Lithofacies and Clay Mineral Analysis of the Upper Cenomanian Ms'ad Formation, Rutbah Area, Western Iraq

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Abstract

The Cenomanian succession in Rutbah City, western Iraq, is composed of siliciclastic carbonate with multicolored paleosoil layers that refer to unconformity surfaces within the Ms'ad Formation. The current study will examine the clay mineralogy and facies to determine the source of these clay minerals and depositional settings. Fifteen carbonate facies have been identified as three distinct facies associations (FA1–FA3). These FAs are supratidal to intertidal (FA1), semi-restricted lagoon (FA2), and shallow open subtidal ramp with patches of a rudist-bivalve reef (FA3). The reported Multispirina Iranica-Nezzat simplex-Chrysalidina gradata assemblage Zone within the Ms'ad Formation indicated the Cenomanian age. Clay mineral analysis displays three distinctive clay mineral assemblages; kaolinite-dominated with illite (assemblage A), R0-dominated (smectite-rich illite/smectite mixed layers) with kaolinite and illite (assemblage B), and illite-dominated (illite and illite-rich illite/smectite mixed layers) with kaolinite and R0 (assemblage C). Most of these clays are detrital, generated by weathering source rocks (igneous, metamorphic, and sedimentary) under various paleoclimatic circumstances. The Kaolinite-dominated assemblage A represents intense chemical weathering from hot, humid circumstances. Smectite-dominated R0 assemblages were created by weathering alkaline rocks in flat pedogenic soils with seasonal humidity. The source of clay minerals in the studied region was subject to a dry climate towards the end of the Cenomanian period, which encouraged physical weathering and the production of illite-rich assemblages.

Keywords: Late Cenomanian; Ms'ad Formation; Lithofacies; Clay mineral analysis; Rutba area; Western Desert

1. Introduction

Few studies were done on the Cenomanian-Turonian deposits in the Rutbah Basin in western Iraq (e.g., Van Bellen et al., 1959; Jasim and Buday in Jasim and Coff, 2006; Sissikian and Mohammed, 2007; and Amer, 2011). In contrast, the equivalent Cenomanian-Turonian successions in central and southern Iraq (Ahmadi, Rumalla, and Mishrif formations) are studied and analyzed in great detail due to their containing huge hydrocarbon reservoir (e.g., Murris, 1980; Burchette and Brittan, 1985; Sherwani and Mohammed, 1993; Sharland et al., 2001; Buchem et al., 2011; Agrawi et al., 2010; Razin et al., 2010; Mahdi and Agrawi, 2014 and 2017; Awadeesian et al., 2015). The Rutbah Formation and the overlain Ms’ad Formation are included in the Cenomanian sedimentary sequence of the Rutbah DOI: 10.46717/igj.56.2C.16ms-2023-9-22
Basin (Van Bellen et al., 1959; Al-Naqib, 1967). However, Amer (2011) and Sissakian and Mohammed (2007) proposed the Cenomanian-Turonian age for the Ms’ad Formation, with transitional boundaries separating the Ms’ad and Rutbah formations. Within the Rutbah Sandstone Formation, the lower white sandstone and the top sandstone-dolomitic mudstone/marl were formed in a shallow marine tidally-driven transgressive-regressive shelf basin, respectively (Rahmani et al., 2022). Dolomitic limestone, reefal limestone, shell breccia, marl, and sandstone tongues with fossiliferous limestone are found in the Ms’ad Formation (e.g., Van Bellen et al., 1959; Al-Naqib, 1967; Buday, 1980; Jasim and Buday in Jassim and Goff, 2006). This study focuses on the Ms’ad Formation, including fieldwork at two different sections in the Rutbah region. A palaeoclimatic condition and depositional environments regulated along the Cenomanian strata in the source region and the basin of deposition will be constructed, focusing on stratigraphy, lower and upper boundaries, litho- and microfacies, clay mineral analyses, and sedimentary environment.

