Petroleum Res.J. Vol. 9 (1997); P. 9–26, 8 FIGS.

Petrography and Palaeoenvironment of the Sidi as Sid Formation in Northwest Libya

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بتروغرافية وبيئة ترسيب تكوين سيدي الصيد في شمال غرب ليبيا

محمود الطاهر البكاي

يتألف تكوين سيدي الصيد المتكشف ضمن سلسلة جبل نفوسة من عضوين هما: عين طبي ويفرن. يتكون عضو عين طبي من الدلوميت الذي يتفاوت في حجم حبيباته بين الدقيقة والخشنة. أما عضو يفرن فإنه يتكون من الأحجار الجيرية الطينية والدولوميتية مع تداخلات من حجر الطين والجبس.

تم تمييز خمسة أنواع من الدولوميت ضمن عضو عين طبي وهي:

النوع الأول: بلورات دقيقة شبه منتظمة الأوجه حلت محل حجر جيري يحتوي على القليل من الحفريات ويظهر متجانس اللون تحت المجهر (CL).

النوع الثاني: بلورات دقيقة جدا، غير منتظمة إلى شبه منتظمة الأوجه حلت محل حجر جيري غني بالحفريات وتتميز بلون برتقالي متلألئ وأصفر تحت المجهر (CL).

النوع الثالث: بلورات دقيقة إلى متوسطة الحجم شبه منتظمة الأوجه متجاورة مع المرو ولها لون برتقالي غير نقي تحت المجهر (CL) بمركز البلورة ولون برتقالي متلألئ عند الحواف.

النوع الرابع: بلورات متوسطة إلى كبيرة شبه منتظمة إلى منتظمة الأوجه وتتميز بلونها البرتقالي غير النقي في المركز ولون برتقالي غامق عند الحواف.

النوع الخامس: بلورات الباروك وهي كبيرة إلى كبيرة جداً شبه منتظمة الأوجه لها حواف ملتوية تتميز بلونها البرتقالي عند المركز غني بالخطوط ولون غامق نقي في الحواف.

البيئة التي ترسب فيها تكوين سيدي الصيد هي جزء من منحدر يقع بين سطحين مستويين من الأرض يتراوح بين منحدر محصور وبرك شاطئية إلى منحدر مفتوح أو شبه محصور يتدرج باتجاه الشمال إلى وسط المنحدر أو حوافه. يمثل عضو يفرن بيئة المنحدر المحصور وعضو عين طبي المنحدر الشبه محصور إلى المفتوح. أما الرسوبيات التي تمثل حاجز المنحدر فقد تمت إزالتها نتيجة لعوامل التعرية التي حدثت بعد إنتهاء الحقبة الطباشيرية أما المنحدر الخارجي فيمثله التكوين المكافئ لتكوين سيدي الصيد في العمر وهو ما يطلق عليه بتكوين العلالقة الذي يقع في المنطقة المغمورة من الرف القاري الليبي.

Abstract *The Sidi as Sid Formation (Upper Cretaceous) outcropped in Jabal Nafusah in NW Libya is composed of very fine to very coarse-grained dolomite of the Ain Tobi Dolostone Member and marly limestone, dolomites and calcareous shales interbeds with bedded gypsum of the Yifran Member. Five diagenetic dolomite types are recognized in the Ain Tobi Member. They are Type-1, fine and subhedral replaces mudstone/wackestone facies that show homogeneous luminescence pattern; Type-2, very fine, anhedral to subhedral replaces packstone/grainstone facies and characterized by bright orange and yellow luminescence pattern; Type-3, fine to medium, subhedral associated with quartz and has dirty orange luminescent cores and bright*

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orange rims; Type-4, medium to coarse, euhedral to subhedral crystalline fabric with orange luminescent cloudy cores and dully luminescent clean rims; Type-5 (baroque), coarse to very coarse, subhedral with curved crystal faces and characterized by orange luminescent inclusion-rich cores and dully luminescent inclusion-free rims.

The environment of deposition of the Sidi as Sid Formation is part of inner ramp which ranged from restricted or lagoonal ramp and open to semi-restricted ramp environments which graded northwards to mid- and outer ramp environments. The Yifran Member represents restricted ramp environment and the Ain Tobi Dolostone Member represents open- to semi-restricted ramp environment. The ramp margin had been removed due to post-Cretaceous erosion and the outer ramp environment is represented by the Sidi As Sid Formation's equivalent (Alalgah Formation) in the offshore Basin.

INTRODUCTION

Sidi as Sid Formation (Cenomanian) is outcropped along Jabal Nafusah in northwestern Libya (Fig. 1). Jabal Nafusah Escarpment extends from the coast of the Mediterranean Sea near Al Khums in a broad arc 350 km south and west to the Libyan–Tunisian border where it is 130 km from the coast. Jabal Nafusah continues into Tunisia, turns north, and dies out near Gabes, and it is known in that area as the Jifarah Escarpment.

Christie (1955) described Ain Tobi and Yifran as separate formations, but El Hinnawy and Cheshitev (1975) assigned the term Sidi as Sid Formation which includes two members (Ain Tobi Member below and Yifran Marl Member above). It is difficult to demarcate these two rock units in many places, so that were mapped together by all authors.

Ain Tobi Member is previously described by El Hinnawy and Cheshitev (1975), Megerisi and Mamgain (1980a,b) as it is composed of greyish limestone and dolomitic limestone with marly intercalations in the lower part and well bedded white to light yellow limestone and dolomitic limestone in the upper part.

The lithotypes of the Ain Tobi Member have been evaluated by systematic measurements and description of the units encountered in the NW Libya. A total of twelve sections have been measured along Jabal Nafusah Escarpment. Two hundred ordinary thin section and same number polished thin sections

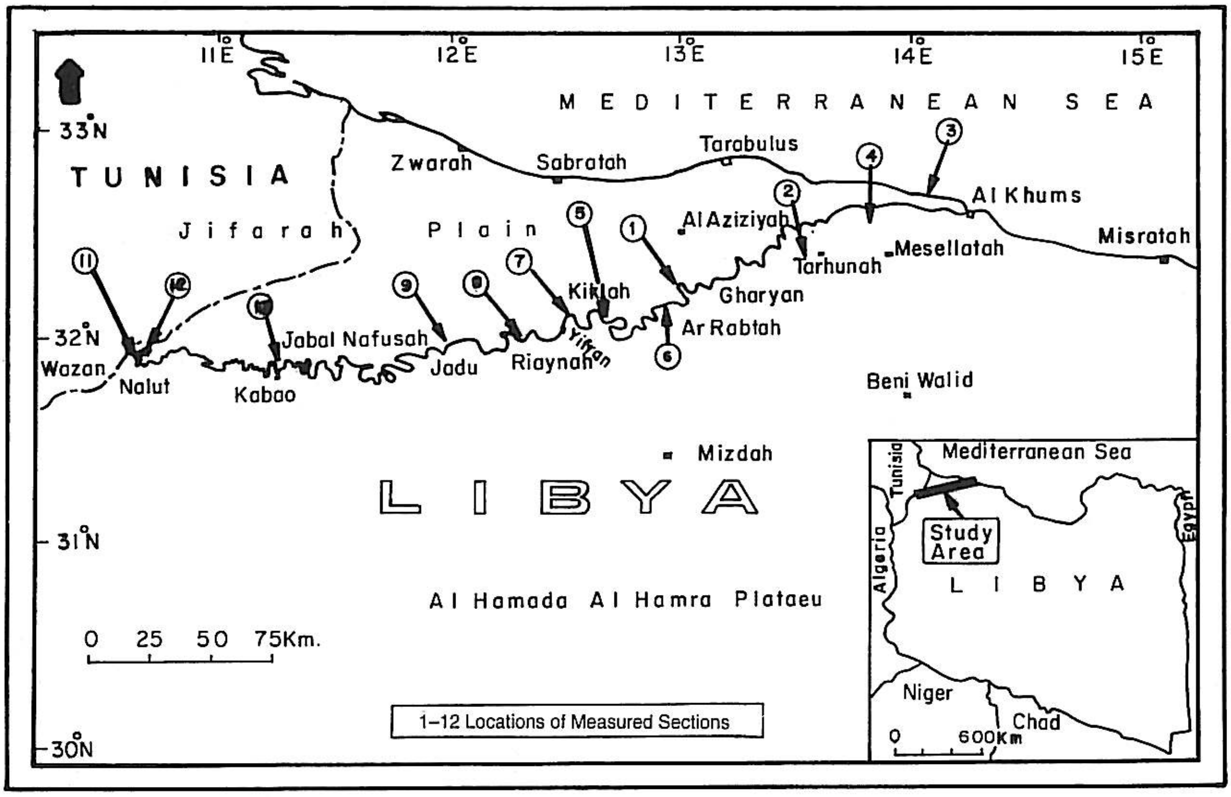

Fig. 1. Location for measured sections: (1) Abu Ghaylan section; (2) Ras Fam Mulghah section; (3) Al Khums (Wadi Ghanimah) section; (4) Wadi Jabbar section; (5) Kiklah section; (6) Ar'Rabtah section; (7) Taghmah section; (8) Riaynah section; (9) Jadu section; (10) Kabao section; (11) Wazan section; (12) Nalut section.

were examined petrographically and by Cathodoluminescence Microscope to determine mineral composition and texture. All ordinary thin sections were stained by alizarin red S and potasium ferricynide according to Dickson (1965). They are all unstained which indicate the completeness of dolomitization and dolomites contain less than 1% FeO (Sperber *et al.,* 1984). 154 sample were analysed by X-ray diffraction and they also show the total replacement by dolomite.

