 97.8 | 79.4 | 85.3 | 65   | 74.8 | 89.9 | 111.9 | 61.9 | 72.8       | 19.0 |
| <b>CIA<sup>(a)</sup></b>                           | 60   | 62   | 69        | 69   | 60   | 69   | 65   | 70   | 69   | 62    | 62   | 65         | 75.3 |
| <b>ICV<sup>(b)</sup></b>                           | 1.15 | 1.18 | 0.96      | 1.02 | 1.12 | 0.58 | 1.12 | 0.83 | 0.92 | 1.04  | 1.1  | 1.02       |      |

Table 2. Major (in wt%) and trace (in ppm) element concentrations with major element ratios and CIA and ICV parameters for the early–middle Jurassic formations compared with those of the PAAS

Table 2. Continue

| Sampl.n                            | Sargelu   |           |       |           |       |       |       |       |       |       |            |
|------------------------------------|-----------|-----------|-------|-----------|-------|-------|-------|-------|-------|-------|------------|
|                                    | Sar 1     | Sar 2     | Sar3  | Sar 4     | Sar5  | Sar6  | Sar7  | Sar8  | Sar9  | Sar10 | Av.        |
| <b>SiO<sub>2</sub></b>             | 9.16      | 16.4<br>3 | 12.23 | 7.33      | 12.34 | 16.18 | 12.44 | 8.68  | 15.14 | 12.66 | 12.21<br>9 |
| <b>Al<sub>2</sub>O<sub>3</sub></b> | 10.8<br>2 | 21.1<br>4 | 18.46 | 16.8<br>8 | 22.14 | 23.44 | 20.82 | 26.24 | 23.88 | 24.24 | 20.30<br>6 |
| <b>Fe<sub>2</sub>O<sub>3</sub></b> | 3.14      | 2.8       | 1.9   | 2.2       | 1.2   | 3.82  | 2.4   | 1.6   | 3.2   | 1.4   | 2.466      |
| <b>CaO</b>                         | 16.4      | 20.2      | 24.6  | 26.2      | 18.2  | 10.21 | 18.2  | 21.2  | 18.86 | 20.8  | 20.48<br>7 |
| <b>MgO</b>                         | 14.5<br>6 | 12.2      | 3.44  | 3.22      | 4.22  | 4.96  | 1.4   | 2.44  | 2.46  | 1.88  | 5.078      |
| <b>Na<sub>2</sub>O<sub>3</sub></b> | 0.06      | 0.04      | 0.02  | 0.03      | 0.02  | 0.07  | 0.03  | 0.05  | 0.04  | 0.02  | 0.038      |
| <b>K<sub>2</sub>O</b>              | 2.6       | 1.4       | 1.6   | 0.94      | 0.68  | 1.52  | 1.36  | 1.78  | 1.66  | 0.96  | 1.306      |
| <b>TiO<sub>2</sub></b>             | 0.24      | 0.44      | 0.14  | 0.26      | 0.34  | 0.22  | 0.12  | 0.42  | 0.38  | 0.4   | 0.296      |
| <b>P<sub>2</sub>O<sub>5</sub></b>  | 0.06      | 0.44      | 0.08  | 0.22      | 0.07  | 0.17  | 0.14  | 0.12  | 0.42  | 0.28  | 0.2        |
| <b>LOI</b>                         | 34.2      | 24.8      | 37.2  | 42.4      | 40.2  | 38.6  | 42.4  | 36.6  | 34.32 | 36.72 | 36.74<br>4 |
| <b>Total</b>                       | 99.8<br>4 | 99.8<br>9 | 99.67 | 99.6<br>8 | 99.97 | 99.19 | 99.31 | 99.13 | 99.36 | 99.36 | 99.54      |
| <b>As</b>                          | 43.9      | 45.6      | 14.8  | 11.4      | 27.8  | 28.5  | 30.8  | 25.2  | 26    | 13.2  | 26.72      |
| <b>Ba</b>                          | 70        | 90        | 66    | 46        | 60    | 68    | 80    | 90    | 78    | 62    | 71         |
| <b>Cd</b>                          | 0.34      | 7.82      | 10.6  | 6.34      | 8.7   | 12.8  | 18.26 | 6.27  | 5.34  | 11.44 | 8.8        |
| <b>Co</b>                          | 6.5       | 32.4      | 8.6   | 6.4       | 4.4   | 4.3   | 10.2  | 30.9  | 5.4   | 12.2  | 13.13      |
| <b>Cr</b>                          | 48        | 54        | 74    | 64        | 34    | 76    | 44    | 34    | 82    | 124   | 63.4       |
| <b>Cs</b>                          | 21        | 17.5      | 4.3   | 0.88      | 1.66  | 10    | 3.46  | 8.6   | 2.86  | 12.6  | 8.29       |
| <b>Cu</b>                          | 24.6      | 70.4      | 126   | 46.8      | 84.6  | 24.6  | 42.62 | 36.42 | 64.8  | 46.80 | 56.76      |
| <b>Hf</b>                          | 4.2       | 2.6       | 0.8   | 1.8       | 1.6   | 6.4   | 5.6   | 5.22  | 0.68  | 6.76  | 3.56       |
| <b>Li</b>                          | 42.4      | 18.6      | 10.4  | 8.6       | 16.46 | 42.4  | 46.4  | 7.66  | 12.42 | 14.66 | 22         |
| <b>Mn</b>                          | 144       | 86        | 46    | 66        | 121   | 78    | 132   | 112   | 126   | 24    | 93.5       |
| <b>Mo</b>                          | 22.4      | 72.2      | 354   | 268       | 468   | 258   | 44.46 | 46.7  | 322   | 218   | 207.3<br>8 |

|                                                  |           |      |            |      |       |            |       |       |       |      |       |
|--------------------------------------------------|-----------|------|------------|------|-------|------------|-------|-------|-------|------|-------|
| Nb                                               | 11.8      | 8.6  | 2.44       | 5.6  | 4.8   | 10.22      | 8.34  | 8.68  | 9.64  | 2.4  | 7.25  |
| Ni                                               | 20        | 442  | 346        | 224  | 478   | 364        | 252   | 326   | 246   | 78   | 277.6 |
| P                                                | 240       | 430  | 820        | 360  | 680   | 1600       | 1320  | 1400  | 824   | 1240 | 891.4 |
| Pb                                               | 10.2      | 20.6 | 4.6        | 8.6  | 4.46  | 8.46       | 7.16  | 8.66  | 2.86  | 10.2 | 8.58  |
| Sb                                               | 2.12      | 3.66 | 18.4       | 12.4 | 3.48  | 7.4        | 4.46  | 8.86  | 2.68  | 7.6  | 7.11  |
| Sc                                               | 12.2      | 4.42 | 10.4       | 6.7  | 3.8   | 5.6        | 7.8   | 7.6   | 4.22  | 3.8  | 6.65  |
| Sr                                               | 98        | 136  | 420        | 482  | 442   | 566        | 720   | 382   | 278   | 128  | 365.2 |
| Th                                               | 2.4       | 6.6  | 4.8        | 2.6  | 2.2   | 6.2        | 5.4   | 3.8   | 1.44  | 6.48 | 4.19  |
| U                                                | 6.8       | 22.8 | 24.46      | 34.4 | 36.4  | 14.2       | 26.2  | 38.4  | 12.4  | 54.6 | 27.07 |
| V                                                | 360       | 142  | 486        | 474  | 164   | 650        | 406   | 620   | 158   | 306  | 376.6 |
| Y                                                | 8.3       | 10.6 | 7.8        | 12.4 | 14.6  | 22.4       | 32.2  | 24.4  | 18.6  | 34.6 | 18.59 |
| Zn                                               | 642       | 44   | 160        | 460  | 286   | 196        | 132   | 86    | 68    | 265  | 233.9 |
| Zr                                               | 82.4      | 24.2 | 20         | 56.4 | 18.2  | 68.8       | 86.4  | 74.6  | 46.4  | 17.4 | 49.48 |
| SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> | 0.84      | 0.78 | 0.66       | 0.87 | 0.56  | 0.79       | 0.82  | 0.93  | 0.93  | 0.92 | 0.82  |
| K <sub>2</sub> O/Al <sub>2</sub> O <sub>3</sub>  | 0.13      | 0.27 | 0.29       | 0.23 | 0.33  | 0.27       | 0.37  | 0.37  | 0.13  | 0.24 | 0.26  |
| K <sub>2</sub> O/Na <sub>2</sub> O               | 43.3      | 35   | 80         | 18   | 32    | 21.7       | 45.3  | 35.6  | 16.5  | 48   | 34.37 |
| Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub> | 82.5<br>8 | 48   | 131.8<br>6 | 64.9 | 65.12 | 106.5<br>5 | 173.5 | 62.48 | 62.84 | 60.6 | 68.60 |
| CIA <sup>(a)</sup>                               | 71        | 69   | 61         | 59   | 74    | 77         | 72    | 71    | 75    | 73   | 70    |
| ICV <sup>(b)</sup>                               | 1.87      | 1.75 | 1.72       | 1.95 | 1.14  | 0.89       | 1.13  | 1.05  | 1.07  | 1.05 | 1.46  |

<sup>(a)</sup>CIA = chemical index of alteration, <sup>(b)</sup>ICV = index of compositional variation.