2. Geological Setting and Lithology

The Ms’ad Formation displays excellent exposure in the Rutbah area, especially around the Baghdad-Amman highway (Fig. 1). The underlying upper Triassic dolomite of the Mulussa Formation crops out in the Rutbah area (Van Bellen et al., 1959). Haq et al. (1988) considered a global drop in sea level during the Pre-Cenomanian unconformity, also known as the Pre-Wasia unconformity in the Arabian Plate. The Pre-Aruma Unconformity, located in northern and eastern Saudi Arabia, is a zone of erosion and karstification at the top of the Cenomanian sedimentary record (Power, 1966; Mohammed et al., 2021). The Rutbah Formation dates back to the early Cenomanian. In contrast, the Ms’ad Formation dates to the late Cenomanian (Van Bellen et al., 1959; Al-Naqib, 1967; Buday, 1980) or Cenomanian-Turonian based on Amer (2011) and Sissikian and Mahommed (2007). The Rutbah Sandstone Formation begins with sandstone and dolomitic mudstone and ends with sandstone and dolomitic mudstone. It ends with sandstone and dolomitic mudstone. The Ms’ad Formation consists of highly dolomitic limestone, green dolomitic marl, and shale at the base. The top sandy, fenestral, algal, stromatolitic, calcitic, geodes and marly dolostone interbedded with green marl, overlain by rudist, oysters, other bivalves, and gastropods, with low benthic foraminifera, has been highly dolomitized. Along with the multiple macrofossils, rich intervals capping transgression cycles of growth are found in layers 30 to 60 cm thick.

3. Materials and Methods

Two outcrop sections have been chosen to study the Ms’ad Formation in the Rutba area: the first section is located 17 km SW of Rutba in the Radhuma area with a thickness of about 62 m (Fig. 2). The second section occurs along the highway in Rutba city, with a thickness of 60 m. Sixty samples were collected from the first section and forty samples from the second section. These sections were described in the field, and then samples were taken to prepare thin sections to study the lithofacies and describe the fossil continent using microscopes. Thirty-three samples were taken from Section 1 to make slides to check the clay minerals to determine the paleoclimate and paleoenvironment. The XRD samples were examined and prepared in Al-Anbar University’s lab. X-ray Diffraction was performed at Iraq’s Ministry of Science and Technology, utilizing Ni-filtered Cu radiation at 40 kV and 30 mA. Orientation clay samples were used to extract qualitative clay minerals by air drying, ethylene glycol, and specific heating to 490 °C. Semi-quantitative clay mineral species studies using Biscaye weighting factors (Biscaye, 1965) and the USGS ethylene glycol solvation method (Poppe, 2001). The paleoenvironment and paleoclimate were deduced through the study of clay minerals. Microfacies texture was determined using Dunham’s classification, modified by Embey and Klovan (1971). The carbonate microfacies were grouped into three facies associations (Table 1) based on Burchette and Wright (1992).
4. Results

4.1. Biostratigraphy of the Studied Section

A few small benthic foraminiferas have been identified, and no planktic foraminifera was found in the investigated sections. The most distinguished benthic foraminifera documented from the studied samples, including *Multispirina iranica*- *Nezzazata simplex*, *Nezzazatinella cf. picardi*, *Chrysalidina gradata*, *Cisalveolina frassi*, *Pseudolituonella reicheli* *Nummulculina heimi Spiroloculina sp.*, *Nezzazat sp.*, *Rotalia sp.*, *Pseudochryssalidina sp.*, and *miliolids Spiroloculina sp.* (Pl. 2a-l). Based on the stratigraphic distribution of diagnosed foraminifera, one biozone named *Multispirina iranica*- *Nezzazat simplex*– *Chrysalidina gradata* assemblage Zone has been established. It is defined from the first occurrence of *Multispirina iranica*- *Nezzazat simplex*– *Nezzazatinella cf. picardi* and *Chrysalidina gradata* and the last occurrence of the nominated taxa. According to the fossils above, the Cenomanian age was obtained from the M’sad Formation in the study area. The present reported zone is identified from section 2 and not found in section 1, where the dolomitization processes were very high, which extends about 20m. The biozone comprises foraminifera intraclasts, grainstone, and benthic foraminifera rudist debris packstone-grainstone (inner ramp) as major microfacies.

4.2. Facies and Facies Associations

Carbonate comprises large fossils (such as rudists and other bivalves). On the other hand, smaller foraminifera fossils are heavily dolomitized and cannot be recognized by petrographic investigations; hence, significant fieldwork was carried out in addition to thin sections examined by petrography to identify fifteen different carbonate facies. These facies were divided into three associations based on the depositional environment, and the depositional system was limited to the shallow inner ramp (Burchette and Wright, 1992) (Table 1).

4.2.1. Tidal flat facies association (FA1)

**Description:** FA1 consists of fine-grained dolomite-rich unfossiliferous carbonate lithofacies, including thin laminated dolomitic argillaceous mudstone (marl), muddy dolostone, red mudstone, thin laminations, and a fine sand-dolomite matrix. Mudstone to wackestone texture (F1) (Pl.1F), laminated fenestral dolostone, microcrystalline aphanitic to very fine-grained, anhedral dolomite (F2) (Pl.1E), horizontal and wavy laminated stromatolitic dolostone (F3) (Pl.1D), massive dolostone (F4) with dolostone breccia, bird-eye porosity and fine to coarse quartz sand, quartz sandy dolo-packstone to dolo-wackestone (F5), gypsum-dolostone, calcite nodules after anhydrite, mud cracks, in situ brecciations filled by evaporite or chert. Evaporite-calcite-ocher nodules (F6) (Pl.1C) and dolomitic sandstone, red horizontal to low angle cross-bedding, skolithos trace fossil, coarse to medium, poorly sorted (F7) FA1, representing significant thicknesses from the lower, middle, and upper parts of the Ms’ad Fm.