PALAEOGEOGRAPHY AND FIELD OBSERVATIONS

Cenomanian Palaeogeography in Northwestern Libya:

The Ain Tobi sediments were deposited during a major marine transgression which began in northwest Libya at the beginning of the Cenomanian and culminated in the Late Turonian.

The Ain Tobi Dolomite Member is a part of a shelf deposit which covers all or part of Algeria, Tunisia, Libya, Egypt, Niger and Chad (Reyre, 1966). The isopach map (Fig. 2) shows that the region of the present Jabal Nafusah in northwest Libya is a part of a wedge of Cenomanian strata which thicken to the south toward the axis of the Ghadamis Basin. The Jabal Nafusah area was adjacent to a topographically high or non-subsident region to the north.

There is a general decrease in carbonate content from northeast to southwest and increasing in siliciclastics. This reflects generally the gradient between an onshore clastic source and offshore carbonate production.

In the subsurface from northwest Libya into the Sirt Basin there are lithologic and nomenclature changes in the Cenomanian section. The Bahi and Lidam Formations (subsurface) are equivalent to the Sidi as Sid and Nalut Formations (outcrop). The Bahi Formation is a siliciclastic composed of interbedded sandstone, siltstone, conglomerate and shale with common glauconite pellets in the uppermost part. The lower part is thought to be non-

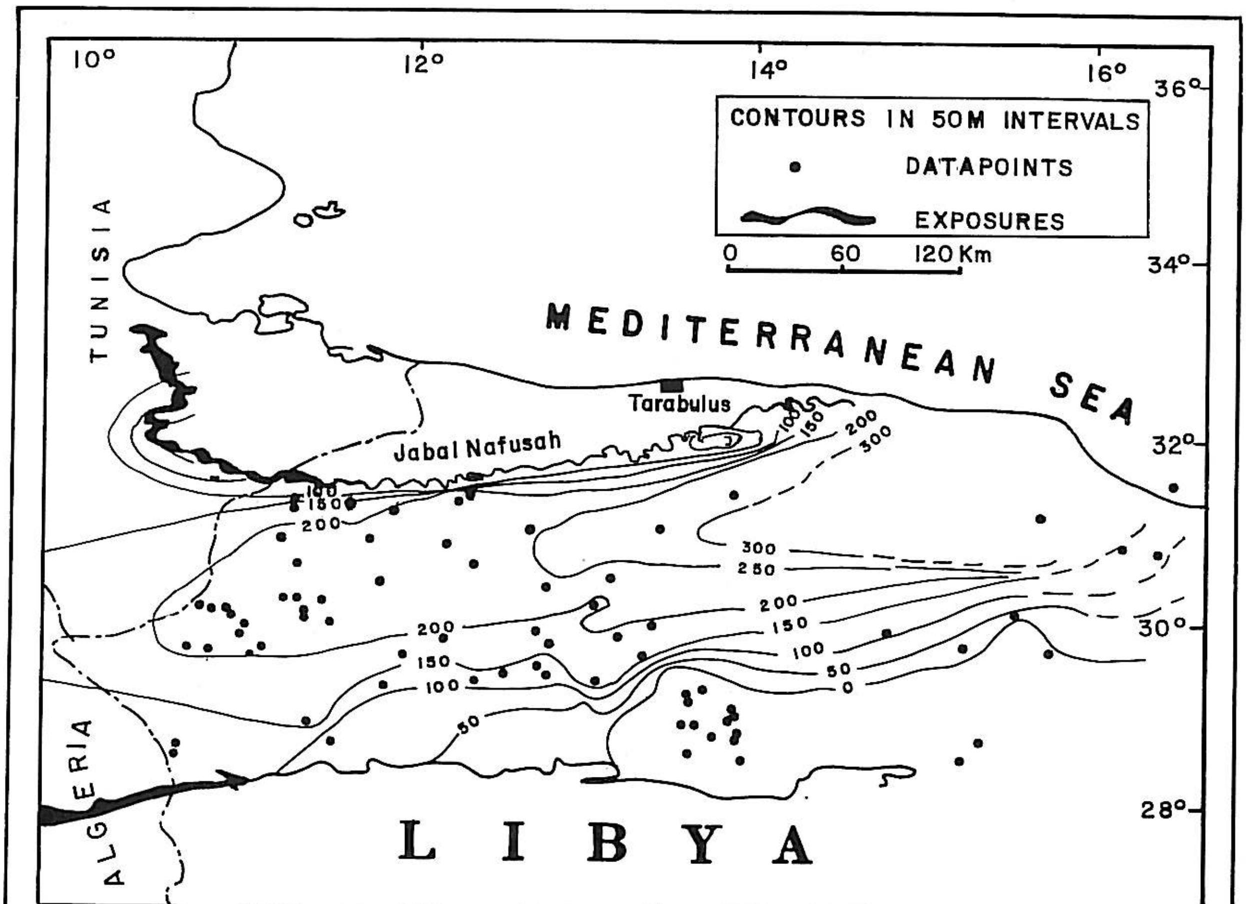

Fig. 2. Cenomanian isopach map in northwestern Libya (Tunisia after Busson, 1970).

marine, but the glauconitic upper part is apparently marine (Sghair, 1993), and is believed to be diachronous unit, ranging in age from Cenomanian to Maastrichtian. The Bahi Formation is conformably overlain by the marine Lidam Formation or other younger Upper Cretaceous strata.

The Lidam Formation is dated as Cenomanian in age (Barr and Weegar, 1972). It is composed mainly of argillaceous dolomite with common glauconite pellets and quartz grains in the lower portion, oolitic packstone and grainstone in the middle part, and fine to medium dolomite associated with anhydrite at the upper part (El-Bakai, 1989; 1991). It was deposited in a shallowing upward ramp in the northwestern part of the Sirt Basin (El-Bakai, 1989; 1992).

The Ain Tobi Dolostone Member is a part of a transgression sequence that can be found throughout most of North Africa. As in the case of Ain Tobi Dolostone Member, most of the transgressive units were deposited on a carbonate platform, possibly a carbonate ramp. The dominance of carbonates and presence of evaporites reflect a warm possibly dry Cretaceous climate. The Sidi as Sid (Ain Tobi and Yifran Members) transgressive sequence is part of a major worldwide Mid-Cretaceous rise in sea-level.

Main Lithologic Units of the Ain Tobi Member:

The Ain Tobi Dolostone Member is widely distributed rock unit, along Jabal Nafusah Escarpment and it forms the topmost of this escarpment. Generally, the thickness of the Ain Tobi sediments increases from southwest to the northeast direction. The thickness ranges from 5 m in Wazan area to more than 110 m in the area between Mesellatah and Qasr Khiar. The maximum thickness of Ain Tobi was observed in Jadu section in the western part of the escarpment, and this is due to the percentage of coarse clastics which was the highest in the area. Ain Tobi Dolostone Member is unconformably underlain by Kiklah Formation (Fig. 3a) and overlain by Yifran Marl Member.

Ichthyosarcolites Band:

The *Ichthyosarcolites* Band is a marker bed across the whole Jabal Nafusah. It is consistently present at each locality at the lower and/or middle of the Ain Tobi Dolostone Member. The band was recognized and described by Christie (1955) in eastern Jabal Nafusah because of leached moulds of the rudist *Ichthyosarcolites* sp. commonly found at its top. Rudists have been destroyed probably by silicification at the western Jabal Nafusah, but the band can still be recognized due to its prominent position, thickness and relatively resistance to weathering comparing with the other beds (Fig. 3b).