**Table 3. Correlation coefficient matrix for the Early–Middle Jurassic shales, Imbricated Zone, North Iraq**

|    | S | A  | F | C | M | N  | K | T | P | L | B | C | C | C | C | H  | M | N  | N | S | S | T | U | V | Y | Z | Z | R |
|----|---|----|---|---|---|----|---|---|---|---|---|---|---|---|---|----|---|----|---|---|---|---|---|---|---|---|---|---|
| Si | 1 |    |   |   |   |    |   |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| A  | - | 1  |   |   |   |    |   |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| F  | - | 0. | 1 |   |   |    |   |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| C  | - | 0. | - | 1 |   |    |   |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| M  | 0 | -  | 0 | - | 1 |    |   |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| N  | 0 | 0. | 0 | - | 0 | 1  |   |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| K  | - | 0. | - | 0 | 0 | -  | 1 |   |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| T  | - | 0. | - | 0 | - | 0. | - | 1 |   |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| P  | 0 | 0. | 0 | 0 | 0 | 0. | - | 0 | 1 |   |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| L  | . | -  | - | 0 | 0 | -  | - | - | 0 | 1 |   |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| B  | 0 | 0. | - | - | 0 | 0. | 0 | 0 | 0 | - | 1 |   |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| C  | 0 | 0. | 0 | 0 | 0 | 0. | - | 0 | 0 | - | . | 1 |   |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| C  | 0 | 0. | 0 | 0 | - | -  | 0 | 0 | 0 | 0 | - | - | 1 |   |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| C  | - | 0. | - | 0 | 0 | .4 | 0 | . | 0 | - | 0 | 0 | 0 | 1 |   |    |   |    |   |   |   |   |   |   |   |   |   |   |
| C  | 0 | -  | - | 0 | - | -  | 0 | - | - | 0 | - | 0 | 0 | - | 1 |    |   |    |   |   |   |   |   |   |   |   |   |   |
| H  | 0 | 0. | 0 | - | - | 0. | 0 | 0 | - | - | 0 | 0 | 0 | 0 | - | 1  |   |    |   |   |   |   |   |   |   |   |   |   |
| M  | 0 | -  | - | - | 0 | 0. | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | - | -  | 1 |    |   |   |   |   |   |   |   |   |   |   |
| N  | 0 | 0. | 0 | - | 0 | .7 | - | 0 | 0 | - | 0 | 0 | - | 0 | - | 0. | . | 1  |   |   |   |   |   |   |   |   |   |   |
| N  | 0 | -  | 0 | - | 0 | -  | - | - | 0 | 0 | 0 | 0 | - | - | . | -  | 0 | -  | 1 |   |   |   |   |   |   |   |   |   |
| S  | 0 | 0. | 0 | 0 | 0 | 0. | 0 | 0 | - | - | 0 | - | - | 0 | - | -  | 0 | 0. | - | 1 |   |   |   |   |   |   |   |   |
| S  | 0 | -  | 0 | - | - | -  | - | - | - | 0 | - | - | - | - | - | 0. | 0 | 0. | . | - | 1 |   |   |   |   |   |   |   |
| T  | 0 | 0. | 0 | 0 | 0 | 0. | - | 0 | 0 | - | 0 | 0 | . | . | 0 | 0. | - | -  | - | - | - | 1 |   |   |   |   |   |   |
| U  | 0 | -  | - | 0 | - | -  | 0 | - | 0 | 0 | - | 0 | 0 | - | 0 | 0. | - | -  | 0 | - | 0 | 0 | 1 |   |   |   |   |   |
| V  | 0 | 0. | 0 | - | - | 0. | - | 0 | 0 | 0 | - | - | - | - | - | 0. | - | 0. | - | . | 0 | 0 | 0 | 1 |   |   |   |   |
| Y  | 0 | 0. | - | - | - | -  | 0 | - | 0 | 0 | 0 | 0 | 0 | - | - | .8 | 0 | 0. | - | - | 0 | - | . | 0 | 1 |   |   |   |
| Z  | - | -  | - | 0 | 0 | 0. | 0 | - | - | 0 | - | - | 0 | 0 | - | -  | 0 | -  | - | 0 | - | - | - | 0 | - | 1 |   |   |
| Z  | 0 | 0. | 0 | - | 0 | .5 | - | 0 | - | 0 | 0 | - | - | 0 | - | 0. | . | .7 | - | . | 0 | 0 | - | . | 0 | 0 | 1 |   |

**R** 0 0. 0 0 0 0 .5 0 0 - - 0 0 0 . - - 0 0. - 0 - 0 - - - 0 0 1  
 0.780 Correlations significant at the 0.01 level; 0.430 Correlations significant at the 0.05 level; n = 21

**Table 4. Rare earth element concentrations (in ppm) with REE and trace element ratios for the shales of Early–Middle Jurassic formations compared with those of PAAS**

| Sample<br>n  | Sehkaniyan |           |           |       |           |       |           |       |           |           |           |       | PAA<br>S   |
|--------------|------------|-----------|-----------|-------|-----------|-------|-----------|-------|-----------|-----------|-----------|-------|------------|
|              | She1       | She<br>2  | She<br>3  | She4  | She<br>5  | She6  | She<br>7  | She8  | She<br>9  | She1<br>0 | She<br>11 | Av.   |            |
| La           | 22.6       | 27.5      | 26.3      | 28.2  | 28.3      | 26.8  | 22.4      | 26.4  | 32.4      | 26.7      | 28.6      | 26.93 | 38.2       |
| Ce           | 26.7       | 29.3<br>4 | 27.1<br>1 | 26.96 | 18.6<br>5 | 28.31 | 18.0<br>7 | 24.55 | 18.6<br>4 | 25.1      | 26.8      | 24.57 | 79.6       |
| Pr           | 3.45       | 2.82      | 3.82      | 2.46  | 3.69      | 2.86  | 2.84      | 2.82  | 2.84      | 2.88      | 2.82      | 3.03  | 8.83       |
| Nd           | 11.3       | 14.6      | 12.8      | 11.1  | 13.2      | 12.6  | 13.2      | 14.2  | 13.3      | 12.1      | 12.1      | 12.77 | 33.9       |
| Sm           | 6.71       | 5.36      | 2.32      | 1.23  | 1.86      | 2.08  | 0.86      | 1.98  | 1.63      | 3.14      | 2.64      | 2.71  | 5.55       |
| Eu           | 0.22       | 0.34      | 0.31      | 0.36  | 0.27      | 0.23  | 0.25      | 0.24  | 0.28      | 0.23      | 0.30      | 0.28  | 1.08       |
| Gd           | 3.88       | 3.48      | 1.86      | 0.92  | 3.21      | 1.88  | 1.48      | 1.87  | 1.63      | 1.77      | 1.61      | 2.14  | 4.66       |
| Tb           | 0.92       | 0.44      | 0.35      | 0.25  | 0.33      | 0.38  | 0.21      | 0.28  | 0.32      | 0.19      | 0.34      | 0.37  | 0.77       |
| Dy           | 3.28       | 3.23      | 1.86      | 0.86  | 3.31      | 3.24  | 2.15      | 1.88  | 1.61      | 1.38      | 1.43      | 2.20  | 4.68       |
| Ho           | 1.22       | 0.81      | 0.42      | 0.41  | 0.58      | 1.41  | 0.36      | 0.53  | 0.42      | 0.27      | 0.28      | 0.61  | 0.99       |
| Er           | 2.12       | 1.92      | 1.21      | 0.83  | 2.32      | 1.81  | 0.63      | 1.24  | 0.69      | 0.78      | 0.84      | 1.31  | 2.85       |
| Tm           | 0.34       | 0.23      | 0.19      | 0.11  | 0.27      | 0.33  | 0.14      | 0.20  | 0.18      | 0.13      | 0.11      | 0.2   | 0.41       |
| Yb           | 1.8        | 1.53      | 0.89      | 0.49  | 1.54      | 1.41  | 0.8       | 0.9   | 0.88      | 0.8       | 0.72      | 1.07  | 2.82       |
| Lu           | 0.4        | 0.3       | 0.13      | 0.1   | 0.24      | 0.26  | 0.14      | 0.20  | 0.16      | 0.12      | 0.16      | 0.2   | 0.43       |
| ΣREE         | 116.6<br>4 | 92.2<br>6 | 57.0<br>7 | 37.08 | 64.9<br>7 | 67.8  | 36.3<br>3 | 65.65 | 45.7<br>9 | 68.11     | 67.4<br>7 | 65.38 | 184.7<br>7 |
| Eu/Eu*       | 0.68       | 0.69      | 0.7       | 0.67  | 0.68      | 0.69  | 0.67      | 0.66  | 0.71      | 0.68      | 0.66      | 0.68  | 0.7        |
| (Gd/Yb)<br>n | 2.16       | 2.27      | 2.09      | 1.88  | 2.08      | 1.33  | 1.85      | 2.08  | 1.85      | 2.08      | 2.24      | 1.99  | 1.34       |
| (La/Yb)<br>n | 12.55      | 17.9<br>7 | 29.5<br>5 | 57.55 | 18.3<br>8 | 19    | 28        | 29.33 | 36.8<br>2 | 33.38     | 39.7<br>2 | 29.30 | 9.15       |
| La/Th        | 2.63       | 3.7       | 4.8       | 8.29  | 2.4       | 1.8   | 2.5       | 5.7   | 3.9       | 3.2       | 3.3       | 3.8   | 2.60       |
| Ce/Ce*       | 1.064      | 0.73<br>6 | 0.86<br>3 | 0.694 | 0.78<br>9 | 0.673 | 0.76<br>4 | 0.749 | 0.82<br>8 | 0.549     | 0.67<br>8 | 0.763 | 1.016      |
| Th/Sc        | 0.34       | 1.16      | 0.56      | 0.39  | 1.35      | 1.08  | 0.1       | 0.53  | 0.36      | 0.048     | 0.71      | 0.62  | 0.90       |
| Zr/Sc        | 7.4        | 5.4       | 2.4       | 6.23  | 3.76      | 12.4  | 8.96      | 9.82  | 8.59      | 4.61      | 5.53      | 6.83  |            |
| La/Sc        | 2.13       | 4.3       | 2.74      | 3.24  | 3.2       | 5.2   | 2.2       | 3     | 5.3       | 5.8       | 3.7       | 3.71  | 2.40       |
| Co/Th        | 1.28       | 3.84      | 1.9       | 2.4   | 7.9       | 1.14  | 10.7<br>5 | 6.17  | 2.9       | 2.3       | 1.6       | 3.83  | 1.60       |

## 4.2. Trace Elements

All the trace elements were normalized to the PAAS values (Taylor and McLennan, 1985), compared with the PAAS values, and plotted in a multielement diagram (Figure 4a). The Early–Middle Jurassic samples of the Sehkaniyan shales are nearly similar to those of the Sargelu shales.

The negative relationship between the concentrations of large-ion lithophile trace elements in Sr and MgO (-0.565\*) is due to the occurrence of dolomite in the shales.

High-field-strength trace elements (Th, Zr, Hf, and Nb) are significantly positively correlated with SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub>. Table 3, which is associated with detrital phases and negatively correlated with CaO and LOI (Table 3), indicates that the carbonate components increase at the expense of detrital phases in Early–Middle Jurassic shales.