**Interpretation:** Laminated fenestral porosity, parallel to wavy micro-laminate of stromatolite of microbial matt, dolomite, and unfossiliferous mudstone, gypsum, calcite nodules after anhydrite, dolomitic sandstone, and dolo-breciated structures, along with unfossiliferous sediments, are typical examples of macrostructures and textures found in intertidal to supratidal marine environments (e.g., Shin, 1983; Hardie and Shinn, 1986; Warren, 2016). Contrast hydrodynamic conditions along the tidal flat of the studied basin, higher energy conditions, reworked the dolomitic firmground, and redeposited inside the supratidal environment in addition to the deposition of quartz sand along the shoreline. In contrast, dolomitic mudstone and muddy dolostone were deposited on the tidal plain in an environment with lower energy. The proximal inner ramp facies assemblage represents a shallow subtidal to the supratidal sand-bar zone of the internal ramp setting. These sedimentary facies occurred in the photic
area and hypersaline water (Wilson, 1975). Thin gypsum beds, calcite geodes, and nodules after anhydrite indicate a warm-arid to semiarid climate.

Fig. 1. Location and geological map of the study area (Sissakian, 2000)
4.2.2. Shallow subtidal lagoon Facies Association (FA2): deposits

**Description:** FA2 consists of fine-grained dolomitic limestone and mudstone, containing peloidal – miliolids doloo-wackestone (F8), bioclastic–benthic foraminifera doloo-wackestone/packstone (F9) dasycladacean algae – benthic foraminiferal doloo-wackestone (F10) and dolomitic mudstone. Benthic foraminifera include *Quinqueloculina* sp., *Choffettela* sp., *Cyclindricacsp* sp., *Pseudochrysaldina* sp., *Praeolveolina* sp., *Dicyclina* sp., *Cuneolina* sp., *Spiroloculina* sp., *Pseudonummoloculina* sp., with some bioclasts of *Dasycladacean*, pelecypod, gastropods, and rudist shells, in addition containing peloids, algal peloids, algal intraclasts, calcareous green algae, quartz silt, and clay minerals (Pl.1 and Pl.2).

**Interpretation:** Fine-grained textures indicate low to moderate energy conditions. The lithofacies of benthic foraminifera, bioclasts, and high dolomitization indicate this association. However, the depositional fabric of the intensive dolomitization along all facies of the Ms’ad Fm, including facies types of FA2, made the benthic fossils poorly preserved. It was deposited in warm, shallow subtidal marine water and euphotic and semi-restricted environments (Enos and Moore, 1983).

4.2.3. Shallow subtidal open marine with rudist-bivalve shoal deposits Facies Association (FA3)

**Description:** FA3 is widely distributed in the studied sections and is characterized by large bivalve and benthic foraminifera-rich dolomitic limestone facies. The fauna collection includes several different kinds of benthic foraminifera and bivalves, including bioclastic doloo-wackestone (F12), rudist-rich framstone to floatstone (F13), peloidal -orbitalis doloo-wackestone (F14), and coarse crystalline dolomitic limestone (F15). These facies may be identified by the comparatively high number of large and tiny benthic foraminifera found within them. Calcareous green algae, oysters, bivalve, Crustose coralline algae, *Dicyclina* sp., *Rotalia* sp., *Alveolina* sp., *Cisalveolina* sp., *Rotalia* sp., *Alveolina* sp., *Cisalveolina* sp., with green and red algae, pelecypods, *Trinocladus*, and *Radiolitids*, make up the rudist bivalve shoal of the Ms’ad Formation (Pl.2, G, and H).

**Interpretation:** FA3 is divided into two sedimentary sub-environments, one based on the presence of rudist-rich lithofacies and the other based on the presence of benthic-bioclastic-rich facies. The first is a patch reef made of rudist-rich floatstone or rudstone restricted to the inner ramp’s central part in shallow water to get started. The rudist biostromes are developing a patch shoal inside the internal ramp (Bebout and Loucks, 1974; Farouk et al., 2022). The second sub-environment, a benthic foraminiferal-rich doloo-wackestone to packstone facies indicating a level platform of the central region from the inner ramp, is interbedded with a discontinuous accumulation of the rudist and another bivalve thinning laterally. This region has a warm, maybe semi-humid, to semi-arid climate. The open and shallow marine euphotic zone is above a fair-weather wave base (Aqrawi et al., 1998; Murris, 1980).

