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RESEARCH ARTICLE - EARTH SCIENCES

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Isotope Stratigraphy of Oligocene Limestone in Al-Ain City, United Arab Emirates

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Abstract The rocks of the Oligocene Asmari Formation represent the outer ridges surrounding Jabal Hafit anticline. The carbonate beds of this formation dip gently under the northern and western sides of Al-Ain city. The beds are dissected by several sets of joints and characterized by the abundance of the connected caves of different sizes, particularly in the thick chalky beds. In this study, petrographic and mineralogical studies by X-ray diffraction analysis and scanning electron microscope revealed that the examined carbonate rock samples are made up mainly of calcite and minor of authigenic dolomite and quartz minerals. The $^{87}Sr/^{86}Sr$ data obtained from the 8 fossils of Asmari Formation range between 0.707989 and 0.707835. The age of the analyzed rocks was estimated from the $^{87}Sr/^{86}Sr$ values that suggest a range from approximately 29.6 to 33.5 my (late Rupelian stage of the Oligocene).

Keywords Sr isotope · Stratigraphy · Oligocene · Asmari formation · Jabal Hafit · Al-Ain · UAE

الخلاصة

تمثل صخور متكون الأسمري التابع لعصر الأوليجوسين الحدود الخارجية لطية جبل حفيت المحدبة. وتميل طبقات الكربونات لهذا المتكون بلطف ناحية الجانب الغربي والشمالي لمدينة العين وهذه الطبقات مقطوعة بالعديد من الفواصل والكسور وتمتاز كذلك بوجود مجموعة من الكهوف ذات الأحجام المختلفة وفي أماكن متفرقة. وقد أظهرت الدراسات المعدنية والصخرية وأشعة الحيود السينية والميكروسكوب الإلكتروني أن صخور الكربونات تتكون من معادن الكالسيت والدولوميت ونسبة قليلة من الكوارتز. ولقد أعطت نظائر الاسترانشيوم لعدد ثماني حفريات من متكون الأسمري عمراً مطلقاً يتراوح ما بين 29 إلى 35 مليون سنة ؛ أي في نهاية عصر الأوليجوسين المبكر.

1 Introduction

Al-Ain city is located in the eastern part of Abu Dhabi Emirate and represents one of the most urbanized cities in the UAE (Fig. 1). Most of the foundation bedrock in this city, particularly its southern part, is composed mainly of limestone beds with several interbeds of marls. These beds belong to the Asmari Formation that is of Early Oligocene age and is well exposed in Hafit Mountain. The time-frame of the rock sequence in Jabal Hafit was established as from Early Eocene to Miocene and divided into 11 informal units [1]. These units were later designated as formations which incorporated the Oligocene part into their Al Jaww Formation [2]. But the formation has been revised to the Asmari Formation and subdivided into three members [3]. The biostratigraphic zonation of the Oligocene and Eocene rock sequences in Jabal Hafit was established from the identified fauna [4]. The reefal limestones of the Asmari Formation represent a shoal margin prograding complex [5]. The age of the formation was assigned as the Early Oligocene (Rupelian) based on a diagnostic

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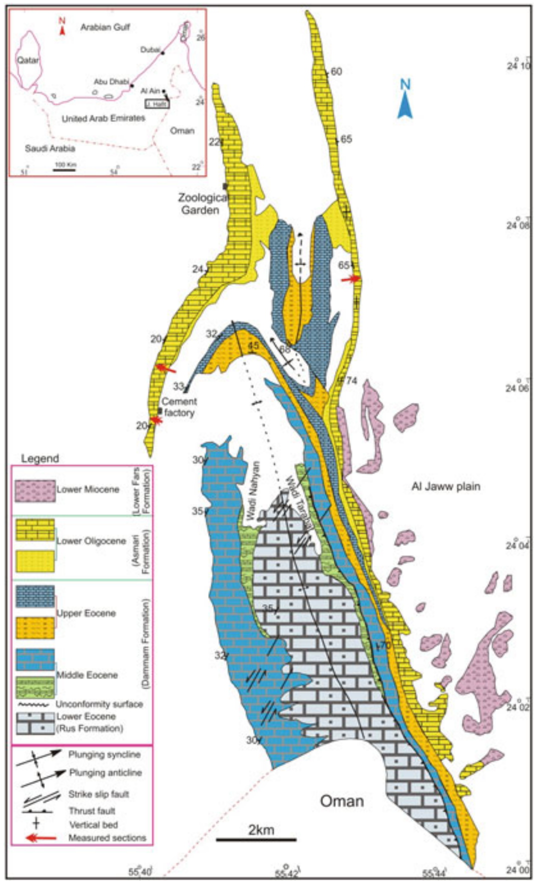