### 4.2.1. Large ion lithophile elements (LILEs: Cs, Ba, and Sr).

Ba has significant positive linear correlations with SiO<sub>2</sub> (0.541\*), Al<sub>2</sub>O<sub>3</sub> (0.515\*), K<sub>2</sub>O (0.537\*), and TiO<sub>2</sub> (0.652\*), suggesting a strong association with the detrital phases. Sr is negatively correlated with MgO (-0.565\*) and TiO<sub>2</sub> (-0.468\*) because of the occurrence of dolomite in the shales. Cs is positively correlated with MgO (0.465\*) and K<sub>2</sub>O (0.529\*), suggesting that their abundance is primarily controlled by clay minerals such as illite.

Table 4. Continue

| Sampl.n              | Sargelu |       |       |       |       |       |       |       |       |       | Av.   |
|----------------------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                      | Sar1    | Sar2  | Sar3  | Sar4  | Sar5  | Sar6  | Sar7  | Sar8  | Sar9  | Sar10 |       |
| La                   | 18.4    | 21.6  | 17.2  | 19.1  | 27.3  | 24.8  | 33.5  | 25.3  | 23.5  | 12.6  | 22.33 |
| Ce                   | 24.7    | 26.2  | 18.21 | 16.26 | 26.85 | 25.34 | 18.07 | 33.6  | 26.68 | 27.3  | 24.32 |
| Pr                   | 1.25    | 6.13  | 4.82  | 2.22  | 4.73  | 2.45  | 2.86  | 3.82  | 2.84  | 4.62  | 3.60  |
| Nd                   | 14.1    | 16.8  | 12.2  | 16.21 | 12.4  | 18.3  | 11.21 | 14.10 | 13.21 | 15.1  | 14.36 |
| Sm                   | 5.81    | 6.26  | 2.42  | 1.64  | 1.74  | 2.28  | 0.96  | 2.11  | 1.43  | 3.22  | 2.79  |
| Eu                   | 0.32    | 0.35  | 0.31  | 0.34  | 0.36  | 0.33  | 0.38  | 0.39  | 0.38  | 0.43  | 0.36  |
| Gd                   | 2.64    | 3.22  | 1.45  | 0.96  | 3.13  | 1.74  | 1.26  | 1.66  | 1.42  | 1.56  | 1.9   |
| Tb                   | 0.84    | 0.63  | 0.44  | 0.36  | 0.47  | 0.42  | 0.32  | 0.36  | 0.41  | 0.17  | 0.44  |
| Dy                   | 3.12    | 2.43  | 1.74  | 0.92  | 2.91  | 3.12  | 2.26  | 1.64  | 1.42  | 1.41  | 2.1   |
| Ho                   | 1.31    | 0.84  | 0.63  | 0.52  | 0.44  | 1.62  | 0.43  | 0.64  | 0.38  | 0.34  | 0.72  |
| Er                   | 1.82    | 1.64  | 1.43  | 0.68  | 1.84  | 1.63  | 0.88  | 1.32  | 0.72  | 0.82  | 1.28  |
| Tm                   | 0.28    | 0.43  | 0.22  | 0.43  | 0.42  | 0.24  | 0.18  | 0.32  | 0.24  | 0.21  | 0.3   |
| Yb                   | 1.62    | 1.44  | 0.68  | 0.52  | 1.61  | 1.53  | 0.78  | 0.88  | 0.97  | 0.76  | 1.08  |
| Lu                   | 0.31    | 0.28  | 0.16  | 0.18  | 0.18  | 0.31  | 0.18  | 0.23  | 0.21  | 0.32  | 0.24  |
| ΣREE                 | 95.32   | 84.72 | 58.81 | 41.44 | 62.08 | 67.21 | 41.52 | 60.94 | 49.05 | 65.86 | 62.70 |
| Eu/Eu*               | 0.69    | 0.68  | 0.7   | 0.68  | 0.68  | 0.69  | 0.67  | 0.69  | 0.7   | 0.69  | 0.69  |
| (Gd/Yb) <sub>n</sub> | 1.63    | 2.24  | 2.13  | 1.85  | 1.94  | 1.14  | 1.62  | 1.89  | 1.46  | 2.05  | 1.80  |
| (La/Yb) <sub>n</sub> | 11.5    | 15    | 25.29 | 36.73 | 16.96 | 12.21 | 42.95 | 28.75 | 24.23 | 16.58 | 23.02 |
| La/Th                | 7.7     | 3.3   | 3.6   | 7.4   | 12.4  | 4     | 23.9  | 6.6   | 16.32 | 2     | 6.2   |
| Ce/Ce*               | 0.671   | 0.81  | 0.429 | 0.566 | 1.004 | 0.777 | 0.99  | 0.402 | 0.591 | 0.786 | 0.703 |
| Th/Sc                | 0.20    | 1.49  | 0.46  | 0.39  | 0.43  | 1.11  | 0.1   | 0.5   | 0.34  | 1.7   | 0.67  |
| Zr/Sc                | 6.75    | 5.48  | 1.92  | 8.42  | 6.5   | 12.29 | 11.1  | 9.82  | 11    | 4.58  | 7.79  |
| La/Sc                | 1.5     | 4.9   | 1.7   | 2.9   | 7.75  | 4.43  | 4.3   | 3.33  | 5.57  | 3.32  | 3.97  |
| Co/Th                | 2.7     | 4.9   | 1.8   | 2.5   | 2     | 0.7   | 6.75  | 8.13  | 3.75  | 1.9   | 5.51  |

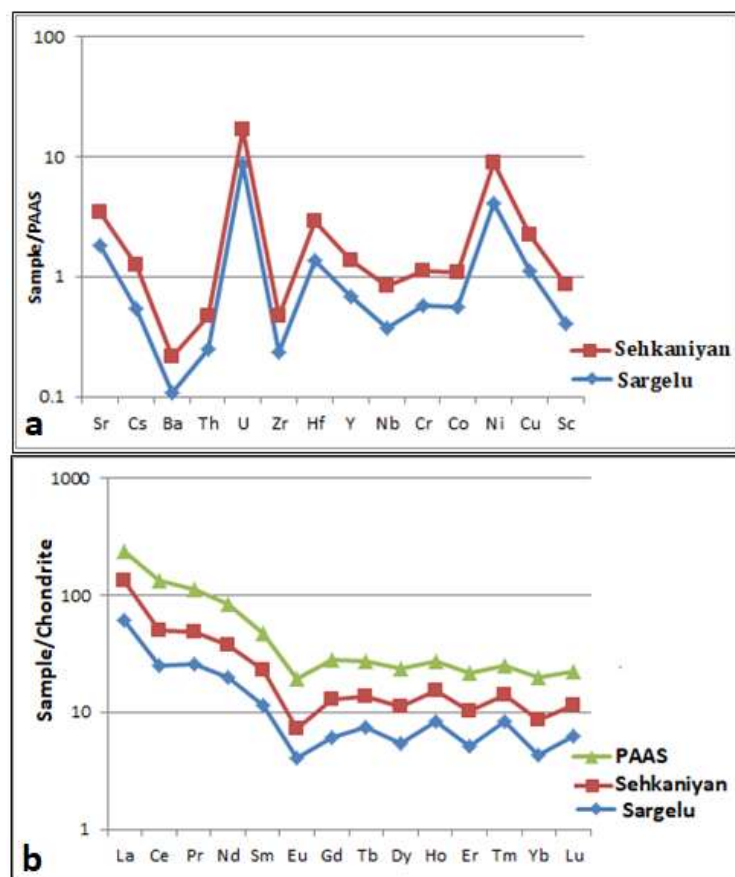
#### 4.2.2. High field strength elements (HFSEs: U, Th, Zr, Hf, Y and Nb).

High-field-strength element (Th, Zr, Hf, and Nb) concentrations in the Early–Middle Jurassic shales are significantly positively correlated with SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub> (Table 3), indicating the association of these elements with detrital phases (Armstrong-Altrin et al., 2018). ; and negative correlations with CaO and LOI (Table 3), U is significantly positively correlated with P<sub>2</sub>O<sub>5</sub> (0.461\*), whereas Y is positively correlated with SiO<sub>2</sub> (0.635\*) and K<sub>2</sub>O (0.475\*), while Zr is strongly positively correlated with Th (0.542\*) and Hf (0.537\*). The average Th/Sc ratios for the Early–Middle Jurassic shales are good for predicting the composition of the provenance, with average values of 0.51 and 0.67 for Sehkaniyan and Sargelu, respectively.

The study shales yield a broad relationship between Th/Sc and Zr/Sc that is conformable with provenance-dependent compositional variation. The Th/Sc and Zr/Sc ratios are lower in the Sehkaniyan deposit than in the Sargelu deposit, whereas Th/Sc ratios are lower in both the Sehkaniyan deposit and the Sargelu deposit than in the PAAS deposit (Table 4). The average Y contents are similar in the Early–Middle Jurassic shales (18.69 ppm for Sehkaniyan) and (18.59 ppm for Sargelu) and lower than those in the PAAS (27 ppm).

#### 4.2.3. Transition trace elements (TTEs: Co, Ni, Cr, Cu, Sc, and V).

Except for Ni, U and somewhat Cu, all the transition trace element (TTE) contents of the study shales are depleted relative to those of the PAAS. The TTEs (Cr, Co, Sc, and V) are positively correlated with SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub> (Table 3), indicating their concentration in clay minerals. (Armstrong-Altrin and Machain Castillo, 2016). In contrast, TTEs (Ni and Cu) and oxides (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub>) are not significantly correlated.



**Figure 4. (a) PAAS-normalized trace element spidergram of the shales from the Early–Middle Jurassic formations (normalization values after Taylor and McLennan (1985)).**

**(b) Average chondrite-normalized rare earth element (REE) patterns for the Early–Middle Jurassic shales compared with those of the PAAS (Taylor and McLennan, 1985).**

#### 4.2.4. Rare earth elements

The REE contents in the shale are generally lower than those in the PAAS. Compared with the Sargelu shale, the Sehkanian shale, which was classified herein as shale and wacke shale, is more enriched in LREEs and shows almost uniform LREE-enriched patterns similar to those of the PAAS, whereas the HREE pattern of the Sehkanian shale is similar to that of the Sargelu shale; chondrite-normalized REE patterns for the Early–Middle Jurassic shales are shown in Figure 4b.