The *Ichthyosarcolites* Band is an unusually thick unit compared to other bedded intervals in the Ain Tobi. It ranges from 3 to 18 m in thickness although it is sometimes difficult to locate the base (specially at the western Jabal Nafusah) due to the diagenetic alteration. The band is composed of dolomite, chert and some quartz sand. Generally, the band is cross-bedded in the central and eastern Jabal Nafusah areas and appears to be uniformly bioturbated in the western area of Jabal Nafusah. In addition to rudists (Fig. 3c), which gives the band its name, other bivalves, gastropods, echinoids, bryozoans and foraminifera occur mainly as moulds. Ooids are also present.

The *Ichthyosarcolites* Band makes a gross change from the dominance of thicker bioturbated beds below to thinner beds above. The overlying beds contain sedimentary structures which indicate deposition in shallower water and some show signs of current activity (e.g. cross-bedding and microbial). Beds below the band are more resistant to weathering than those above. The upper beds are often soft and powdery while the underlying beds tend to be crystalline. This is due to differences in depositional lithology across the band. Sediments above the band contain more argillaceous material and gypsum than those below it, thus this part of the Ain Tobi Member has the steepest weathering profiles found in the section. The *Ichthyosarcolites* Band may be the result of a facies change in response to a change in sea level. The change in bedding thickness, dominated types of sedimentary structures, and lithology are probably due to a shift from deposition in tens of meter to less than that. The coincidence of the band and sea level fluctuation is only suggested here because the microfuna does not provide the necessary biostratigraphic detail.

In summary, the *Ichthyosarcolites* Band of the Ain Tobi Dolostone Member is a distinctive marker bed throughout Jabal Nafusah. In the eastern part of the escarpment it is characterized by a distinc-

Fig. 3. Field photographs showing: (a) The angular unconformity between the Kiklah Formation below and the Ain Tobi Member above at Abu Ghaylan area: (b) Tabular bedding which is the dominant sedimentary structure within the Ain Tobi Dolostone Member; (c) General view of the *Ichthyosarcolites* Band at Tarhunah area; (d) The extensive bioturbation at Wadi Jabbar section. →

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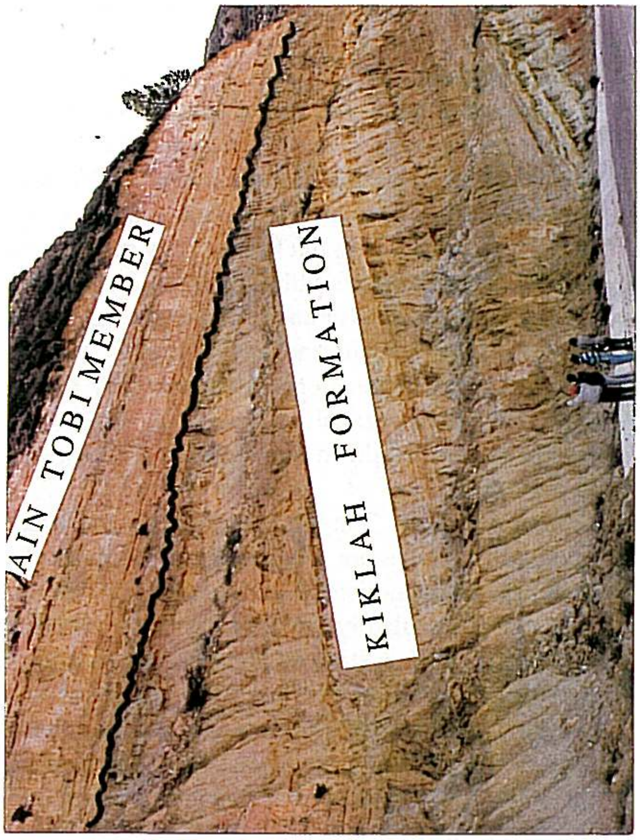

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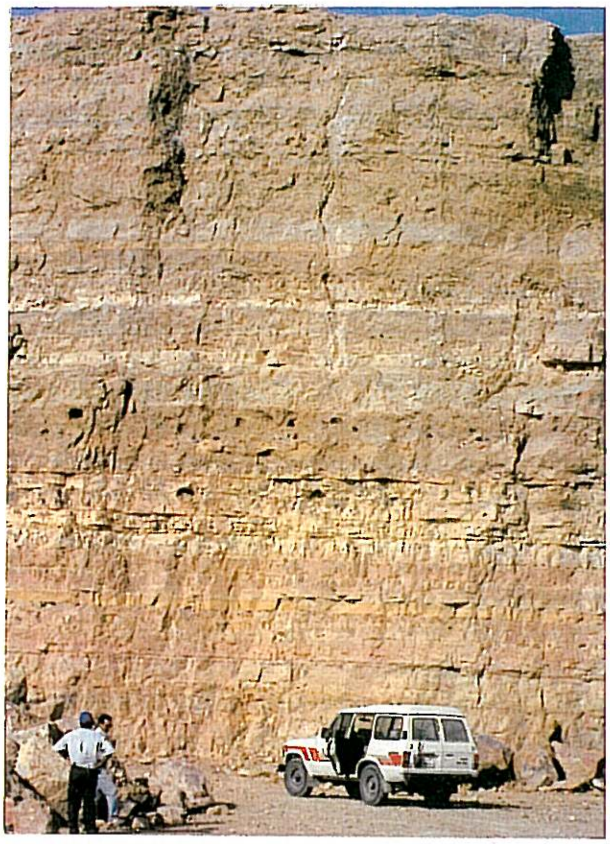

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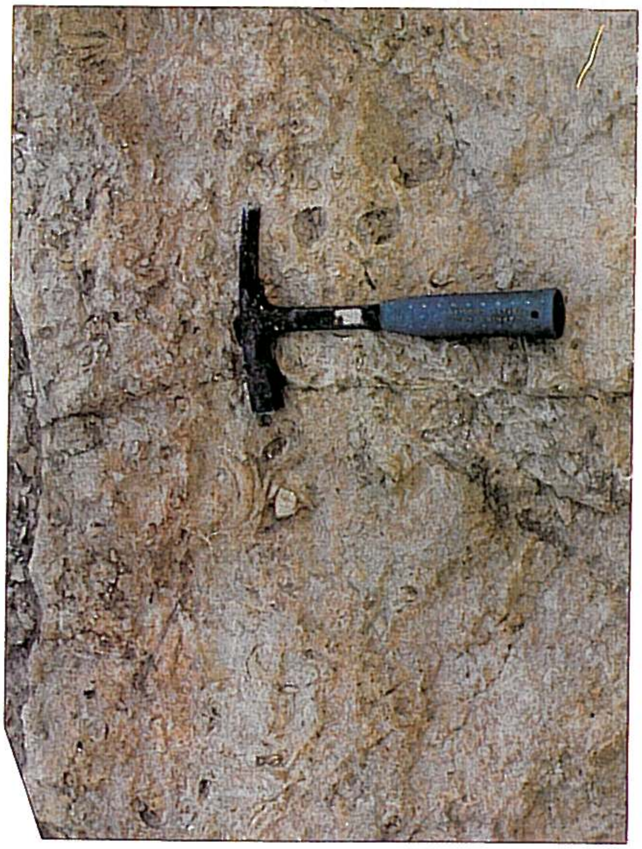

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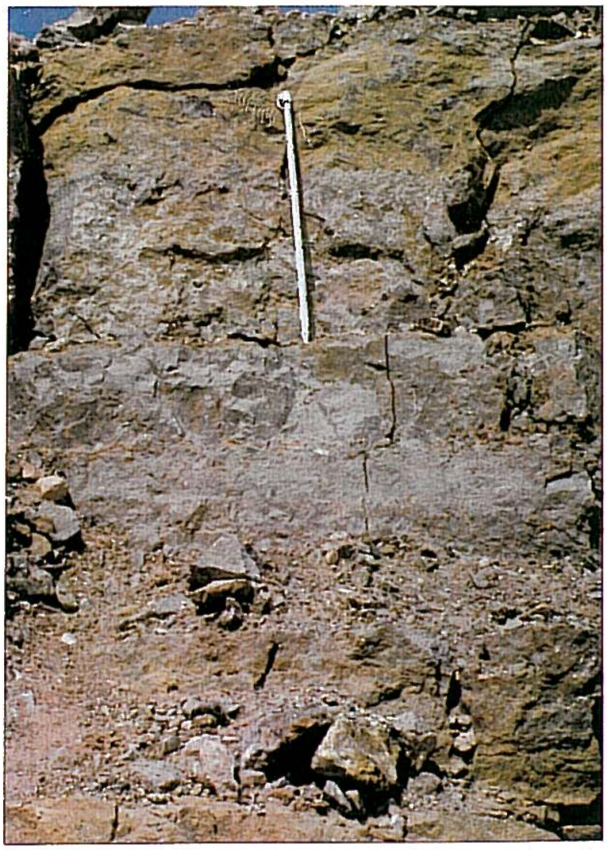

tive fauna including rudist bivalves. In the west it is represented by dolomite. The band represents the culmination of a basin filling sequence which may mark a drop and subsequent rise in sea level. Because water depths were different before and during deposition of the band versus after the band it makes at least a facies change if not a minor disconformity due to change in sea level.