4.3. Clay Minerals

4.3.1. Mineralogy

Along the Ms’ad Fm, smectitic or R0 (smectite-rich illite/smectite), kaolinite, and illite-rich (illite and illite-rich illite/smectite mixed layers, in different amounts) were recorded. In addition, palygorskite was found at the top of one sample.

4.3.1.1. R0 (smectite: rich illite/smectite mixed layers and discrete smectites)

It makes up 10–80% of the clay minerals in the successions. It is good to medium crystalline, with a lot of smectites (more than 60% smectite) in the R0 illite/smectite mixed layers, as shown by broad and asymmetrical peaks in the 14.3 A when air-dried, which get more significant to 16.9–17.1 A when ethylene-glycation is done.
4.3.1.2. Kaolinite

It is the second most common mineral in the carbonated facies of the Ms'ad Fm (10–85%). In contrast, samples from Rutbah FM have a very high amount of kaolinite. 3.54 Å d-space indicates either no chlorite mineral or very little; the kaolinite in the Ms'ad and Rutbah formations has thin, sharp peaks, which show that the material is well-crystallized (Moore and Reynolds, 1997; Wilson, 1989).

4.3.1.3. Illite and illite-rich illite/smectite mixed layers

Illite is the third most common clay mineral, making up 0–75% of the total. It has been shown that smectite and kaolinite are the opposite of where illitic minerals are found. Illite-rich illite/smectite mixed-layers have broad, asymmetrical peaks fixed with the lower angle shoulder of the illite peak near 10.2 to 11 Åo and shift to higher-order when saturated by EG. This suggests that it was a weakly crystalline and illite-rich illite/smectite mixed layer disordered with a low smectite ratio of type R0, this mineral is formed by weathering old sedimentary rocks (Keller, 1962).

Table 1. The facies association and microfacies of the Ms'ad Formation in the two studied sections

<table>
<thead>
<tr>
<th>Facies association</th>
<th>Facies types</th>
<th>Thickness</th>
<th>Sedimentary environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal flat deposits (proximal inner ramp) FA1</td>
<td>F1-Dolomitic marl to marly dolostone</td>
<td>F1: 6 m thick within the base of the formation</td>
<td>The warm-arid to semi-arid climate</td>
</tr>
<tr>
<td></td>
<td>F2-Dolostone has a fenestral lamination and a dolomitic mudstone texture belonging to the</td>
<td>F2: 0.50 to 0.70 m thick within the middle part</td>
<td>Supratidal to the intertidal environment (Sabkha model)</td>
</tr>
<tr>
<td></td>
<td>F3-Algal – stromatolitic laminates bindstone</td>
<td>F3: 0.60 m thick near the top of the middle part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4-Massiv unfossiliferous dolomudstone</td>
<td>F4 &amp; F5: 9.5 m thick near the middle part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5-dolo-breccia floatstone/rudstone</td>
<td>F6: 1 meter at the base. F7: 4 m thick at the bottom and the top</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F6-gypsum – dolomudstone with calcite geodes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F7-Sandy dolostone to dolomitic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow subtidal lagoon deposits (proximal inner ramp) FA2</td>
<td>F8-peloidal-miliolids dolowackestone</td>
<td>F8: 7 m thick within the middle part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F9-bioclastic–benthic foraminifer dolowackestone / packstone</td>
<td>F9: 8 m within the middle and upper part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F10-Dasychadacean algae – benthic foraminifer dolowackestone</td>
<td>F10, 11: 9 m thick within the lower and upper part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F11-Dolomiticmarl-shale. benthic foraminifera</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow subtidal marine with rudist shoal deposits (central to distal inner ramp) FA3</td>
<td>F12-Bioclastic wacke/packstone</td>
<td>F12: 4 m thick middle PartF13: 5.5 m thick within the upper part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F13-Rudist–rich floatstone /rudstone</td>
<td>F14: 15,5 m thick near the upper part</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F14-Peloidal–Orbitolites Dolowackestone. F15-Coarse crystalline dolomitic limestone</td>
<td></td>
<td>Moderate to high energy, shallow open marine shoal/ patch reef</td>
</tr>
</tbody>
</table>
**Fig. 2.** Distribution of microfacies, sedimentary environment, and clay mineral assemblage the section 1 of the Ms’ad Formation.
Fig. 3. Distribution of microfacies, sedimentary environment, and basin type the section 2 of the Ms’ad Formation.