Fig. 1 Location and geological map of the study area and its surroundings (modified by [16] after [1,2] and [7])

larger foraminiferal assemblage [6]. The rocks of the Asmari Formation form the outer ridges surrounding Jabal Hafit (Fig. 1). This Hafit Mountain represents a large doubly plunging highly asymmetric anticline that developed over a thrust fault underlying its eastern limb [7–9].

This paper aims mainly to apply the technique of radioactive dating of the carbonate beds of the Asmari Formation in Jabal Hafit area using Sr isotope obtained from different fossils acquired from these beds.

2 Sample Collection

About 60 rock samples were collected from three investigated sections (Fig. 1) for different analyses. These analyses include separation and identification of fossils, microfacies, mineralogy and petrographic analysis. Eight different types of the collected fossils were used for the Sr age dating methods.

3 Geological Setting

3.1 Stratigraphy

The studied Oligocene rock sequence is known as Asmari Formation.This Formation consists of cream-to-brownish colored, jointed limestone with yellowish marl intercalations. The type section of this formation is located at Tang-e Gel-e Tursh located on the south western flank of the Kuh-e Asmari Anticline, Khuzestan, Iran. It was assigned as Oligocene to Early Miocene age [11]. The Asmari Formation unconformably overlies the Upper Eocene Dammam Formation, and underlies the Lower Fars Miocene Formation and Quaternary deposits (Fig. 1). In the study area, this formation can be lithostratigraphically subdivided into three informal

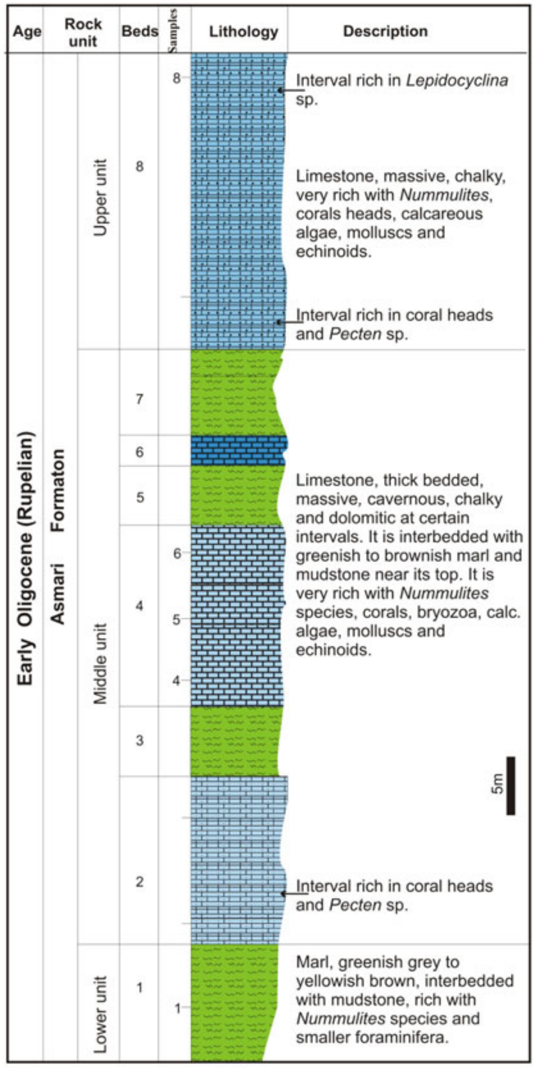

Fig. 2 The stratigraphic section of the Asmari Formation in Jabal Hafit

units (Fig. 2) and Table 1. The exposed basal unit is about 10 m thick and is formed of greenish grey mudstone interbedded with yellowish brown marl (Fig. 3). The middle unit is about 55 m thick. It is made up of thick bedded to massive dolomitic and chalky limestone (Fig. 4) which in turn, interbedded with greenish to brownish mudstone and marl. This part is highly fossiliferous and characterized by the abundance of the joints and karsts. The upper unit has 25 m thickness and is composed of chalky limestone, that is massive and very rich in containing different types of coral heads (Fig. 5) and also *Nummulites* spp. that dominates at all intervals.