Compared with those of PAAS, lower values of chondrite-normalized rare earth elements (REEs) in Early–Middle Jurassic shales and high values of CaO and MgO indicate that the dilution of carbonates has an effect on reducing these values.

The REE patterns show clear negative Ce/Ce\* anomalies for the Sehkanian (0.763) and Sargelu (0.703) shales, and the Ce anomalies of the studied shales are lower than those of the PAAS (1.016), as shown in Figure 4b, which reflects the dilution of the shales with carbonate materials.

The average (La/Yb)<sub>n</sub> ratios are 29.30 and 23.02 for the Sehkanian and Sargelu shales, respectively, which are higher than those of the PAAS (9.15), indicating enrichment of the Sehkanian and Sargelu shales with LREEs compared with HREEs (Table 4).

The shales are characterized by prominent negative Eu anomalies with similar average Eu/Eu\* values (0.68 for Sehkanian and 0.69 for Sargelu), which are nearly similar to those of PAAS (0.71).

The HREEs of the shales are moderately fractionated, with (Gd/Yb)<sub>n</sub> ratios of 1.99 for Sehkanian and 1.80 for Sargelu, which are higher than the PAAS (1.34) of Taylor and McLennan (1985).

There is a positive correlation between the total REEs and other oxides and SiO<sub>2</sub> (0.613\*), Al<sub>2</sub>O<sub>3</sub> (0.654\*), Fe<sub>2</sub>O<sub>3</sub> (0.665\*), TiO<sub>2</sub> (0.502\*), Cr (0.551\*), Cs (0.866\*\*) and Th (0.462\*), and a negative correlation with Sr (-0.672\*\*).

## 5. Discussion

### 5.1. Elemental Distribution

Most of the time, the  $\text{Al}_2\text{O}_3$  content in clastic rocks corresponds to that of  $\text{SiO}_2$  and is generally a good measure of detrital flux. The positive correlations of  $\text{Al}_2\text{O}_3$  with  $\text{K}_2\text{O}$  (0.775\*\*),  $\text{TiO}_2$  (0.446\*),  $\text{Ba}$  (0.515\*),  $\text{Co}$  (0.511\*),  $\text{Cr}$  (0.556\*) and  $\text{Zr}$  (0.551\*) indicate the association of these elements with detrital phases (Armstrong-Altrin et al., 2018).

The enrichment of the shales with  $\text{CaO}$  and the positive correlation between  $\text{CaO}$  and  $\text{LOI}$  (0.645\*) indicate that the  $\text{LOI}$  and  $\text{CaO}$  are incorporated into calcite rather than plagioclase and that a high content of  $\text{CaO}$  strongly dilutes the other oxides in the Early–Middle Jurassic shales. The positive relationships of  $\text{K}_2\text{O}$  with  $\text{Al}_2\text{O}_3$  (0.775\*\*),  $\text{Cs}$  (0.529\*),  $\text{Cu}$  (0.696\*), and  $\text{Ba}$  (0.537\*) suggest that their absolute abundances are primarily controlled by clay. The lower  $\text{TiO}_2$  values than those of the PAAS (Taylor and McLennan, 1985) suggest more evolved (felsic) material in the source rocks.

The significant negative correlation of  $\text{Ba}$  with  $\text{CaO}$  (-0.629\*) and the  $\text{LOI}$  (-0.718\*) suggest that its distribution is not controlled by carbonate phases. The study shales have low  $\text{Cr}$  contents in general; this may demonstrate the absence of ultramafic rocks in the source area.

The negative relationship between  $\text{Sr}$  and  $\text{MgO}$  (-0.565\*) is due to the occurrence of dolomite in the shales. Moreover,  $\text{Cs}$  is positively correlated with  $\text{K}_2\text{O}$  (0.529\*) and  $\text{MgO}$  (0.465\*), probably indicating that their distributions are controlled mainly by illitic and chloritic phyllosilicate phases (Tapia-Fernandez et al., 2017). High-field-strength element ( $\text{Th}$ ,  $\text{Zr}$ ,  $\text{Hf}$ , and  $\text{Nb}$ ) concentrations are associated with the detrital phase. Furthermore, the positive relationships of  $\text{Zr}$  with  $\text{Th}$  (0.542\*) and  $\text{Hf}$  (0.537\*), as verified by their significant correlation, indicate that  $\text{Th}$  and  $\text{Zr}$  behave similarly during the differentiation of the magma (Dokuz and Tanyolu, 2006). The concentrations of transition trace elements (TTEs;  $\text{Cr}$ ,  $\text{Co}$ ,  $\text{Sc}$ , and  $\text{V}$ ) are positively correlated with  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{TiO}_2$  (Table 3), indicating their concentrations in heavy and clay minerals (Armstrong-Altrin and Machain Castillo, 2016).

In contrast, there are no systematic correlations between  $\text{Ni}$ ,  $\text{Cu}$ , or the abovementioned oxides, suggesting that additional factors control their distribution. The highly fractionated REE patterns and low  $\text{EuEu}^*$  values of the shales suggest their derivation from a provenance predominated by felsic rocks. The REE patterns show clear negative  $\text{Ce}$  anomalies for Sehkaniyan (0.763) and Sargelu ( $\text{Ce}/\text{Ce}^* = 0.703$ ), which may reflect the dilution of the shales with carbonate materials. The significant positive correlations between the total REEs and other oxides and  $\text{SiO}_2$  (0.613\*),  $\text{Al}_2\text{O}_3$  (0.654\*),  $\text{Fe}_2\text{O}_3$  (0.665\*),  $\text{TiO}_2$  (0.502\*),  $\text{Cr}$  (0.551\*),  $\text{Cs}$  (0.866\*\*) and  $\text{Th}$  (0.462\*) reflect their association with detrital minerals.

### 5.2. Weathering of the Source Area

Paleoweathering of source rocks is considered an important process affecting the composition of clastic sedimentary rocks (Fu, X. et al., 2016). Chemical index of alteration (CIA) and index of compositional variability (ICV) contribute to explaining the composition of the Early–Middle Jurassic shales. During weathering, large cations ( $\text{Ba}$  and  $\text{Al}$ ) persist in the weathering residue; moreover, smaller cations ( $\text{Na}$ ,  $\text{Ca}$ , and  $\text{Sr}$ ) can be selectively removed (Nath et al., 2000; Akarish and El Gohary, 2008). The intensity of chemical weathering is controlled by several factors, such as the composition of the source rock, climate, intensity of weathering and degree of tectonic uplift of the source area (Akarish and El Gohary, 2008; Moosavirad et al., 2011).

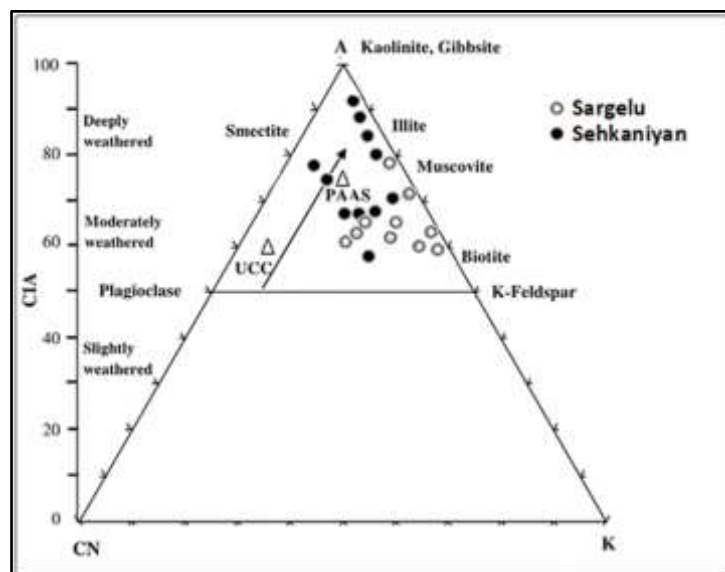
The intensity of weathering can be determined from the chemical index of alteration (CIA) (Nesbitt and Young, 1984), defined as  $\text{Al}_2\text{O}_3/[\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O}] \times 100$  (molar contents, with  $\text{CaO}^*$  being the  $\text{CaO}$  content in the silicate fraction).  $\text{CaO}$  was corrected by the method of McLennan et al. (1993), whereby  $\text{CaO}$  values were accepted only if  $\text{CaO} < \text{Na}_2\text{O}$ ; when  $\text{CaO} > \text{Na}_2\text{O}$ , it was assumed that the moles of  $\text{CaO}$  equaled that of  $\text{Na}_2\text{O}$ . Unweathered igneous rocks have CIA values between 45 and 55, whereas moderately weathered shales range from 70 to 75 (Nesbitt and Young, 1984).

The average CIA values of the shales are 65 and 70 for Sehkaniyan and Sargelu, respectively, which are greater than those of the UCC (56.90) and less than those of the PAAS (75.30). It is clear that the intensity of weathering is moderate for both formations. Moreover, the intensity of weathering tends to increase from early to Middle Jurassic, and the weathering trend can be illustrated by an  $\text{Al}_2\text{O}_3 - (\text{CaO}^* + \text{Na}_2\text{O}) - \text{K}_2\text{O}$  (A–CN–K) triangular diagram, as shown in Figure 5, proposed by Nesbitt and Young (1984, 1989), which is useful for determining the effects of K-metasomatism and for identifying the composition of the source rock. The trend of the shales was somewhat parallel to the A–K axis, implying that no K metasomatism occurred and that the intensity of alteration was moderate and increased from the Early to Middle Jurassic or from the Sehkaniyan to Sargelu shales, as shown in Figure 5.

The Sehkaniyan shales are somewhat clustered between the muscovite and kaolinite fields, whereas the Sargelu

deposit is between the biotite and muscovite fields.

Shadan and Hosseini Barzi (2013) suggested a semihumid to humid climate for shale with moderate to high weathering index values.