4.3.2. Clay mineral assemblages

Based on the relative abundance of the clay minerals in the studied succession, three clay mineral assemblages have been identified: kaolinite-dominated (assemblage A), smectite-dominated (assemblage B), and an illite-rich assemblage (assemblage C).

4.3.2.1. Assemblage A

The lowermost part and the middle part from the Ms’ad Fm and the upper part from the upper unit from the Rutbah Sandstone Formation. The clay mineral of assemblage A contains abundant kaolinite (60–95%) with relatively medium to high crystallinity (Fig 2). Minor components are illite and illite-rich illite/smectite mixed layers associated with kaolinite.
4.3.2.2 Assemblage B

It is smectite-dominated (R0) and is one of the most widespread clay minerals along the whole succession of the studied Ms’ad Fm. Assemblage B was dominated by smectite (40% to 80%) and is one of the most widespread clay minerals along the whole succession of the studied Ms’ad Fm. Assemblage B was dominated by smectite (40% to 80%), with a subordinate amount of kaolinite and illite (Fig. 2). The presence of R0-defeated clay minerals in the overlying strata of the Rutbah Basin, which range in age from the Late Campanian to the Eocene (Mohammed et al., 2022), and the studied Ms’ad succession.

4.3.2.3 Assemblage C

Clay minerals include illite-rich minerals associated with minor kaolinite and smectite. Palygorskite did not occur elsewhere in the investigated succession but was recognized in one sample in this clay mineral assemblage. This assemblage was only found in the uppermost part of the Ms’ad FM (Fig. 2).

5. Discussion

5.1. Biostratigraphy and Depositional Environment

*Nezzazata simplex* indicates it is reported from the Cenomanian age in southern Iraq (Al-Naqib, 1967; Gaddo, 1971). Several authors also recorded these assemblages within the Cenomanian age strata of the Mishrif Formation from several oil wells in south Iraq (Al-Nuaimy, 1990; Al-Dulaimy & Al-Sheikhly, 2013; Al-Dulaimi et al., 2020). It was also important to clarify that *Nezzazata simplex* and *N. conica* have been recorded before from the middle Cenomanian sequence in some parts of the middle east (Iran, Turkey, and Jordan) by many researchers (e.g., Husinec et al., 2000; Schulze et al., 2003; Sari et al., 2009; Filkorn & Scott, 2011; Orabi et al., 2012; Ghanem & Kuss, 2015; Afghah & Fadaei, 2015; Omidi et al., 2018; Afghah & Fadaei, 2020; Schlagintweit & Yazdi-Moghadam, 2021) confirmed *N. conica-Neta simplex* Assemblage Zone of Cenomanian in the Zagros area from Iran. In Egypt, Orabi & Hamad (2018) determined several benthic taxa were comparable with the Middle Cenomanian *Psededomia drorimensis* Rang Zone of Ogg (2004). *Nezzazatinella picardi, Nezzazata simplex, Praealveolina tenuis*, and *Cuneolina pavonia* are among those.
Plate 1. All filed photos from the Ms’ad Formation (A) General view of section 2, along a highway in Rutba city; (B) General view of section one, in Umm ErRadhuma, 17 km southwestern of Rutba city; (C) Calcite nodules-geode after anhydrite; (D) Algal-Stromatolite; (E) Fensetral dolostone, (F) Marl lamination; (G) Rudist fragment; (H) Rudist.
Plate 2. All photos from Ms’ad Formation in section 2:- (a) Nezzazata cf. picardi, (40X), (b) Pseudochrysalidina fragment, (M7,40X), (c) Pelecypoda fragments, (M7,20X), (d) Chrysalidina grade (M14,80X), (e) Rhypidion sp., Ms’ad Formation (section 2) (M14, 80X), (f) Multispirina iranica (M14,40X), (g) Miliolids (spirolocuillina sp.),(M16,40X),(h) Nezzazata sp., (M21, x80X),(i) Nummulocalina heimi, (M21, 40X), (j) Nezzazata cf simplex (M34, 80), (k) Red algae coating Rudist, (M30,20X), Cisalveolina sp., (M30, 40X).