3.2 Structure

The rocks of the Oligocene Asmari Formation occupy the outer eastern and western limbs of Jabal Hafit anticline. The rocks on the western limb are typified by wide outcrops as they dip gently with angles ranging from 20° to 25° towards the west and southwest, whereas, the same rocks have steeper attitudes on the tightly outcropping eastern limb (see Fig. 1). The studied limestone beds of the Asmari Formation on both limbs are dissected by different types of fractures (Fig. 6) that was developed during the folding which started just before the Middle Eocene till the end of the Miocene [8]. The presence of these fractures controlled the origin of the

Table 1 Lithostratigraphic correlation chart of Abu Dhabi (UAE) and neighboring countries modified after [3]

Time Units		Ma	Iran: Nolan et al., 1990	Oman: James and Wynd, 1965	Southern Iraq, Kuwait Saudi Arabia, Qatar and United Arab Emirates: Jones and Racey, 1994	Oman	Abu Dhabi: Hunting, 1979	Abu Dhabi: Cherif and El Deeb, 1984		Abu Dhabi: Hamdan and Bahr, 1992		Abu Dhabi: Boukhary et al., 2003	Lithology
Oligocene Epoch	Late	23–28	Asmari Formation			Al Jaww Formation	Tlo2	Al Jaww Formation	Upper Member	Asmari Formation	Muwaiji Member		
									Lower Member		Mutaredh Member		
	Early	28–33	Pabdeh Formation			Seeb Limestone Formation	Tlo1				Zakher Member	Asmari Formation	
Eocene Epoch	Late	33–37		Seeb Limestone Formation	Dammam Formation		Tle7	Senaiya Formation	Members A, B, C, D, E	Dammam Formation	Mazyad Member	Senaiya Formation	
							Tle6						
	Middle	37–49					Tle5				Ain Al Faydah Member	Tawi Uwayyir Formation	
							Tle4	Hafit Formation	Upper Member				
							Tle3		Middle Member		Wadi Al Nahyan Member		
	Early	49–53		Rusayl Formation	Rus Formation	Rusayl Formation	Tle2		Lower Member	Rus Formation	Hilli Member	Saah Formation	
							Tle1				Wadi Tarabat Member		

Fig. 3 The mudstone and marl beds at the base of the Asmari Formation

Fig. 4 The massive chalky limestone in the middle part of the Asmari Formation

Fig. 5 A coral heads at the upper part of the Asmari Formation

Fig. 6 Sets of fractures dissecting the beds causing rock fall at the slope

Fig. 7 The cuestas formed at the western limb of the Hafit Mountain

different cuestas along the Oligocene ridges in the study area (Fig. 7). The solution karst cavities represent the most common surface features in the outcrops of the beds (Fig. 8). These cavities are the product of the surface water erosion. In other localities within Al-Ain city, the groundwater produced caves with different sizes that, in turn, became connected and created a severe engineering problems for the overlying buildings.

3.3 Facies Analysis

The petrography of the rocks of the Oligocene Asmari Formation at Jabal Hafit was studied following the classifications of Folk [17,18] and Dunham [19]. This resulted in the recognition of three facies as follows:

Fig. 8 The abundance of the karst cavities in the chalky beds

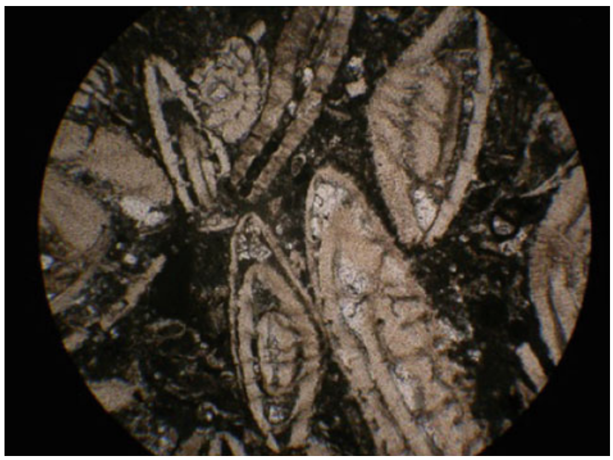

Fig. 9 Packstone facies ($X = 100$)