**Figure 5. A–CN–K ternary diagram of molecular proportions for the Early–Middle Jurassic shales (after Nesbitt and Young, 1984). The average Upper Continental Crust and Post Archean Australian Shale are also plotted (Taylor and McLennan, 1985).**

The index of compositional variability  $ICV = [Fe_2O_3 + K_2O + Na_2O + CaO + MgO + TiO_2]/Al_2O_3$  is potentially useful for evaluating the intensity of chemical weathering and maturity of sediments, which illustrates the formation of Al clays over framework silicates (Cox and Lowe, 1995). ICVs decrease with increasing intensity of weathering and/or maturity of the shale. Moreover, the sediments with an  $ICV > 1$  have immature compositions, with the first cycle deposited in an active tectonic setting. Moreover, those with an  $ICV < 1$  are mature and deposited in a quiescent tectonic environment, where sediment recycling is active (Cox and Lowe, 1995) (Jacobson et al., 2003). The ICVs are 1.02 and 1.46 for Sehkaniyan and Sargelu, respectively. On the basis of the average ICVs, the Sehkaniyan shale suggests moderate weathering and/or immature source and was deposited in a region that was subjected to low tectonic activity, whereas the Sargelu shale is compositionally immature and deposited in an active tectonic setting.

McLennan et al. (1993) used a Th/Sc (an indicator of chemical differentiation) versus Zr/Sc (a useful indicator of sediment recycling) diagram to distinguish the contrasting effects of source composition and sedimentary processes on the composition of clastic sedimentary rocks. On the Zr/Sc versus Th/Sc diagram for Early–Middle Jurassic shales, one trend is observed (significant correlation), indicating the direct contribution of these shales from source rocks and compositional homogeneity, and the shales have no Zr enrichment, as shown in Figure 6. No clear fractionation between Al, Ti, and Zr in the study shales is observed, which is indicated by the positive relationship and clustering near the PAAS, as shown in Figure 7.

The relationships between the ICV and CIA in the study area are as follows: high ICV and low CIA. (the Ca bound to carbonates excluded). The increasing chemical index of the alteration CIA trend may indicate progressive chemical weathering. However, the lower values of the trace and rare-earth elements compared with chondrite indicate that the dissolution of carbonate led to a reduction in these element values; therefore, the CaO values were excluded when the CIA values were calculated, whereas low to moderate CIA values suggest moderate chemical weathering. The relatively high index of compositional variation (ICV) values indicate compositionally immature sediments derived predominantly from felsic to intermediate continental sources.

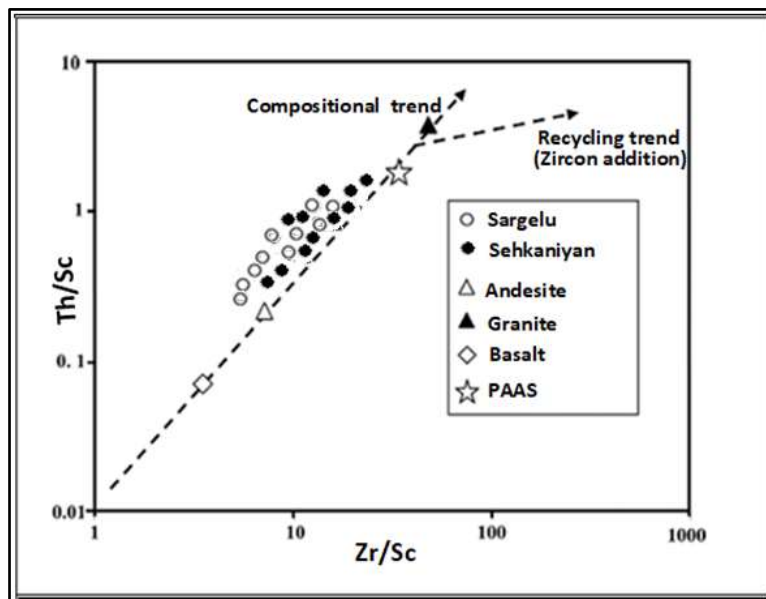


Figure 6. Th/Sc versus Zr/Sc diagram (after McLennan et al., 1993); the average source rock compositions are Proterozoic in age (after Condie, 1993)

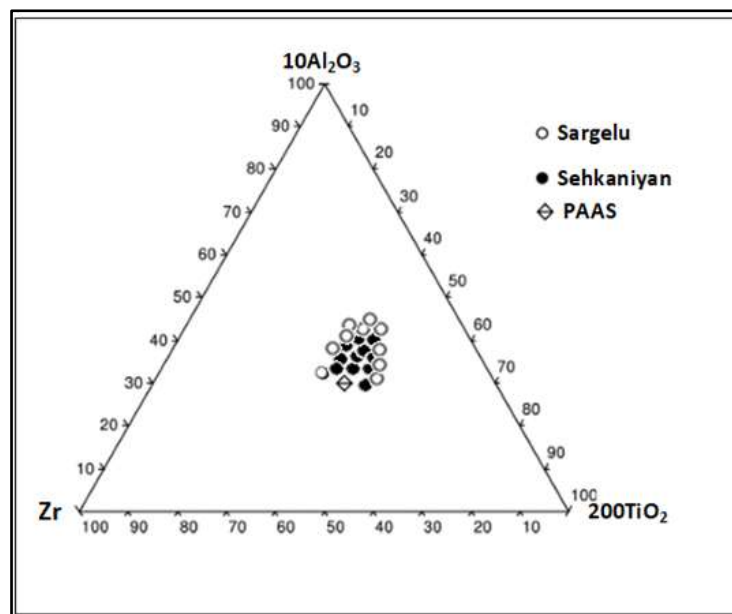


Figure 7. Ternary  $10\text{Al}_2\text{O}_3$ - $200\text{TiO}_2$ -Zr (Garcia et al., 1991) for the Early–Middle Jurassic shales.

### 5.3. Source Rock Characteristics

Source rock studies require geochemical parameters to predict the provenance of sediments, and major element data support the determination of rock composition and the influence of sedimentary processes, such as weathering and sorting (McLennan et al., 1993; Omar et al., 2026).

The high  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios of the Sehkaniyan and Sargelu shales (72.8 and 68.60, respectively) in relation to those of the PAAS (19.0; Taylor and McLennan, 1985) and the lower  $\text{TiO}_2$  values (0.39 and 0.296, respectively) compared with those of the PAAS (0.99; Taylor and McLennan, 1985) suggest the presence of felsic material in the source rocks.

Some chemical elements are reliable for provenance analysis of rocks because of their insolubility and immobile character during transport and weathering, such as Sc, REEs, and HFSEs (McLennan and Taylor, 1991; McLennan et al., 1995). Sometimes, the element ratios Th/Sc, La/Th, La/Yb, Co/Th,  $(\text{Gd}/\text{Yb})_n$ , and  $\text{Eu}/\text{Eu}^*$  are remarkably useful in the study of the chemical composition of source rocks (Cullers, 1994; Girty et al., 1994), and the Th/Sc ratio is a reliable marker for source composition and differentiation between mafic and felsic source components (Armstrong-Altrin, 2009).

The Th/Sc average ratios of the studied samples (0.62 and 0.67 for Sehkaniyan and Sargelu, respectively) and

somewhat near the upper crustal composition UCC (0.70; McLennan, 2001) indicate intermediate sources. The average (La/Yb)<sub>n</sub> ratios are 29.30 and 23.02 for the Sehkanian and Sargelu shales, respectively, which are higher than those of the PAAS (9.15), indicating enrichment of the Sehkanian and Sargelu shales with LREEs compared with HREE, as shown in the REE pattern (Figure 4.b, Table 4). La/Th ratios are useful indicators of felsic or mafic source components.

The La/Th ratios (3.8) and Hf (4.57) contents of the Sehkanian shales are comparable to those of the acidic source, and the La/Th ratios (6.2) and low Hf (3.56) contents of the Sargelu deposit plot between those of the acidic and andesitic source fields, as shown in Figure 8a. The average contents of total REEs for the Early–Middle Jurassic shales (65.38 and 62.70 for Sehkanian and Sargelu, respectively) are depleted relative to the PAAS (184.77) and UCC values (146.37; Taylor and McLennan, 1985) because of carbonate dilution. Chondrite-normalized REE patterns for the analyzed samples are characterized by significant LREE enrichment, negative Eu anomalies, and relatively flat HREEs, which are typical of upper crustal rocks or felsic source rocks (McLennan et al., 1990).

The shales are characterized by prominent negative Eu anomalies with similar average Eu/Eu\* values (0.68 for Sehkanian and 0.69 for Sargelu), which are nearly similar to those of PAAS (0.71), indicating an upper continental crust or felsic source. In the Eu/Eu\* and Th/Sc plots (Figure 8b; Cullers and Podkovyrov, 2000), the Sehkanian shales plot near the average values of the granite and the Sargelu shales, which are near the average values of granodiorite.

The (Gd/Yb)<sub>n</sub> ratio is also evidence of the composition of continental crustal source rocks (Taylor and McLennan, 1985; Nagarajan et al., 2007). In the Eu/Eu\* versus (Gd/Yb)<sub>n</sub> diagram shown in Figure 8c, the Early–Middle Jurassic shales plot in the post-Archean field and are near the PAAS value, which suggests that the post-Archean felsic rocks could be the source rocks for the study shales.