Bioturbation Unit:

Bioturbation structures are the most common form of structures found in units of the Ain Tobi of Jabal Nafusah (Fig. 3d). They are the most continuous in the escarpment, commonly extending for 5 km. The *Ichthyosarcolites* Band is bioturbated throughout Jabal Nafusah in NW Libya where diagenesis has had a less obscuring effect on primary fabric. Bioturbated units can be found above and below any of the other sedimentary units.

Generally, dolomitization has obscured most of the primary deposition textures of the bioturbated beds. Most of the grains have either been leached and left as mouldic porosity or they have been replaced. The precursor matrix material was probably limestone because of the random orientation of dolomite crystal axes and the uniform crystal size (Evamy, 1967). Intercrystalline and leached mouldic porosity averages between 10–20% (estimates from thin sections). If each of the leached mouldic pores is assumed to be precursor grain, bioturbated units were wackestones, packstones and possibly grainstones. The original bioturbated sediments of the Ain Tobi Member were probably bioturbated by the combined activity of worms, enhinoderms and molluscs.

Interpretation: Deposition of Ain Tobi sediments probably has occurred on an open marine platform with alternating periods of storm reworking and bioturbation. Storm generated currents and bioturbation rather than tidal currents are thought to be principally responsible for disturbing sediments over the Ain Tobi platform. Bioturbation is indicated by lack of internal layering. Storm activity is indicated by cross-bedded carbonate sand units up to 4 m thick in and above the *Ichthyosarcolites* Band. Tidal currents are thought to play a minor roll in the Ain Tobi deposition particularly in the oolitic intervals because of the absence of extensive channel development, absence of levees and limited development of distinctly intertidal or supratidal environments.

Laminated Unit:

Laminated units are found principally in the dolomudstone units (Fig. 4a), but may be present in dolowackestones and dolopackstones. The laminated units are generally less than 1 m thick, but may range up to 2 m in thickness. They may extend laterally for kilometres although units are difficult to trace because of differences in weathering. These lamination are smooth and flat to slightly undulatory. Individual laminations extend laterally from 1 to 30 m. Narrow vertical burrows (Fig. 4b) may be present and extend down for 5 to 6 cm. The burrows do not branch.

Interpretation: The flat to undulatory laminated units with fenestra are most easily recognizable as cryptalgal stromatolites. The fenestrs, fine laminations, flat to undulatory surfaces are the criteria used to identify them as stromatolites. Most of fenestral and non fenestral units are flat, therefore could have been originated in several environments. Laminated units of the Ain Tobi are attributed to the trapping and binding of algae. The inferred location of microbial development is in some type of lagoonal setting in the intertidal zone.

The thickness of the flatness laminae, the lack of fenestra and probably the aridity of the climate of the Ain Tobi sedimentary environment (judging from Cretaceous palaeotemperature curves of Savin, 1977 and the presence of gypsum in Yifran Marl Member of Jabal Nafusah and Ghadamis Basin) indicate that Ain Tobi laminated units probably deposited in intertidal environment.

Cross-bedding Unit:

The cross-bedding units of the Ain Tobi Member increase in thickness towards the northeast. The dominant types of cross-bedded units are dune or tabular which mainly occurred in the Ras Fam Mulghah (Section #2) and Taghmah (Section #7). Trough cross-bedding occurs at the Abu Ghaylan (Section #1, Fig. 4c). The thick cross-bedded unit in the Ras Fam Mulghah is composed of dolograinstones. The grains which form these carbonate sands include ooids, peloids, foraminifera, quartz grains and fragments of gastropods, bivalves and echinoids.

Fig. 4. (a) Field photographs showing laminated dolomudstone unit at Wadi Jabbar section; (b) Polished slab photograph of sample taken from Taghmah section. Note well preserved lamination in a completely dolomitized mudstone. Some laminae are disturbed by burrows; (c) Outcrop photograph at Abu Ghaylan section showing small-scale cross-bedded oolitic doloplackstone/dolograinstone; (d) Field view showing mudcracks structure at Abu Ghaylan section. →

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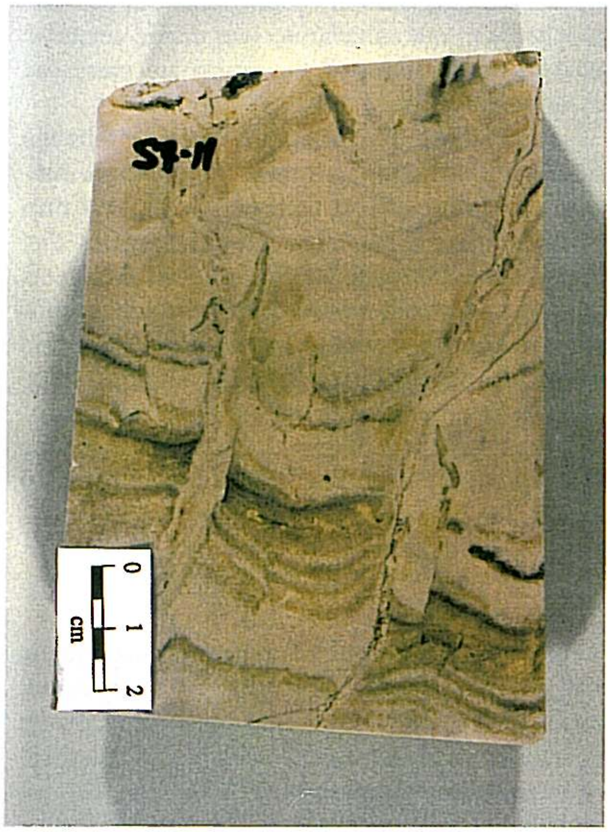
b



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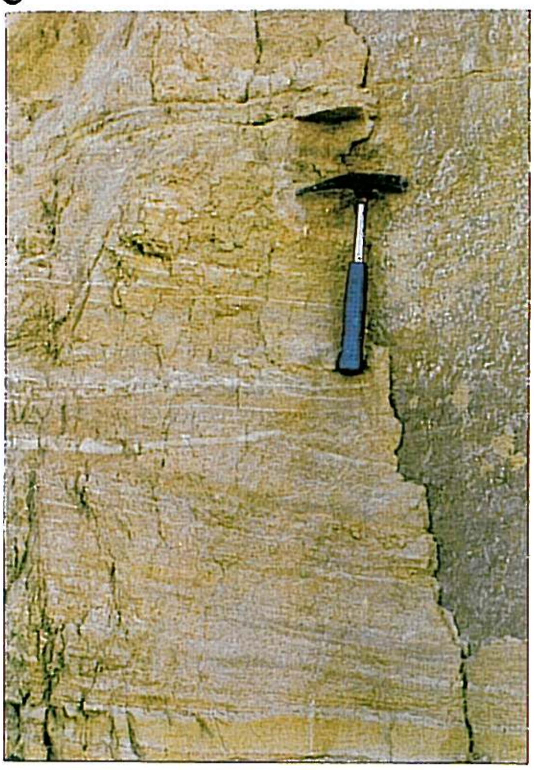

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Cross-bedded carbonate sands are the only units that commonly contained recognizable ooids. These units are the only ones in which grains can be identified because dolomitization, was fabric retentive and the exterior forms of the grains are preserved (non-mimetic replacement).

Interpretation: The generation of ooid grains and grainstone sand bodies in Recent carbonate environments occurs in shallow agitated waters, less than 2 m (Milliman, 1974). Hine (1977) suggests that ooids generated through interaction of tidal currents and storm generated waves. Tidal currents are primarily responsible for ooid generation while storm currents distributed them. Because ooids make up a significant proportion of the grains in these units, some tidal activity is indicated. These cross-bedded units represent the highest energy environment of the Ain Tobi Member and probably are shoal deposits.