3.3.1 Packstone (Foraminiferal Biomicrite) Facies

This facies constitutes the lower parts of the Asmari Formation and made up of skeletal and non-skeletal grains embedded in partially recrystallized micritic groundmass (Fig. 9). The skeletal grains are represented mainly by tests of larger foraminifera (*Nummulites sp.*) and echinoid fragments. Other skeletal grains are rare and represented by non-coiled forams, algae, unidentifiable shell fragments and corals. The non-skeletal grains are represented by coarse peloids and fine fecal pellets. Dolomitization by microcrystalline unzoned dolomite is frequently observed. Micritization is manifested by the development of micritic envelopes and coarse peloids.

3.3.2 Wackestone (Biomicrite)

The wackestone facies is relatively less abundant than packstone facies. The allochems of this facies are represented by skeletal and non-skeletal grains (Fig. 10). The former grains are dominated by echinoid fragments, small forams and unidentifiable shell debris with less abundant larger foraminifera (Nummulites) and algae. Corals are more abundant in the western limb. The non-skeletal allochems are dominated by fine pellets of fecal origin, whereas the coarse peloids are less common. Rare dedolomitized crystals and silicified echinoid fragments are observed.

3.3.3 Grainstone (Biosparite)

The grainstone is the less abundant facies. Coarse peloids, algae and foraminifera tests are the main allochemical components of this facies (Fig. 11). Subordinate amounts of echinoid fragments and fine pellets of fecal origin are observed. The rock groundmass is made up of partially micritized sparite.

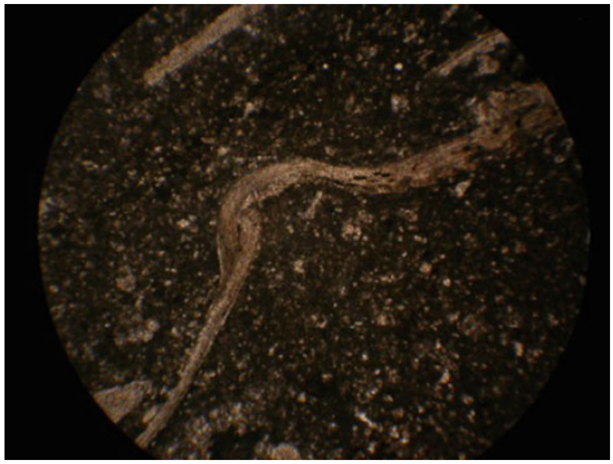

Fig. 10 Wackestone facies ($X = 100$)

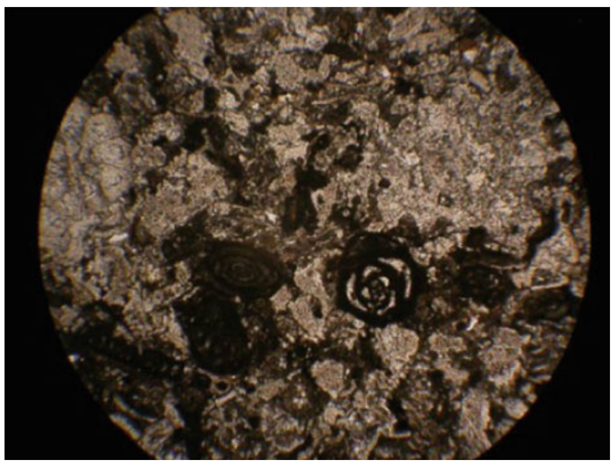

Fig. 11 Grainstone facies ($X = 100$)

The described facies suggested that depositional environment of the Asmari Formation at Jabal Hafit is shallow marine in which the Oligocene carbonate platform in the study area was formed.