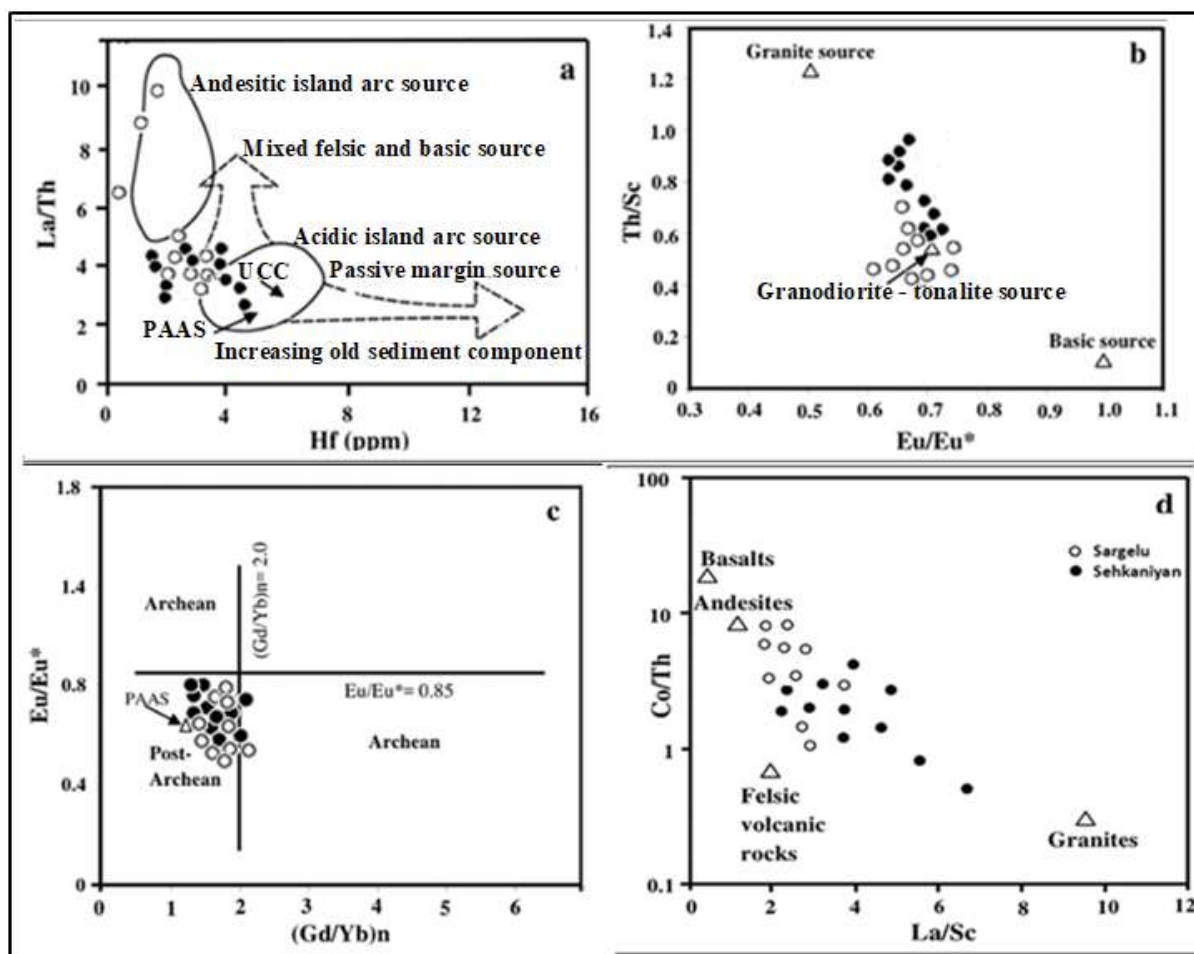


Figure 8. Discriminant diagrams for the shale of the Early–Middle Jurassic Formations

As shown in Figure 8d, the Sehkanian Formation shale is near the felsic rocks, whereas the Sargelu shales have high Co/Th ratios toward the andesite rocks. Finally, all the mentioned geochemical parameters suggest intermediate to felsic source rocks for the Early–Middle Jurassic shales.

- (a) Hf versus La/Th plot. Fields are after Floyd and Leve Ridge (1987);
- (b) Eu/Eu versus Th/Sc plot (Cullers and Podkovyrov, 2000);
- (c) Eu/Eu versus (Gd/Yb)<sub>n</sub> plot. Fields are after McLennan and Taylor (1991);
- (d) Co/Th versus La/Sc plot (after Cullers, 2002).

#### 5.4. Tectonic Setting

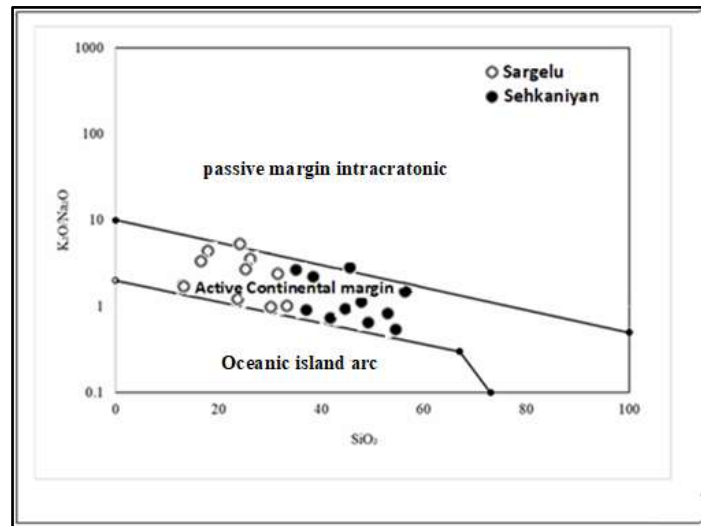
The index of compositional variability (ICV) and chemical index of alteration (CIA) explain the composition of the Early–Middle Jurassic shale. ICV is useful for evaluating the intensity of chemical weathering and maturity of sediments. Sediments with an  $ICV > 1$  have immature compositions, with the first cycle deposited in an active tectonic setting (Cox and Lowe, 1995). The ICVs are 1.02 and 1.46 for Sehkanian and Sargelu, respectively. On the basis of the average ICVs, the Sehkanian shale suggests moderate weathering and/or immature source and was deposited in a region that was subjected to low tectonic activity (Jacobson et al., 2003). However, the Sargelu shale is compositionally immature and deposited in an active tectonic setting. The relationships between the ICV and CIA in the study area are as follows: high ICV and low CIA. (the Ca bound to carbonates excluded). The average ICVs are 1.02 and 1.46 for Sehkanian and Sargelu, respectively, and the average CIA values of the shale are 65 and 70, respectively, which are less than that of the PAAS (75.30). and compatible with tectonically active source areas such as active continental collision margins.

The  $Al_2O_3/TiO_2$  ratios of the investigated sediments (72.8 and 68.60 for Sehkanian and Sargelu, respectively) are higher than the ratio of PAAS, which indicates felsic source rocks (19.0; Taylor and McLennan, 1985).

A plot of  $SiO_2$  vs.  $K_2O/Na_2O$  is used to determine whether the shale was deposited on passive continental edges, active continental margins, or oceanic island arc margins (Keskin, S. 2011).

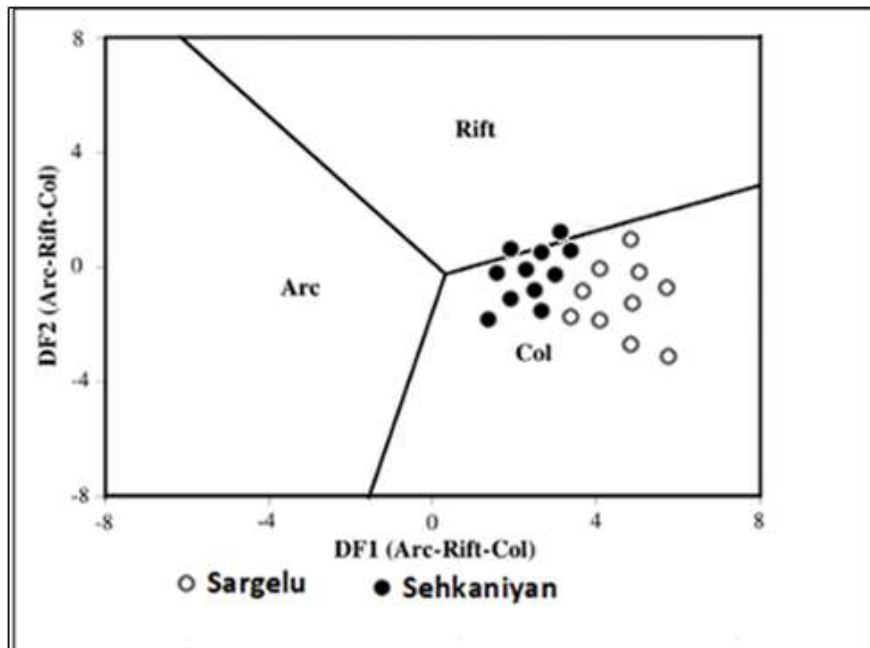
The binary diagram shows that all samples plot within the active margin field, indicating that the Sehkanian and Sargelu Formations were deposited within an active margin environment, as shown in Figure 9. The Th/Sc ratio is a reliable marker of source composition and differentiation between mafic and felsic source components (McLennan and Taylor, 1991).

The Th/Sc average ratios of the studied samples are 0.62 and 0.67 for Sehkanian and Sargelu, respectively, and are somewhat similar to those of the upper crustal UCC (0.70; McLennan, 2001) or intermediate source rocks. The shales are characterized by prominent negative Eu anomalies with similar average Eu/Eu\* values (0.68 for Sehkanian and 0.69 for Sargelu), which are nearly similar to those of PAAS (0.71), indicating an upper continental crust or felsic source. The studied shales, including their trace element ratios and REE patterns, suggest derivation from a predominantly felsic to intermediate continental source. The provenance signatures, together with the tectonic discrimination diagrams, are consistent with deposition along an active continental collision margin. Relatively high ICVs indicate compositionally immature sediments derived from an active source area, whereas low to moderate CIA values suggest moderate chemical weathering. Combined with the felsic–intermediate provenance indicated by the REE patterns and elemental ratios, these characteristics are consistent with the rapid erosion of an uplifted continental source associated with an active continental collision margin. Recently, Verma and Armstrong-Altrin (2013) proposed two discriminant function-based major element diagrams for the tectonic discrimination of siliciclastic sediments from three main settings, namely, island or continental arc, continental rift, and collision, created for the tectonic discrimination of high-silica [ $(SiO_2)_{adj} = 63–95\%$ ] and low-silica [ $(SiO_2)_{adj} = 35–63\%$ ] types. In addition, Armstrong Altrin (2015) evaluated these two tectonic discrimination function diagrams and suggested that the two multidimensional diagrams can be considered important tools for discriminating the tectonic setting of older sedimentary basins.



**Figure 9.** Plot of  $\text{SiO}_2$  versus  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  after (Keskin, S., 2011) for the shales of the Sehkaniyan and Sargelu Formations.