In the present study, the sedimentary facies of the Ms’ad Formation in the studied two sections in the Rutbah area are devoid of planktic foraminifera and a minor amount of benthic foraminifera because their sedimentary environment is mainly within a partial environment, which is characterized by high salinity seawater and is very shallow. Despite the macro- and microfossil investigations confirming the existence of fossil assemblages mostly affected by intensive dolomitization along the succession, which reduced the chance of obtaining decisive age-diagnostic fossils of the Ms’ad Fm, their carbonate succession in the type area is a long-standing controversy. Cenomanian age has been assigned to this formation in the type area (Van Bellen et al., 1959; Al-Naqib, 1967), whereas Amer (2011) studied outcrops and one borehole in the area between east Rutbah and K160 and advocated an age between
Cenomanian and Turonian based on two planktic biozones. Large and small foraminifera contain benthic foraminifera, rudist, and other bivalves (Table 1), which suggests the Late Cenomanian age, correlative with benthic foraminifera of other lithostratigraphic units in northern and southern Iraq (Dr. Fadil Lawa, personal communication, 2022). The rocks studied by Amer (2011) are relatively far from the Al-Rutbah area, which may represent a complete succession of these rocks within deeper sedimentary environments within the open sea area; in addition, at the uppermost part of the formation characterized by evaporite-dolomite collapse, under the effect of extensive exogenetic diagenesis and karst development, which may have represented a long-time hiatus in the Rutbah and support the missing of the Turonian succession in the study area.

The open marine inner ramp facies association of the Ms’ad Fm (FA3) includes shallow subtidal to lower intertidal rudist rich in Radiolitidae (. Rudist-rich biofacies are not studied in detail because the rudist shells are highly dolomitized within hard dolomitic limestone. Brachiopods, gastropods, other bivalves, small benthic foraminifera, and green and red algae are associated with rudist as abundant secondary species. Rudist types and associated large fossils suggest high energy conditions within shallow bathyal, warm shoal sediments within the inner ramp facies zone (Gili et al., 1995, Goldbeck and Langer, 2009; Steuber, 2002). Rudist-rich biofacies are diagnostic and widespread facies of the Cenomanian Mishrif Formation of southern Iraq and Arabian Gulf countries and the Sarvak Formation of western Iran (Van Bellen et al., 1959). The shoreward to lagoon environment consists of large and small benthic foraminifera of high diversity, associated with fecal pellets and peloids, shell fragments of rudist, pelecypods, and other large shell fragments. Most of the benthic foraminifera are highly dolomitized too.

The occurrence of the horizontal and wavey stromatolite, dasyclad algae, detrital sand, and coarse sand quartz suggests a very shallow, open, restricted environment with a shallow inner ramp (e.g., Hohenegger, 1999; Hottinger, 1997). The co-occurrence in the stromatolite, green algae, large and small benthic foraminifera, rudist, and other bivalve and gastropod fossil assemblages with high dolomitization and evaporite mineralization can be ascribed to the upper Cenomanian, warm tropical Tethyan Sea; the uppermost part of the formation with intensive karstification maybe represents the uppermost Cenomanian-Turonian weathered or non-deposition. Rudist recovery is widespread in the Cretaceous southern Tethyan margin due to a change in oceanic circulations during the opening of the Atlantic (Steuber 2002), and the Cenomanian-Campanian rudist reef development in western Iran is linked to the marginal marine system in a warm and arid climate with high evaporation and salinity (Hay et al., 1999). Rudist-rich and benthic fauna-rich Ms’ad ramps were developed in the southern and eastern parts of the Rutbah High flanks. The studied sections in the Rutbah area are marginal deposits, mixed semi-restricted lagoonal facies, supratidal/Sabkha, and open shallow normal marine waters. The condition changed from a warm-humid climate favorable to a siliciclastic supply by rivers from the Arabian Shield in the upper Cenomanian. Siliciclastic supply decreased, and the depositional system from siliciclastic to carbonate with evaporite horizons changed from warm-humid to warm arid/semiarid.