3.4 Petrographic and Mineralogical Analysis

The petrographic and mineral investigations of the carbonate rocks were carried out to investigate their textural and compositional characteristics using thin section description, scanning electron microscope with energy dispersive X-ray and X-ray diffraction analysis. This revealed that the examined carbonate rock samples are made up mainly of calcite and minor of authigenic dolomite and quartz minerals in some stratigraphic levels as shown in the diffractogram (Fig. 12).

The textural and compositional characteristics of the carbonate Oligocene rocks were also investigated by the SEM with EDX as detected from the following plates (Fig. 13a, b). Note the description of dolomite as authigenic as shown from SEM micrographs (Fig. 13a, b).

4 Sr Isotope Study

Determination of Sr isotopes was conducted on eight representative fossil samples from the Asmari Formation of Jabal Hafit (Table 2). The method requires measurement of the $^{87}Sr/^{86}Sr$ value of minerals that precipitated from seawater and had not been subjected to diagenetic alteration; thus retaining the original $^{87}Sr/^{86}Sr$ value.

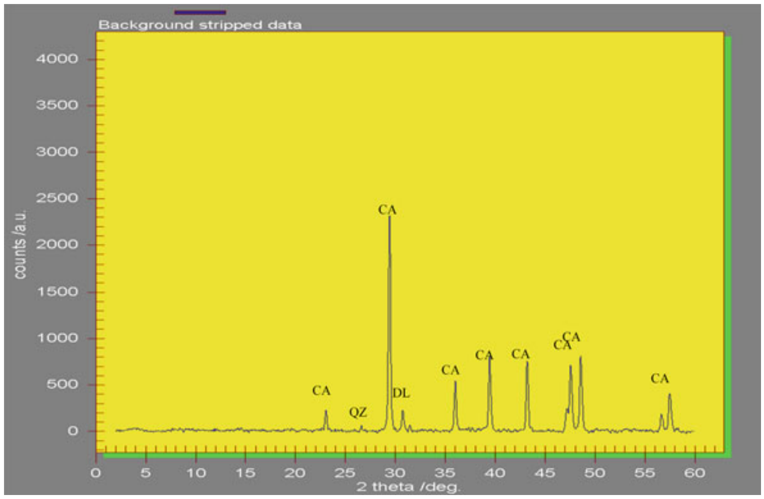

Fig. 12 X-ray diffractogram of a carbonate sample

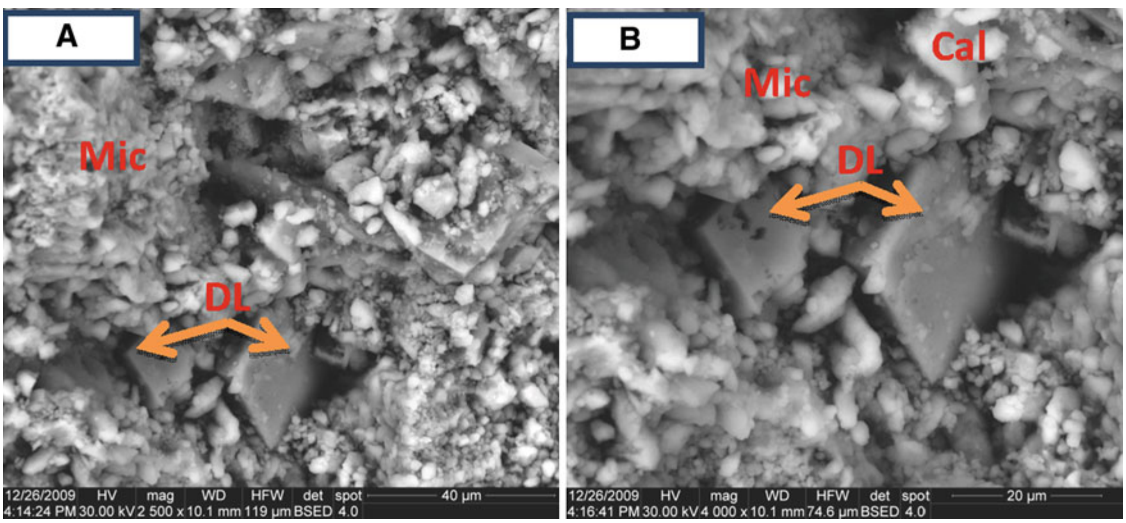

Fig. 13 a, b Illustration of pore lining and pore filling of well-developed authigenic rhombohedral dolomite crystals (*DL*), *Mic* (micrite) and *Cal* (calcite)