These discriminant function-based major element diagrams were employed in this study to determine the tectonic environment of the Early–Middle Jurassic shales. The shales are characterized by low silica contents. According to the low-silica diagram shown in Figure 10, Sehkaniyan and Sargelu are plotted in the collision field (active setting), which reveals the possibility that these shales may consist of sediments derived from active regions. These results are consistent with the ICV values, where Sehkaniyan and Sargelu indicate that shales have an ICV > 1 and moderate weathering and/or maturity of the source and are deposited in tectonically collision-active settings.



**Figure 10.** Discriminant-function multidimensional diagram for low-silica clastic sediments (fields after Verma and Armstrong-Altrin, 2013). The discriminant function equations are as follows:

$$\begin{aligned} \text{DF1 (Arc-Rift-Col)} &= (0.608 \times \ln(\text{TiO}_2/\text{SiO}_2)_{\text{adj}}) + (-1.854 \times \ln(\text{Al}_2\text{O}_3/\text{SiO}_2)_{\text{adj}}) + (0.299 \times \ln(\text{Fe}_2\text{O}_3/\text{SiO}_2)_{\text{adj}}) \\ &+ (-0.550 \times \ln(\text{MnO}/\text{SiO}_2)_{\text{adj}}) + (0.120 \times \ln(\text{SiO}_2/\text{SiO}_2)_{\text{adj}}) + (0.194 \times \ln(\text{CaO}/\text{SiO}_2)_{\text{adj}}) + (-1.510 \times \ln(\text{Na}_2\text{O}/\text{SiO}_2)_{\text{adj}}) \\ &+ (1.941 \times \ln(\text{K}_2\text{O}/\text{SiO}_2)_{\text{adj}}) + (0.003 \times \ln(\text{P}_2\text{O}_5/\text{SiO}_2)_{\text{adj}}) - 0.294; \\ \text{DF2 (Arc-Rift-Col)} &= (-0.554 \times \ln(\text{TiO}_2/\text{SiO}_2)_{\text{adj}}) + (-0.995 \times \ln(\text{Al}_2\text{O}_3/\text{SiO}_2)_{\text{adj}}) + (1.765 \times \ln(\text{Fe}_2\text{O}_3/\text{SiO}_2)_{\text{adj}}) \\ &+ (-1.391 \times \ln(\text{MnO}/\text{SiO}_2)_{\text{adj}}) + (-1.034 \times \ln(\text{MgO}/\text{SiO}_2)_{\text{adj}}) + (0.225 \times \ln(\text{CaO}/\text{SiO}_2)_{\text{adj}}) \\ &+ (0.713 \times \ln(\text{Na}_2\text{O}/\text{SiO}_2)_{\text{adj}}) + (0.330 \times \ln(\text{K}_2\text{O}/\text{SiO}_2)_{\text{adj}}) + (0.637 \times \ln(\text{P}_2\text{O}_5/\text{SiO}_2)_{\text{adj}}) - 3.631. \end{aligned}$$

## 6. Conclusions

- (1) The high contents of CaO have an effect on the dilution of other oxides and elements (including REEs).
- (2) Generally, the REE contents in the Early–Middle Jurassic shales are depleted relative to the PAAS and UCC values (Taylor and McLennan, 1985), and the chondrite-normalized REE patterns for the analyzed samples are characterized by significant LREE enrichment, negative Eu anomalies, and relatively flat HREEs.
- (3) The geochemical parameters  $\text{Al}_2\text{O}_3/\text{TiO}_2$ , Th/Sc, and La/Th ratios; REE patterns; (Gd/Yb)<sub>n</sub> ratios; lower  $\text{TiO}_2$  values than PAAS; and relatively high index of compositional variation (ICV) values suggest that the source rock was derived from an upper continental crust dominated by intermediate to felsic rocks.
- (4) The relatively high index of compositional variation (ICV) > 1 values indicate compositionally immature sediments derived from an active tectonic setting source area, and the tectonic discrimination diagrams are consistent with deposition along an active continental collision margin (Figure 9 and Figure 10).
- (5) The intensity of weathering is moderate for both formations; moreover, the intensity of weathering increases from early to Middle Jurassic, and moderate CIA values suggest moderate chemical weathering. The relationships between the ICV and the CIA in the study area are as follows: high ICV and low CIA; the increasing chemical index of the alteration CIA trend indicates progressive chemical weathering, and the CIA and ICV parameters and A–CN–K diagram indicate increasing degrees of moderate chemical weathering from the Early to Middle Jurassic.

## Acknowledgments

The authors extend their sincere gratitude to the Department of Earth Sciences and Petroleum, College of Science, Salahaddin University, Erbil, Erbil, Kurdistan Region, Iraq, for their continuous support and for providing the necessary laboratory facilities and academic guidance that made this study possible.

**Author contribution:** The author completed the entire research himself.

**Conflict of Interest** The authors declare that they have no conflicts of interest.

## Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors' respective institutions supported the work through internal resources and academic collaboration.

## Data Availability Statement

The data that support the findings of this study are currently not publicly available, as the manuscript is under review and the study has not yet been published. However, the data may be made available from the corresponding author upon reasonable request.

## References

1. Akarish, A.I.M. and El-Gohary, A.M., 2008, Petrography and geochemistry of lower Paleozoic sandstones, East Sinai, Egypt: implications for provenance and tectonic setting. *Journal of African Earth Sciences*, 52, 43–54. <https://doi.org/10.1016/j.jafrearsci.2008.04.002>
2. Al-Ameri, T. K., & Al-Nagshbandi, S. F. (2015). Age assessments and palynofacies of the Jurassic oil source rocks of North Iraq. *Arabian Journal of Geosciences*, 8(2) 759–771. <https://doi.org/10.1007/s12517-013-1245-2>
3. Armstrong-Altrin, J.S., Lee, Y.I., Kasper-Zubillaga, J.J., Carranza Edwards, A., Garcia, D., Eby, N., Balaram, V., and Cruz-Ortiz, N.L., 2012, Geochemistry of beach sands along the Western Gulf of Mexico, Mexico: implication for provenance. *Chemie der Erde*, 72, 345–362. <https://www.scrip.org/reference/referencespapers?referenceid=2349604>
4. Armstrong-Altrin, J.S., Nagarajan, R., Lee, Y.I., Kasper-Zubillaga, J.J., and Córdoba-Saldana, L.P., 2014, Geochemistry of sands along the San Nicolas and San Carlos beaches, Gulf of California Mexico: implications for provenance and tectonic setting. *Turkish Journal of Earth Sciences*, 23, 533–558. <https://doi.org/10.3906/yer-1309-21>
5. Armstrong-Altrin, J.S., 2015, Evaluation of two multidimensional discrimination diagrams from beach and deep-sea sediments from the Gulf of Mexico and their application to Precambrian clastic sedimentary rocks. *International Geology Review*, 57, 1446–1461. <https://doi.org/10.1080/00206814.2014.936055>
6. Armstrong-Altrin, J.S., Machain-Castillo, M.L., Rosales-Hoz, L., Carranza-Edwards, A., Sanchez-Cabeza,

- J.A., and Ruíz-Fernández, A.C., 2015a, Provenance and depositional history of continental slope sediments in the Southwestern Gulf of Mexico unraveled by geochemical analysis. *Continental Shelf Research*, 95, 15–26. <https://doi.org/10.1016/j.csr.2015.01.003>
7. Armstrong-Altrin, J.S., Nagarajan, R., Balaram, V., and Natalhy-Pineda, O., 2015b, Petrography and geochemistry of sands from the Chachalacas and Veracruz beach areas, western Gulf of Mexico, Mexico: constraints on provenance and tectonic setting. *Journal of South American Earth Sciences*, 64, 199–216. <https://doi.org/10.1016/j.jsames.2015.10.012>
8. Armstrong-Altrin, J.S. and Machain-Castillo, M.L., 2016, Mineralogy, geochemistry, and radiocarbon ages of deep sea sediments from the Gulf of Mexico, Mexico. *Journal of South American Earth Sciences*, 71, 182–200. <https://doi.org/10.1016/j.jsames.2016.07.010>
9. Condie, C.K., Noll, P.D., Jr., and Conway, C.M., 1992, Geochemical and detrital mode evidence for two sources of Early Proterozoic sedimentary rocks from the Tonto Basin Supergroup, central Arizona. *Sedimentary Geology*, 77, 51–76. [https://doi.org/10.1016/0037-0738\(92\)90103-X](https://doi.org/10.1016/0037-0738(92)90103-X)
10. Condie, K.C., 1993, Geochemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. *Chemical Geology*, 104, 1–37. [https://doi.org/10.1016/0009-2541\(93\)90140-E](https://doi.org/10.1016/0009-2541(93)90140-E)
11. Cox, R. and Lowe, D.R., 1995, A conceptual review of regional scale controls on the compositions of clastic sediments and the coevolution of continental blocks and their sedimentary cover. *Journal of Sedimentary Research*, 65, 1–12. <https://doi.org/10.1306/D4268009-2B26-11D7-8648000102C1865D>
12. Cullers, R.L., 1994, The controls on the major and trace element variation of shales, siltstones, and sandstones of Pennsylvanian–Permian age from uplifted continental blocks in Colorado to platform sediment in Kansas, USA. *Geochimica et Cosmochimica Acta*, 58, 4955–4972. [https://doi.org/10.1016/0016-7037\(94\)90224-0](https://doi.org/10.1016/0016-7037(94)90224-0)
13. Cullers, R.L. and Podkovyrov, V.N., 2000, Geochemistry of the Meso proterozoic Lakhanda shales in southeastern Yakutia, Russia: implications for mineralogical and provenance control, and recycling. *Precambrian Research*, 104, 77–93. [https://doi.org/10.1016/S0301-9268\(00\)00090-5](https://doi.org/10.1016/S0301-9268(00)00090-5)
14. Cullers, R.L., 2002, Implications of elemental concentrations for provenance, redox conditions, and metamorphic studies of shales and limestones near Pueblo, CO, USA. *Chemical Geology*, 191, 305–327. [https://doi.org/10.1016/S0009-2541\(02\)00133-X](https://doi.org/10.1016/S0009-2541(02)00133-X)
15. Dokuz, A. and Tanyolu, E., 2006, Geochemical constraints on the provenance, mineral sorting and subaerial weathering of Lower Jurassic and Upper Cretaceous clastic rocks of the eastern Pontides, Yusufeli (Artvin), NE Turkey. *Turkish Journal of Earth Sciences*, 15, 181–209.
16. Fu, X., Wang, J., Chen, W., Feng, X., Wang, D., Song, C., Zeng, S., 2016, Elemental geochemistry of the Early Jurassic black shales in the Qiangtang Basin, eastern Tethys: constraints for paleoenvironment conditions. *Geological Journal*, 51, 443–454. DOI: 10.1002/gj.2642.
17. Garcia, D., Coehlo, J., and Perrin, M., 1991, Fractionation between TiO<sub>2</sub> and Zr as a measure of sorting within shale and sandstone series (northern Portugal). *European Journal of Mineralogy*, 3, 401–414.
18. Girty, G.H., Hanson, A.D., Knaack, C., and Johnson, D., 1994, Provenance determined by REE, Th, and Sc analyses of metasedimentary rocks, Boyden Cave roof pendant, central Sierra Nevada, California. *Journal of Sedimentary Research*, 64, 68–73. <https://doi.org/10.1306/D42682CA-2B26-11D7-8648000102C1865D>
19. Herron, M.M., 1988, Geochemical classification of terrigenous sands and shales from core or log data. *Journal of Sedimentary Petrology*, 58, 820–829. <https://doi.org/10.1306/212F8E77-2B24-11D7-8648000102C1865D>
20. Jacobson, A.D., Blum, J.D., Chamberlain, C.P., Craw, D., and Koons, P.O., 2003, Climate and tectonic controls on chemical weathering in the New Zealand Southern Alps. *Geochimica et Cosmochimica Acta*, 37, 29–46. [https://doi.org/10.1016/S0016-7037\(02\)01053-0](https://doi.org/10.1016/S0016-7037(02)01053-0)
21. Keskin, S., 2011, Geochemistry of Çamard Formation sediments, central Anatolia (Turkey): implication of source area weathering, provenance, and tectonic setting. *Geosciences Journal*, 15, 185–195. [https://wayf.springernature.com/?redirect\\_uri=https%3A%2F%2Flink.springer.com%2Farticle%2F10.1007%2Fs12303-011-0014-z](https://wayf.springernature.com/?redirect_uri=https%3A%2F%2Flink.springer.com%2Farticle%2F10.1007%2Fs12303-011-0014-z)
22. Keshmiri, M., Khanehbad, M., Rahimi, B., 2026, Geochemistry of the Miankuhi Formation shales in northeastern Iran: implications for the Cimmerian orogeny and the closure of the Paleo-Tethys Ocean. *International Geology Review* <https://doi.org/10.1080/00206814.2025.2612209>
23. McLennan, S.M., 1989, Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes. In: Lipin, B.R. and McKay, G.A. (eds.), *Geochemistry and Mineralogy of Rare Earth Elements. Reviews in Mineralogy*, *Mineralogical Society of America*, 21, p. 169–200. <https://pubs.geoscienceworld.org/msa/rimg/article/21/1/169/87254/Rare-earth-elements-in-sedimentary-rocks-influence>
24. McLennan, S.M., Taylor, S.R., McCulloch, M.T., and Maynard, J.B., 1990, Geochemical and Nd-Sr isotopic