Paleogeographically, In the Cenomanian, the Rutbah Basin was located in the east-southern margin of the Neo-Tethys north of the palaeo-equator. Siliciclastic-dominated early Cenomanian and carbonate-dominated Late Cenomanian reveal a climate shift from hot, humid to warm subhumid to semi-arid. The Ms’ad Formation was deposited in the Cenomanian cycle of the Rutba Basin, bounded by regional unconformities; the lower unconformity surface rests over the Upper Triassic Mulussa Formation (e.g., Van Bellen et al., 1959; Al Naqib, 1967), and the upper unconformity surfaces are characterized by collapse karst, underlying the Campanian-Maastrichtian Tayarat Fm (Moh et al., 2022). The studied succession of the Ms’ad Formation is assigned to a shallow inner ramp zone above the fairweather fair base, including three facies associations: open shallow with rudist-bivalve patch reef, semi-restricted lagoon, and tidal flat with Sabkha depositional environment. Supratidal to upper intertidal largely dominate the lower, middle, and uppermost intervals, as indicated by the abundant episodic
exposed sediments, such as fenestral dolostone, stromatolite laminae, evaporite thin layers, and calcite nodules after anhydrite. Typically, precipitation occurred within a warm, arid to semi-arid palaeoclimate as seawater evaporated and increased salinity. Tidal flat facies was vertically and laterally passing to the shallow open marine and rudist reef or the semi-restricted lagoonal facies associations, indicating the gradual and continuous transgression expressed by open shallow marine taxa, such as rudist, bivalve, dasycladacean green algae, and red algae, in addition to the large and small benthic foraminifera, which indicated the shallow open marine sedimentary environment (about 10 m water depth) of their accumulations (Berger and Kaever, 1992), where the Radiolitidae and hippuritidae rudist, especially bouquet elevator setting also indicated shoal barrier setting (Simone et al., 2012). Moreover, the Ms'ad Formation was affected by ecological stress, which displayed salinity fluctuation with higher salinity water in sabkha and semi-restricted lagoonal environments, with normal marine salinity conditions indicated by the presence of Rudist and increased diversity and populations of fauna. No planktic foraminifera was accompanied by a wide variety of shallow marine benthic foraminifera species, green algae, and detrital quartz as a marine constituent (van der Zwaan et al., 1990 Spratidal of the Sabkha type, dolomitic sandstone, and sandy dolostone facies within the higher topographic area (Rutbah High); these factors made the studied sections in the center of the Rutbah Basin shallower than the other Cenomanian succeeded in the eastern and southern basins (east Abu-Jer Fault system and Nakhab area, respectively).

5.2. Clay Mineral Assemblages: Origin and Paleoclimate

5.2.1. Distribution

The distribution of clay mineral assemblages along the studied Upper Cenomanian succession significantly contrasts vertical variations. The lower part of the Upper Rutbah unit and the middle parts of the Ms’ad Formation is usually kaolinite-dominated with minor illite and I/S mixed layers (assemblage A). The uppermost Rutbah Sandstone Formation and the lower part of the Ms’ad Formation are smectite-dominated, with a variable amount of kaolinite and illite (assemblage B). Finally, the upward section was dominated by assemblage C, characterized by the decrease of smectite and kaolinite, relative illite increases, and palygorskite’s appearance in the uppermost part of the formation. The bulk of clay minerals found in sedimentary succession is detrital in origin, as a part of the siliciclastic sediments of the Rutbaha and Ms’ad formations, with no evidence of burial diagenesis or authigenic origin (Wilson and Pittman, 1977; Chamley, 1989; Thiry, 2000). Source rock compositions, climatic conditions, and tectonic-topographic setting are the main factors controlling detrital clay mineral developments (Chamley, 1989), while authigenic clays are formed by thermal diagenesis controlled by burial gradient (smectite-rich illite-smectite (I-S R0) to illite-smectite mixed layers to illite-rich illite-smectite (R1 & Pollastro, 1993) or surface temperature, like volcanic material transformation to bentonites or diagenetic transformations if precursor smectite or direct chemical precipitation under alkaline marine and continental waters (e.g., Milllot, 1970; Singer, 1984; Srodon, 2013; Mohammed et al., 2022). The exposed Cenomanian succession of about 100 m thickness does not show any criteria of volcanic or burial diagenesis due to the occurrence of detrital quartz-rich sediments in the lower part and various amounts of detrital quartz within the carbonate succession of the upper part. A high to medium quantity of smectite has been recorded at several beds and upward along the carbonate with low to medium crystallinity. In I-S type R0, the co-occurrence of smectite, illite, kaolinite, and detrital quartz does not display any mineralogical features of burial diagenesis and no evidence of volcaniclastic components.
5.2.2. Kaolinite

is the advanced stage of the chemical weathering of clay minerals and other silicate minerals, such as feldspar and mica, under acidic conditions in tropical (hot and humid) regions (e.g., Millot, 1970; Chamley, 1989; Thiry, 2000). Kaolinite dominated the lower part of the Upper Rutbah Sandstone Formation and a different part of the Ms’ad Formation (Fig. 4), which are of detrital origin and reflect a tropical climate in the southern exposed Arabian Shield with hot and humid conditions and intense chemical weathering of acidic igneous and high-grade metamorphic rocks of the shield. Well-sorted white, clean quartz and very rich sandstone associations without silicate mineral associations indicate all alkaline's intensified chemical weathering and cleaning. Upward decreases of kaolinite from a very high quantity (85% available) to a low-medium amount (20%–40%) may be supplied from the erosion of the kaolinite-rich exposed sediments when the sea level falls in seasonal rainfall.