Table 2 Strontium isotope analyses for selected samples

No.	Fossils name	$^{87}Sr/^{86}Sr$
1	*Nummulites* sp.	0.707932 ± 8
2	*Pecten* sp. shell fragments	0.707928 ± 8
3	*Pecten* sp. shell fragments	0.707940 ± 8
4	Pelecypod shell fragments	0.707835 ± 9
5	Calcareous red algae	0.707896 ± 7
6	Corals	0.707915 ± 12
7	Host rock limestone for *Pecten* shells	0.707972 ± 9
8	*Lepidocyclina* sp.	0.707989 ± 7

The most reliable material is biogenic calcite, especially when present as unaltered mollusk shells large enough to be physically separated from the surrounding rock. Other materials of potential use include recrystallized lime-mud matrix, anhydrite and dolomite. Some intervals of geological time are particularly favorable for this method because they show high rates of change of marine $^{87}Sr/^{86}Sr$, and the Oligocene (Rupelian–Chattian) is considered to be characteristic of such time (Fig. 14).

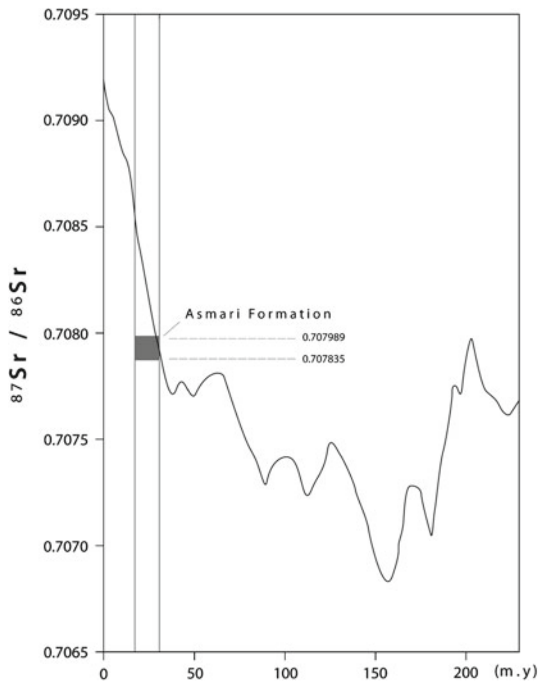

Fig. 14 Variation in the strontium-isotope composition of seawater through Mesozoic and Cenozoic time [15]

The validity of ages determined from Sr isotope analysis of macrofossils may be evaluated by examining the degree to which a series of such analyses shows a consistent trend of changing age through conformable stratigraphic successions, and by comparison with age constraints from other sources. Once a consistent stratigraphic age framework has been established from the Sr isotope compositions of macrofossils, the dating potential of other types of materials can be assessed by examining whether they give similar ages at similar stratigraphic levels.

Strontium isotope sample preparation and analyses were conducted at Institute of Precambrian Geology & Geochemistry, Russian Academic of Sciences, St. Petersburg University. Details of the method are described in [12–14]. Bioclasts were physically separated by removing surrounding matrix material with a microdrill, acid washing and then dissolution in 2.5 M HCl for extraction of Sr by standard methods of ion exchange. Dolomite samples were pulverized and then pre-leached with dilute acetic acid prior to dissolution of most remaining carbonate in 50 % acetic acid. Leachate from the second stage of dissolution was separated from undissolved material by double centrifugation and evaporated to dryness with ultrapure 6M H Cl before dissolution of evaporated sample residue in 2.5 M HCl for extraction of Sr. The pre-leach is designed to remove Sr in acid-soluble contaminant phases before dissolution of the cleaned residue in the second acid leach step [13].

Experiments showed that most of the Sr content in such samples was removed by leaching with distilled water, such that Sr contained in any Celestite present is effectively removed by the pre-leach step in sample preparation. The acid-leaching technique used thus separates the strontium within calcite and dolomite from strontium contained in other minerals present, including anhydrite, siliciclastic and Celestite.