- composition of deep-sea turbidites: crustal evolution and plate tectonic associations. *Geo chimica et Cosmochimica Acta*, 54, 2015–2050. [https://doi.org/10.1016/0016-7037\(90\)90269-Q](https://doi.org/10.1016/0016-7037(90)90269-Q)
25. McLennan, S.M. and Taylor, S.R., 1991, Sedimentary rocks and crustal evolution: tectonic setting and secular trends. *Journal of Geology*, 99, 1–21. <https://www.journals.uchicago.edu/doi/epdf/10.1086/629470>
26. McLennan, S.M., Hemming, S., McDaniel, D.K., and Hanson, G.N., 1993, Geochemical approaches to sedimentation, provenance, and tectonics. In: Johnson, M.J. and Basu, A. (eds.), Processes Controlling the Composition of Clastic Sediments. *Geological Society of America*, Special Papers, 284, p. 21–40. <https://doi.org/10.1130/SPE284-p21>
27. McLennan, S.M., Hemming, S.R., Taylor, S.R., and Eriksson, K.A., 1995, Early Proterozoic crustal evolution: geochemical and Nd-Pb isotopic evidence from metasedimentary rocks, southern North America. *Geochimica et Cosmochimica Acta*, 59, 1153–1177. [https://doi.org/10.1016/0016-7037\(95\)00032-U](https://doi.org/10.1016/0016-7037(95)00032-U)
28. McLennan, S.M., 2001, Relationships between the trace element composition of sedimentary rocks and upper continental crust. *Geochemistry Geophysics Geosystems*, 2, 1021–1045. <https://doi.org/10.1029/2000GC000109>
29. Moosavirad, S.M., Janardhana, M.R., Sethumadhav, M.S., Moghadam, M.R., and Shankara, M., 2011, Geochemistry of lower Jurassic shales of the Shemshak Formation, Kerman Province, Central Iran: provenance, source weathering and tectonic setting. *Chemie der Erde*, 71, 279–288. <https://doi.org/10.1016/j.chemer.2010.10.001>
30. Nagarajan, R., Madhavaraju, J., Nagendra, R., Armstrong-Altrin, J.S., and Moutte, J., 2007, Geochemistry of Neoproterozoic shales of the Rabanpalli Formation, Bhima Basin, northern Karnataka, southern India: implications for provenance and paleoredox conditions. *Revista Mexicana de Ciencias Geologicas*, 24, 150–160.
31. Nath, B.N., Kunzendorf, H., and Pluger, W.L., 2000, Influence of provenance, weathering and sedimentary processes on the elemental ratios of the fine-grained fraction of the bedload sediments from the Vembanad Lake and the adjoining continental shelf, southwest coast of India. *Journal of Sedimentary Research*, 70, 1081–1094. <https://doi.org/10.1306/100899701081>
32. Nesbitt, H.W. and Young, G.M., 1984, Predictions of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochimica et Cosmochimica Acta*, 48, 1523–1534. [https://doi.org/10.1016/0016-7037\(84\)90408-3](https://doi.org/10.1016/0016-7037(84)90408-3)
33. Nesbitt, H.W. and Young, G.M., 1989, Formation and diagenesis of weathering profiles. *Journal of Geology*, 97, 129–147. [https://ui.adsabs.harvard.edu/link\\_gateway/1989JG....97..129N/doi:10.1086/629290](https://ui.adsabs.harvard.edu/link_gateway/1989JG....97..129N/doi:10.1086/629290)
34. Omar, N., McCann, T., Al-juboury, A., Al-Haj, M. A., Sharazwri, A. O., Armstrong-Altrin, J.S., 2026, Provenance and tectonic setting of the Lower Jurassic-Lower Cretaceous shales from the northeastern Iraq: mineralogical and geochemical approaches. *Sec. Geochemistry*, V.13. <https://doi.org/10.3389/feart.2025.1716704>
35. Rasool, R.H., Al-juboury, A. L., Ali, S. A., Omar, N., McCann, T., Harry, R., Zaroni, G., AlObeidi, A.H., & Alarifi, N., 2025, Paleoenvironmental reconstruction of the middle-upper Jurassic strata in the Iraqi Zagros Suture Zone, southern Tethys: Implications from stable isotopic data and scanning electron microscopy. *Environmental Earth Sciences*, 84(19). DOI: 10.1007/s12665-025-12473-0.
36. Shadan, M. and Hosseini-Barzi, M., 2013, Petrography and geochemistry of the Ab-e-Haji Formation in central Iran: implications for provenance and tectonic setting in the southern part of the Tabas block. *Revista Mexicana de Ciencias Geologicas*, 30, 80–95.
37. Sissakian, V.K. and Fouad, S.F., 2012, Geological Map of Iraq (1:1,000,000). *Iraqi Bulletin of Geology and Mining*, 11, 9–16.
38. Srivastava, A.K., Randive, K.R., and Khare, N., 2013, Mineralogical and geochemical studies of glacial sediments from Schirmacher Oasis, East Antarctica. *Quaternary International*, 292, 205–216. <https://doi.org/10.1016/j.quaint.2012.07.028>
39. Tapia-Fernandez, H.J., Armstrong-Altrin, J.S., and Selvaraj, K., 2017, Geochemistry and U–Pb geochronology of detrital zircons in the Brujas beach sands, Campeche, Southwestern Gulf of Mexico, Mexico. *Journal of South American Earth Sciences*, 76, 346–361. <https://doi.org/10.1016/j.jsames.2017.04.003>
40. Taylor, S.R. and McLennan, S., 1985, The Continental Crust: Its Composition and Evolution. Blackwell, Oxford, 312 p. *Condie*, 1993
41. Verma, S.P. and Armstrong-Altrin, J.S., 2013, New multidimensional diagrams for tectonic discrimination of siliciclastic sediments and their application to Precambrian basins. *Chemical Geology*, 355, 117–133. <https://doi.org/10.1016/j.chemgeo.2013.07.014>
42. Verma, S.P. and Armstrong-Altrin, J.S., 2016, Geochemical discrimination of siliciclastic sediments from active and passive margin settings. *Sedimentary Geology*, 332, 1–12. <https://doi.org/10.1016/j.sedgeo.2015.11.011>
43. Zaid, S.M., Elbadry, O., Ramadan, F., and Mohamed, M., 2015, Petrography and geochemistry of Pharaonic

sandstone monuments in Tall San Al Hagr, Al Sharqiya Governorate, Egypt: implications for provenance and tectonic setting. *Turkish Journal of Earth Sciences*, 24, 344–364.

44. Zhang, Y., He, B., and Xu, Y., 2013, Mineralogy and geochemistry of clay stones from the Guadalupian–Lopingian boundary at Penglaitan, South China: insights into the pre-Lopingian geological events. *Journal of Asian Earth Sciences*, 62, 438–462. <https://doi.org/10.1016/j.jseaes.2012.10.028>

45. Zimmermann, U. and Spalletti, L.A., 2009, Provenance of the Lower Paleozoic Balcarce Formation (Tandilia System, Buenos Aires Province, Argentina): implications for paleogeographic reconstructions of SW Gondwana. *Sedimentary Geology*, 219, 7–23. <https://doi.org/10.1016/j.sedgeo.2009.02.002>