Collapse Breccia:

Units interpreted as solution breccias occurred in small intervals in most of the measured sections. Solutions breccia has implied dissolution of evaporite minerals and the subsequent collapse of interbedded or overlying material. In the Ain Tobi Member true solution breccias are rare. This type of feature occurs commonly on sabkhas (Wilson, 1975). In this case precipitation and dissolution of the gypsum may have occurred during a brief period of exposure, despite the fact that there is little real evidence of subaerial exposure in the Ain Tobi. Distinct mudcracks are found only in the Tarhunah area (Ras Fam Mulghah section), the Wadi Jabbar section and Abu Ghaylan section (Fig. 4d). The lack of horizontal surface may have hindered the recognition of mud cracks and makes positive identification of vertical cross sections through possible mud cracks difficult. The mud cracks generally are uncommon, and suggests that subaerial exposure was rare during the deposition of the Ain Tobi Member.

LITHOTYPES OF AIN TOBI MEMBER

The Ain Tobi Member is an arenaceous to argillaceous dolostones. The dolomitized limestone or dolostone contains a varying proportion of poorly sorted, subangular to subrounded quartz sand. According to the field observations and petrographic studies of samples from twelve measured sections, Ain Tobi Member can be divided into five lithotypes:

Lithotype 1. Cross-bedded dolograinstones and dolopackstones. The scale of cross-bedded locally decreases upward and may show erosional relief at the basal surfaces. Channel geometry is suggested in some areas by the lateral changes into marls.

Lithotype 2. Bioturbated dolowackestones and dolopackstones. These contain subhorizontal fractures and burrows belonging to trace fossils.

Lithotype 3. Bedded dolomudstones and dolopackstones with rare wavy laminations and bioturbation. This facies is generally interbedded with bioturbated dolowackestones and dolopackstones.

Lithotype 4. Laminated dolomudstones and dolowackestones with microbial, birds-eye structure and gypsum.

Lithotype 5. Solution breccias consisting of angular clasts, commonly silicified in a dolomitized matrix.

These lithotypes of the Ain Tobi Dolostone Member are interpreted as a shallow-shelf or ramp carbonate deposit (discussed below). These represent a shoaling-upward cycles deposited during regressive phases.

Ain Tobi Dolostone Member is overlain by Yifran Marl (upper member of the Sidi as Sid Formation). It consists of yellow soft marls, marly limestone and dolomites and calcareous shales with uncommon interbeds of bedded gypsum, gypsiferous shales and oolitic limestone. Marls with bedded gypsum predominate west of Yifran whereas to the east the thickness decreases and dolomitic limestone predominate. Recrystallization makes identification of textures difficult, mudstones, wackestones, and wackestones/packstones occurred with occasional oolitic grainstone. Parallel lamination is the most common sedimentary structure and sparse fauna generally consists of molluscs. Bioturbation is commonly occurred throughout the member. The lithology of Yifran Marl Member is interpreted as a restricted ramp (inner-ramp) in the western and south of Jabal Nafusah, and as an open to semi-restricted ramp in the eastern Jabal.

PETROGRAPHY

In this study Ain Tobi Member is assigned as "Ain Tobi Dolostone Member" because the petrographic details and XRD analysis of samples taken from 12 measured sections scattered throughout the study area (Fig. 1) show that all Ain Tobi sediments have been completely dolomitized (more than 95% dolomite) and only traces of calcite occurred in the form of calcitization or dedolomitization. Yifran Marl Member will not be treated petrogaphically in this study.

According to the crystal shape and size distribution, five different types of dolomite recognized in the studied sections. These differences may reflect the variation of origin, mechanisms, chemistry and may be the timing of dolomitization. Detailed geochemistry and origin of these types of dolomite is a separate study now in progress. Some individual samples of these sections composed of more than one type of dolomite. The dolomite types are classified according to Friedman (1965) and Sibley and Gregg (1987). All types of dolomite are calcian, nonferroan and have more than 52% $CaCO_3$, except Type-1 which is stoichiometric (49–50% $CaCO_3$). All types are moderately to well ordered as determined by XRD.

Hand Specimen Petrography

Type-1 dolomite is yellowish-grey, porous and laminated mainly replaced wackestone/packstone. The laminae usually pinkish in colour. This type of dolomite is associated with birds-eye structure, ripples and microbial with gypsum nodules or collapse breccia and quartz grains in the western part of the study area. Type-2 dolomite is very fine, whitish-grey, cross-bedded, slightly porous and calcareous crystalline replaced mainly packstone and grainstone facies. Type-3 is also laminated, tan to grey, calcareous and interbedded with quartz sandstone. Type-4 dolomite is light-grey to yellowish, slightly porous and calcareous being replaced the highly fossiliferous sediments and occurred mainly at all positions of almost all measured sections. Type-5 dolomite is grey, coarse to very coarse, porous crystalline with pearly lustre appearance (Fig. 5a) replaced calcerenitic packstone lithofacies. This type is restricted to the eastern part of the study area and rarely occurred at western part of the study area.

Transmitted Light and Cathodoluminescent Microscopy:

Type 1 dolomite:

It is an early and pervasively non-ferroan dolomite, generally consists of unimodal or very fine to fine (10–100 μm, average 70 μm), closely packed nonplanar-*a* or xenotopic (anhedral) dolomite crystalline (Fig. 5b). These dolomite cystals have totally replaced the precursor sediments which probably were lime mudstones and wackestones and its crystals have inclusions. The cores of some crystals are selectively dissolved out leaving intracrystalline pores. The texture is mainly xenomorphic. The commonly observed cathodoluminescence pattern in Type-1 dolomite is homogeneous orange luminescence at zones succeded dissolved cores and very thin bright yellow luminescent outer rims (Fig. 5c). Type-1 dolomite is the most common type in the Ain Tobi Dolostone Member and occurred at all locations.

Type 2 dolomite:

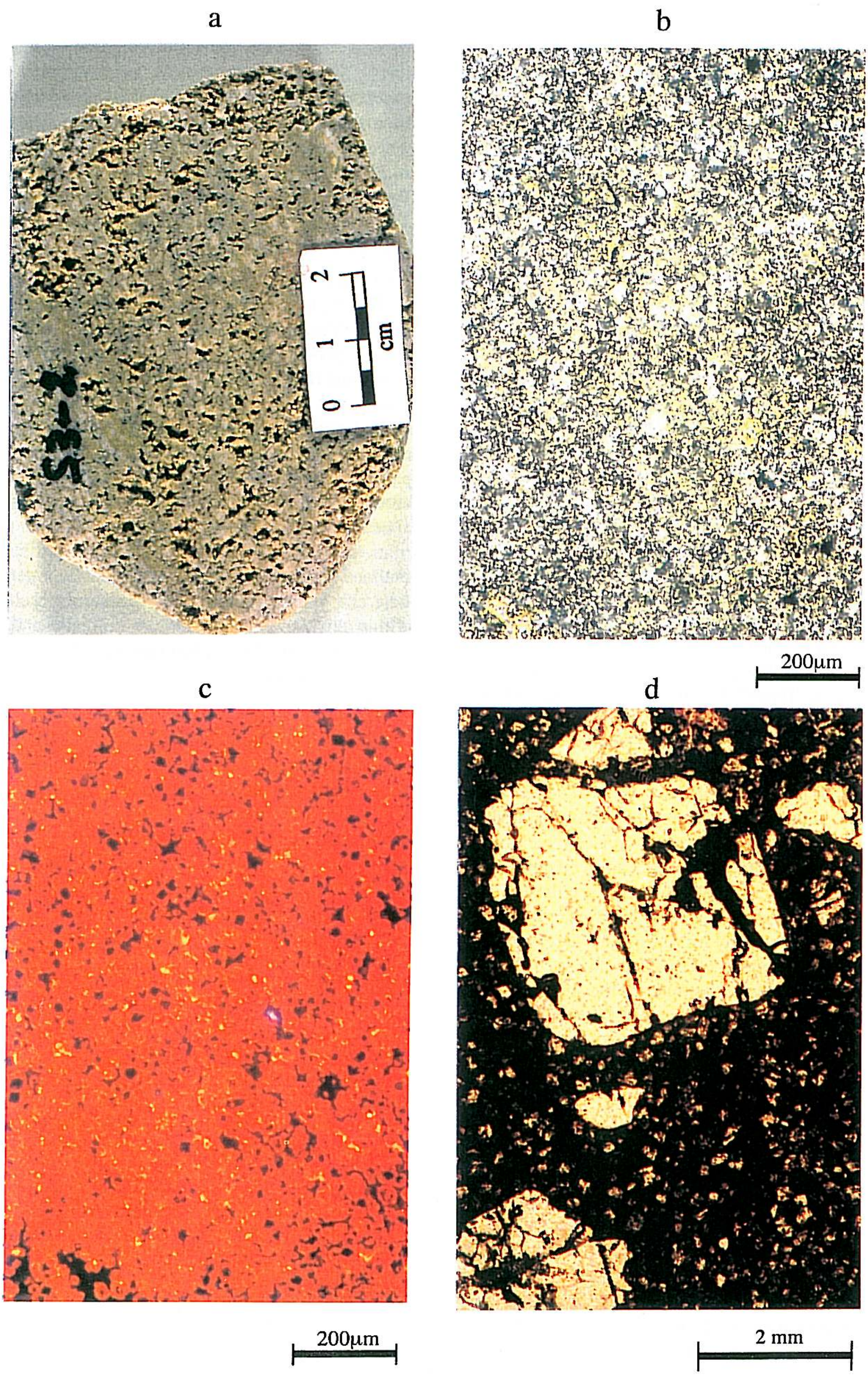
The crystals of this type of dolomite are made up of unimodal or very fine mainly less than 10 μm, closely packed nonplanar-*a* or xenotopic dolomite crystalline (Fig. 7a). The crystals are usually dirty or cloudy and mainly nonmimetically replaced skeletal and non-skeletal allochems. Crystals of Type-2 dolomite exhibit bright yellow orange luminescent pattern whereas late crystals occurred as a cement around pores show red to dark brown luminescent appearance (Fig. 7b). In fabric-destructive or nonmimetic replacement, original fabrics are commonly outlined by abundant inclusions. Mouldic, interparticle and vuggy porosities are commonly occurred within this xenomorphic mosaic dolomite and has been found in the lower and middle intervals of most measured sections.