4.1 Calibration

The numerical age of the samples was determined by comparing the measured $^{87}Sr/^{86}Sr$ value with the curve of marine $^{87}Sr/^{86}Sr$ calibration of [15], which gives robust statistical uncertainties on any measured numerical age. The ratio of $^{87}Sr/^{86}Sr$ isotopes was analyzed using an automated Finnegan 261 mass spectrometer equipped with nine Faraday collectors. Correction for isotopic fractionation during the analyses was made by normalization to $^{86}Sr/^{88}Sr = 0.1194$. The mean standard error of mass spectrometer performance was ± 0.00003 for standard NBS-987. The uncertainty in the calibration line is available from tables and is looked up for the time of interest; for the period 41 Ma to 21 Ma it is around ± 0.000007 to ± 0.000009. The combined uncertainly is computed as the geometric mean of individual uncertainties. This mean value is then used to determine maximum and minimum ages from tables of numerical age against $^{87}Sr/^{86}S$.

The main probable sources of scattering in the trends of increasing age with stratigraphic depth determined for our macrofossil data include: 1. diagenetic alteration of material analyzed, 2. the simplest possible line segments consistent with data, and 3. compiling data from different locations.

The $^{87}Sr/^{86}Sr$ data from the 8 fossils of Asmari Formation of Jabal Hafit range between 0.707989 and 0.707835. Age estimates obtained from the $^{87}Sr/^{86}Sr$ values were calculated following the look-up tables of [14] and [15] and suggest a range between about 29.6 and 33.5 my (late Rupelian stage of the Oligocene).

5 Discussion and Conclusion

The precise age of the Asmari Formation in the UAE was always a matter of suspect and debate for a long time. It was assigned Oligocene to Early Miocene by [11] as 33.9–15.97 my. Other previous studies [2,3,10] assigned the Lower to Middle Oligocene age (33.9 to 23.03 my) based on taxonomic, biostratigraphic and paleoecological data on the smaller and larger foraminifera obtained from the Oligocene marls and limestones outcrops in the UAE (Asmari Formation, Jabals Hafit and Malaqet). But [6] studied the content of the larger foraminifera (such as *N. fichteli*, *N. intermedius* and *N. emiratus* n. sp.) in this formation and concluded its age as Early Oligocene (Rupelian age). Hence, it was important to end this debate by determining the absolute age of this formation by applying the technique of the Sr isotope.

The Oligocene limestone of the Asmari Formation is of about 90 m thick. This formation can be subdivided into three units. The lower unit is about 10 m thick and is formed of greenish grey mudstone interbedd with yellowish brown marl. The middle unit is about 55 m thick. It is made up of thick bedded to massive dolomitic and chalky limestone which in turn, interbedded with greenish to brownish mudstone and marl. This part is highly fossiliferous and characterized by the abundance of the joints and karsts that cause problems as a foundation material in Al-Ain City and its surrounding areas. The upper unit has 25 m thickness and is composed of chalky limestone, that is massive and very rich in containing different types of coral heads and also *Nummulites* spp. that dominates at all intervals.

In Jabal Hafit anticline, the rocks of the Oligocene Asmari Formation present as eastern and western limbs. The western limb is typified by wide outcrops as they dip gently with angles ranging from 20° to 25° towards the west and southwest, whereas, the eastern limb have steeper attitudes on the tight outcropping. The limestone beds of the Asmari Formation on both limbs are dissected by different types of fractures that were developed during the folding which started just before the Middle Eocene till the end of the Miocene.

The described facies suggested that depositional environment of the Asmari Formation at Jabal Hafit is shallow marine in which the Oligocene carbonate platform was formed. The textural and compositional characteristics of the carbonate Oligocene rocks revealed that the limestone is composed of mainly calcite and minor authigenic dolomite and quartz minerals.

The estimated age of the studied samples obtained from the $^{87}Sr/^{86}Sr$ values was calculated following the look-up tables and suggests a range between about 33.5 and 29.6 my (late Rupelian stage of the Oligocene).

This precise determination of the absolute age of the studied Asmari Formation by the Sr isotope technique instead of the relative age of fossils is considered as a good contribution to our understanding on the geological history in this region.

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