5.2.3. Smectite

In this investigation, we utilized smectite to include both discrete smectite and smectite-rich illite-smectite mixed layers (I-S R0); in general, the 001 peaks in ethylene-glycolate near the 16.9 Å, broad asymmetrical 001 peaks, and an inclined rise between 8 and 9 two-theta suggest that the smectite is medium to poorly crystalline. The uppermost part of the Rutbah Sandstone and the lower part of the Ms’ad Fm may have represented climatic changes from the hot-humid conditions to the tropical warm-temperate region (Fig. 4) (contrasting seasonal humidity). This is because the I-S R0/smectite-rich uppermost part is found in the upper part of the Rutbah Sandstone and the lower part of the Ms’ad Formation (e.g., Chamly, 1989; Ruffell and Worden, 2000; Mohammed, 1993, and 2019). Weathering intensity in the source rocks in the south was affected by less chemical weathering than the transformation of the aluminosilicate and ferromagnesian silicate, including the primary clay minerals (illite and chlorite), into mixed-layer clays in a different range of smectite: illite ratio, depending on the hydrolysis effect (Millot, 1970) and relative stability of the tectonic conditions, rather than changing the source area or any volcanic activity (Moham et al., 2022).

5.2.4. Illite

The illite co-occurrence with different kaolinite and smectite proportions is recorded in the uppermost part of the Ms’ad Fm and represents the primary detrital origin in the clay mineral species (e.g., Chamly, 1989; Velde and Meunier, 2008) (Fig. 4). Illite within assemblage C is detrital, transported from the southern Arabian Shield, and formed within the interval of weakly weathered more aridity suitable to developing illite-rich clays. When the humidity is ideal for creating Smectitic clays within the early stage of chemical weathering, it is not enough to change the illite-rich clays to Smectitic or kaolinitic clays (Jackson and Sherman, 1953; Fu et al., 2021). The kaolinite content shows light fluctuations along the succession, possibly related to the erosion of exposed kaolinite-rich formations. In addition, the palygorskite mineral, recorded at the uppermost part and associated with illite, smectite, and kaolinite within sandy dolostone and dolomitic sandstone facies in a regression stage of the carbonate deposition, was most probably authigenic due to the transformation of smectite within saline and alkaline in a hot and more arid climate and semi-closed basin (Ruffell and Worden, 2000; Mohammed et al., 2022).
Fig. 4. X-ray diffraction of the clay fraction of the Ms’ad Formation, (a) assemblage C, (b) assemblage B and (c) assemblage A.
6. Conclusions

The following significant conclusions based on the results and discussions are given below:

- Ms'ad Formation in the Rutbah City is represented by large-size fossils of highly dolomitic limestone with thin to medium mudstone beds (marl and shale).
- Two unconformity surfaces bounded the formation. At the base, red and multi-colored soil beds interbedded with sandstone and sandy mudstone, while new recrystallized carbonate-gypsum-rich karst beds, highly oxidized, characterized the upper boundary.
- The lithofacies of the formation are subdivided into 15 macro- and microfacies and three facies associations, graded from supratidal, including Sabkha facies, to intertidal and shallow subtidal with rudist patch reefs, semi-closed lagoons, and open typical marine environments.
- Small benthic foraminifera represented by _Multispirina iranica_, _Nezzazat simplex_, _Nezzazatinella cf. picardi_, _Chrysalidina gradata_; _Cisalveolina frassi_; _Pseudolituonella reicheli_; _Nummulculina heimi_; _Spiroloculina sp._; _Nezzazat sp._; _Rotalia sp._ and _Pseudochrysalidina sladina_ refers to _Multispirina iranica- Nezzazat simplex– Chrysalidina gradata_ assemblage Zone of Cenomanian age.
- Depending on the petrographic study and microfacies analysis, the accessible, immediate sedimentary environments are recognized as supratidal-intertidal environments, semi-restricted lagoons, and shallow subtidal open marines with rudist-bivalve shoal deposits.
- Clay mineral analysis shows three main clay mineral assemblages, including kaolinite-dominated smectite/R0- dominated Illite-dominated; the vertical distribution of these three assemblages is interpreted as the palaeoclimatic change from hot-humid (hot-house) represented by kaolinite-rich clays to warm-humid and seasonal contrast (green hose) suitable for less chemical weathering and cold-house of arid and cold climates characterized by physical weathering produce Illite clay minerals.
- Depending on X-ray diffraction results, smectite (R0), kaolinite, and illite rich composed the main clay mineral types in the studied samples of the Ms'ad Formation in two sections. As a result, the clay minerals of the succession of the Ms'ad Formation in the studied area changed from hot-humid (hot-house), represented by kaolinite-rich clays, to warm-humid and seasonal contrast (green hose), suitable for less chemical weathering, and cold-house in arid and cold climates.

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