Type 3 dolomite:

Type-3 dolomite is unimodal (average 100 μm), nonplanar- *a* and planar-*s* replacive crystalline. This type is mainly associated with quartz grains (Fig. 5d) and may be occured post-compaction. It is mainly found at bottom of all measured sections. Quartz grains associated with this type are subrounded medium to coarse and unicrystalline, cemented by quartz overgrowth. They are usually coarser than dolomite crystals and sometimes fractured probably due to compaction. Type-3 dolomite is characterized by dully luminescent cores and orange luminescent rims (Fig. 6a).

Type 4 dolomite:

It is polymodel or fine to medium (average 200 μm), nonplanar-*s* or hypidiotopic and nonferroan dolomite crystalline (Fig. 6b). The crystals are cloudy at cores and more cleaner rims, and exhibits undulose extinction. Some times this type occurred as an isolated euhedral rhombs (Fig. 6c). This type believed to be an intermediate to late diagenetic dolomite and has completely replaced the original sediments which probably were bioclastic wackestone/packstone. Some crystals show replacement or recrystallization of precursor fine and nonplanar-*a* (Type-1) dolomite crystals, whereas others have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200µm
2 mm

their cores partially or completely dissolved out due to continued dissolution, leaving irregular voids indicating dedolomitization. In some instances dissolution has proceeded to the point where almost the whole crystal has been dissolved out leaving a rhombic moulds. The texture of Type-4 dolomite is generally hypidiomorphic. Cathodoluminescence microscopy shows that the cores are mainly dirty orange luminesent due to inclusion-rich, whereas inclusion-free rims exhibit dully orange luminescent (Fig. 6d). These differences reflect that the Fe and Mn values are considerably lower in the inclusion-rich than in the inclusion-free zones (Fairchild, 1980; Coniglio and James, 1988; Amthor and Friedman, 1991; 1992) due to recrystallization (Nielsen *et al.*, 194). Intercrystalline, mouldic and vuggy porosities are associated with this dolomite type which occurs in various stratigraphic intervals.

Type 5 dolomite:

This type of dolomite occurred in the eastern Jabal Nafusah only and has been observed in Al Khums and Wadi Jabar areas. Type-5 dolomite is composed of coarse to very coarse or polymodal (500 μm–2 mm), planar-*s* and zoned baroque or saddle crystalline (Fig. 7c). These replacive crystals have curved faces or boundaries and cleavage planes. They show extremely undulose extinction. The crystals characterized by euhedral cloudy cores and clean rims, which indicate their replacement to the original micritic sediments. The cloudy cores exhibit orange luminescent and rims show dully luminescent, but the cleavage lines have bright yellow pattern (Fig. 7d).

Dedolomitization:

The term dedolomitization was first proposed by Von Morlot (1848) to describe a possible mechanism by which the mineral calcite replaces the mineral dolomite. Evidences for dedolomitization have been observed under the microscope and by XRD analysis of whole rock of the Ain Tobi dolomite sediments. Presence of euhedral or idiomorphic dolomite crystals with their cores leached out leaving itracrystalline pores and sometimes the whole rhomb dissolved out leaving euhedral mouldic pores, indicating dedolomitization. The dissolved cores of some crystals are filled or replaced by calcite (Fig. 8a). Some other rhombohedral crystals are replaced by large or blocky non-ferroan, and late calcite crystals. These calcite crystals being as an overgrowth with an optical continuity with dolomite substrates. In some cases the dolomite rhombs are corroded or rounded crystals, whereas elsewhere some dolomite crystals float in a coarser calcite crystals with irregular contacts between them indicating dedolomitization. Under cathodoluminescence microscope the dedolmitizated crystal show complex zonation (Fig. 8b). Dolomite zones show bright yellow luminescent pattern whereas the replacive calcite zone exhibit dully orange luminescent.

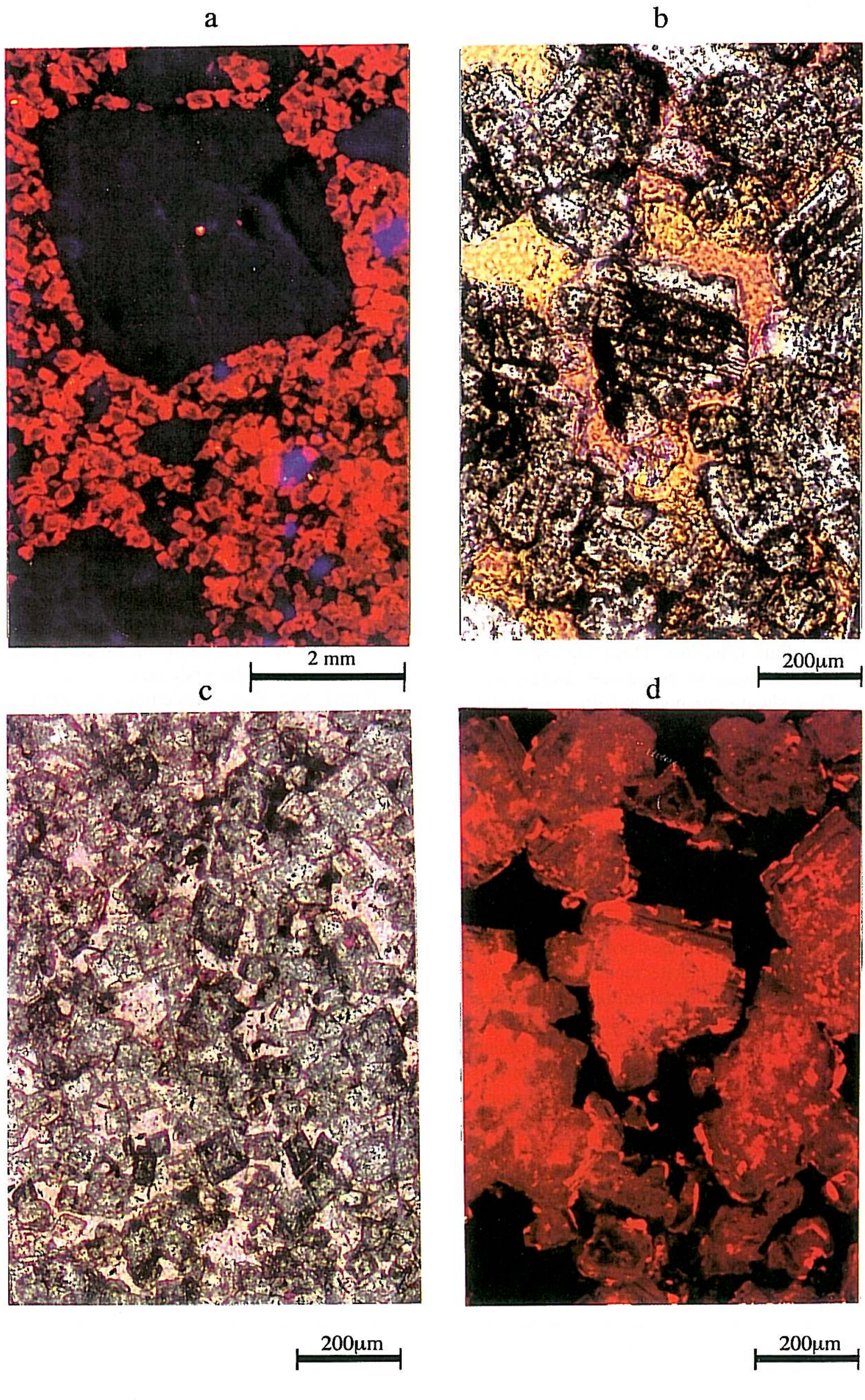
Several authors attributed the phenomenon of dedolomitization to early diagenesis and/or surface chemical weathering (Evamy, 1967; Braun and Friedman, 1970; Magaritz and Kafri 1981) or to oxidation of pyrite (Evamy, 1963), all epigenetic process. Budai *et al.* (1984) pointed out that dedolomitization can occur any where (surface and subsurface) conditions are favourable for it.

Distribution of dolomite

Dolomite has been found to replace all Ain Tobi sediments in all measured sections, only traces of limestone remain. Sandstone occurred in the lower part or below the *Ichthyosarcolites* band occurred in the western part of the study area.

Type-1 and Type-4 dolomites occurred in all sections in different stratigraphic positions. Type-3 dolomite is mainly occurred at bottom of all sections and in higher position in section #9 at Jadu area. Type-2 dolomite has been found mainly at the middle parts of measured sections in the western and central parts of the study area within the *Ichthyosarcolites* band or replacing packstone and grainstone facies. It replaces the oolitic grainstone intervals in the lower and middle parts of the measured sections at the eastern part of Jabal Nafusah (east Wadi Ghan). Finally, Type-5 dolomite restricted to the eastern part of the study area at the top of measured sections in Fam Mulghah, Wadi Jabbar and Al Khums area and rarely at Riaynah and Jadu area. Dedolomitization or the replacement of the dolomite by calcite crystals has been observed at various stratigraphic positions. It has been found at the bottom of section #9 and section #10, close to the unconformity between Kiklah Formation below and Ain Tobi Member above, and occurred also at top of sections #4, #5, $6, #8, and section #9 (Fig. 1).

← Fig. 5. (a) Polished slab photograph showing the very coarse saddle dolomite seen at Al Khums coast; (b) Photomicrograph of Type-1 dolomite (PPL); (c) Luminescence microscopy of the same sample (b) showing the homogeneous orange luminescence pattern; (d) Photomicrograph of Type-3 dolomite associate with quartz grains (PPL).


a
b
2 mm
200μm
c
d
200μm
200μm

ENVIRONMENT OF DEPOSITION

A sedimentary model was proposed for the Sidi as Sid Formation (El Hinnawy and Cheshitev, 1975) in the Jabal Nafusah escarpment and Ghadamis Basin to the south. In this section the term facies is avoided because the depositional environments could be defined on the basis of sedimentary structures and because dolomitization has obliterated most of the criteria used to define microfacies based on textures and grain types.

The Cenomanian depositional environments, found on the Jabal Nafusah escarpment and in the Ghadamis Basin are part of inner ramp sequence according to definition of Ahr (1973); Buxton and Pedley (1989); Elrick and Read (1991); Burchette and Wright (1992) which ranged from open to semi-restricted ramp and a restricted or lagoon ramp. In this study the open to semi-restricted and restricted ramps will be discussed, because they occur in the exposures of the Sidi as Sid Formation and in the subsurface of Ghadamis Basin where well logs are available. In the offshore Gabes–Tarabulus–Misratah Basin most drilled wells did not penetrate deeper than the Maastrichtian and in Tunisia the data are not available. Published data on the Gabes–Tarabulus–Misratah Basin and Tunisia areas and data gathered during this study from outcrop and subsurface Ghadamis Basin will be used in order to propose a model for the Cenomanian in northwestern Libya.

Inner Ramp:

Restricted or lagoon Ramp:

The restricted ramp environment is represented by the Yifran Marl Member of the Sidi as Sid Formation in the subsurface of Ghadamis Basin, southern Nafusah uplift and in Jabal Nafusah. Yifran Member is composed of approximately 70 m of marls, marly limestone, dolomites and calcareous shales interbeds of bedded gypsum in western Jabal Nafusah and dominated by limestone in eastern part of the study area. In the subsurface (Ghadamis Basin) it consists of 150 m of interbedded dolomite, shale and evaporites. In both Jabal Nafusah and the Ghadamis Basin it overlies open to semi-restricted dolostones of the Ain Tobi Member and is overlain by Nalut Formation. Units associated with restricted ramp occurred commonly above the *Ichthyosarcolites* Band close to the contact between Ain Tobi and Yifran Marl.

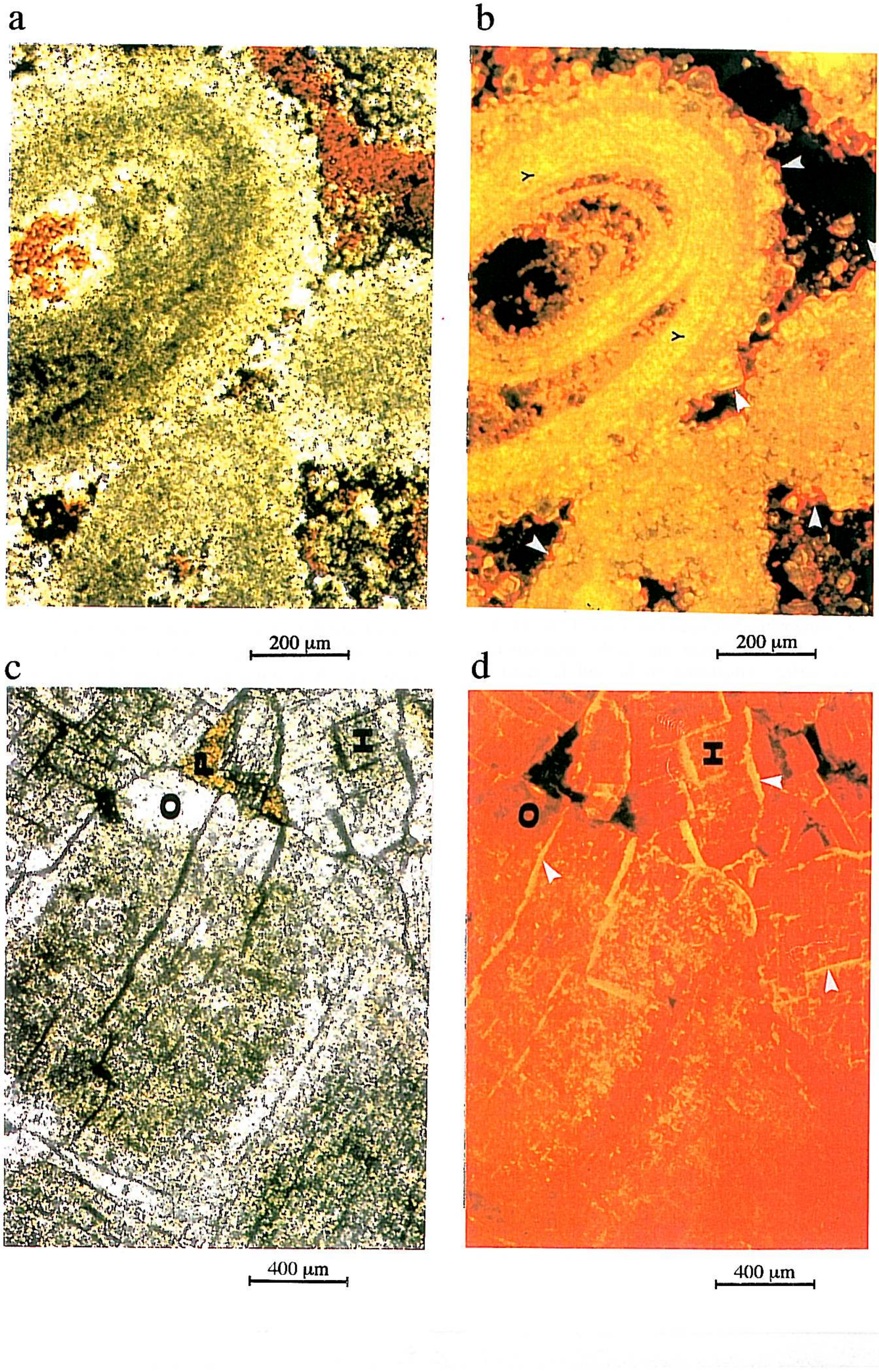
The rare fauna present in the Yifran Marl suggest deposition in a shallow, marine, neritic environment (Fig. 9) with restricted lagoonal conditions (intertidal and supratidal) with no tidal channels in the western part of the basin (Megerisi and Mamgain, 1980a). A lagoonal palaeoenvironment is suggested because it could impound water whose evaporation would result in evaporite deposition indicated by the solution breccias in the Ain Tobi Dolostone Member (lithotype-5) and in actual evaporite layers in the Yifran Marl Member.

Open to Semi-Restricted Ramp:

The open to semi-restricted ramp environment is represented by the Ain Tobi Dolostone Member of the Sidi as Sid Formation in the Jabal Nafusah escarpment and in the subsurface of Ghadamis Basin where it can be traced on completion logs. In the Ghadamis Basin the open to semi-resricted ramp consists of dolomite which overlies Early Cretaceous siliciclastics of the Kiklah Formation and underlies lagoonal rocks of the Yifran Marl Member. The Ain Tobi Member thins to the south as the Yifran Marl thickness. In the Jabal Nafusah escarpment the open to semi-restricted ramp consists of dolostones, sandy dolomite, chert and quartz sandstone. It is composed mainly of bioturbated bedded carbonate units, with cross-bedded oolitic dolograinstones and laminated dolomudstones. The bioturbated units especially those containing rudists such as the *Ichthyosarcolites* Band and cross-bedded sands are more abundant towards the north of the Nafusah escarpment. The carbonate muds and associated evaporites are more abundant south of the escarpment and at the top of the escarpment (Yifran Marl Member) towards the restricted or lagoon ramp.

The vertical change from dolowackestones/dolopackstones through dolomudstones and dolowackestones to thinly bedded dolomudstones probably represent cycles of shoaling-upward deposited during regressive phases. The lower part of each cycle is composed of interbedded, bioturbated dolowackestones/dolopackstones and bedded dolomudstones (lithotype-2 and 3). The upper part consists of thinly bedded dolomudstones with gypsum nodules, algal

← Fig. 6. (a) Luminescence microscopy of same sample shown in (Fig. 5d). Note that Type-3 dolomite, which is associated with quartz, has a dull luminescent core and bright rims; whereas quartz shows dark blue colour; (b) Photomicrograph of Type-4 dolomite, characterized by cloudy cores and clean rims; (c) Photomicrograph of sample taken from Jadu section showing isolated crystals of Type-4 dolomite. Note the crystal shapes are planar-*e* and are loosed interlocking (PPL).


a
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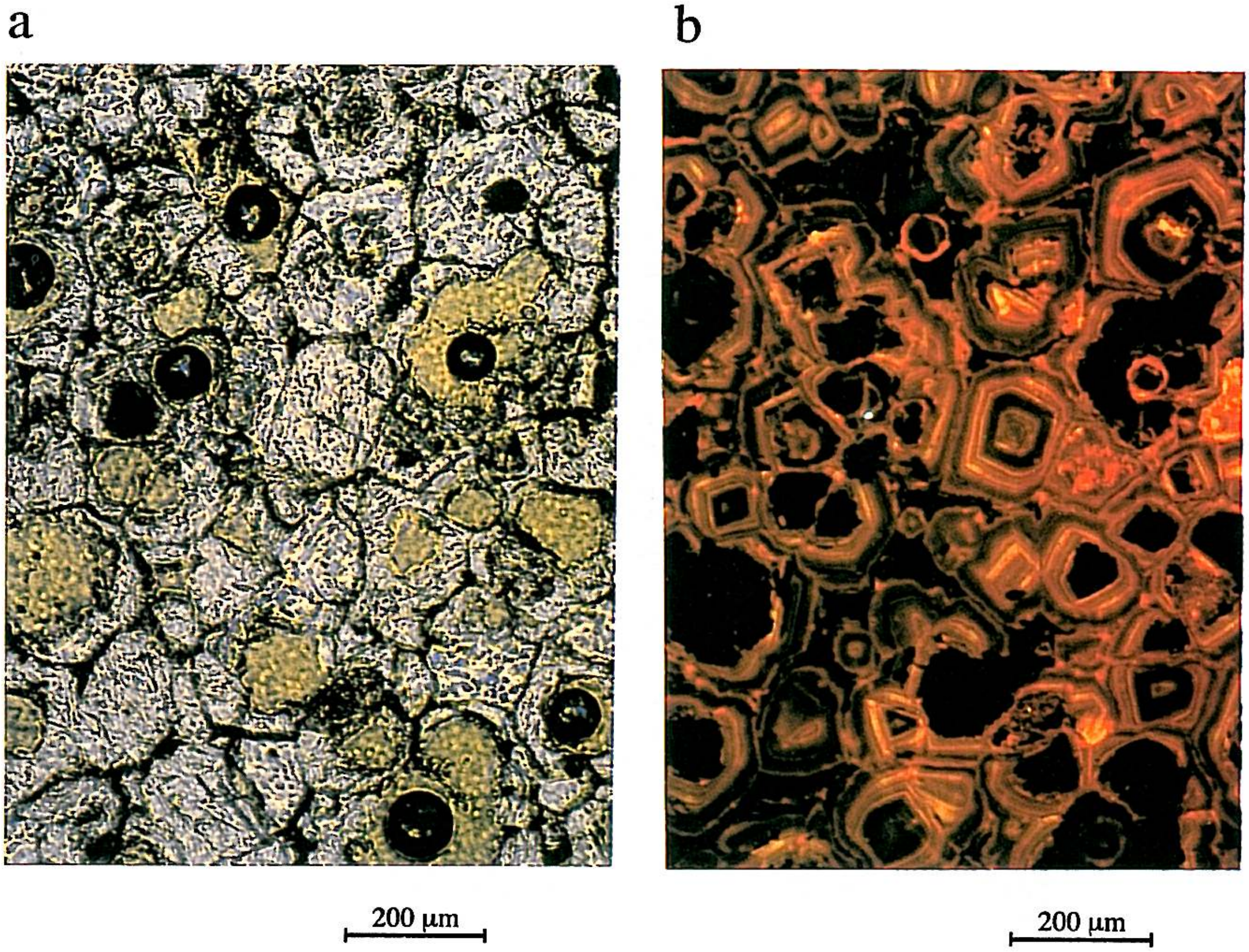

Fig. 8. (a) Thin-section photomicrograph of sample taken from Kabao section showing dedolomitization and dissolution. Note that cores of some crystals are selectively dissolved out leaving intracrystalline pores and some of them are replaced by calcite in later stage (PPL); (b) Luminescence microscopy of sample shown in (a). Note the complex zonation of the dedolomitization where dolomite zones show bright luminescent and calcite zones show dull luminescence and the pores are black.

laminations and solution breccias (lithotype-4 and 5). Each cycle was initiate by a rapid rise in sea level, a conditions suggested by the sharp contact between the intertidal lithotype-4 and the overlying carbonates lithotype-2 at Tarhunah and in the Abu Ghaylan area. Gradual shallowing as a result of sedimentation created extensive tidal flats and evaporitic sabkhas in which lithotype-3 and 4 were deposited. The bedded dolomudstones and dolopackstones of lithotype-3 were deposited in a low intertidal zone, and the algal mats or microbial of lithotype-4 were deposited in a higher intertidal zone.

Evaporites formed at the top of the cycles in sabkha type environment were probably extensive at the time of deposition. However, subsequent leaching, during subaerial exposure, removed many of the evaporite layers, now represented by solution breccias (lithotype-5). These are best developed in the thinner sequences of western outcrops (Wazan and Nalut area), which show rather restricted marine aspect. Cycles involving lithotype-1 (large-scale cross-bedded dolograinstones and dolopackstones) are well developed in sequence northeast at Tarhunah area. This cycle is interpreted as a tidal-channel deposit. Deposition occurred during progradation of broad shoals or lateral migration of tidal channels.

Based on the subsurface data it is thought that the lithotypes of the Sidi as Sid Formation (Ain Tobi

← Fig. 7. (a) Photomicrograph showing Type-2 crystalline dolomite which is very fine nonplanar-*a* being replaced by oolitic grainstone (PPL); (b) Luminescence microscopy of same view (a). The very fine dolomite replacing concentric structure of ooids have bright yellow luminescence (Y), whereas dolomite within intraparticle porosity or lining interparticle pores have red luminescence (arrow); (c) Thin-section photomicrograph of Type-5 saddle dolomite crystalline. It shows cloudy cores and clean rims (PPL); (d) Luminescence microscopy of same view shown in (c). Note that cloudy cores have brighter luminescence than clean rims whereas cleavage lines show bright yellow luminescent pattern (arrow).

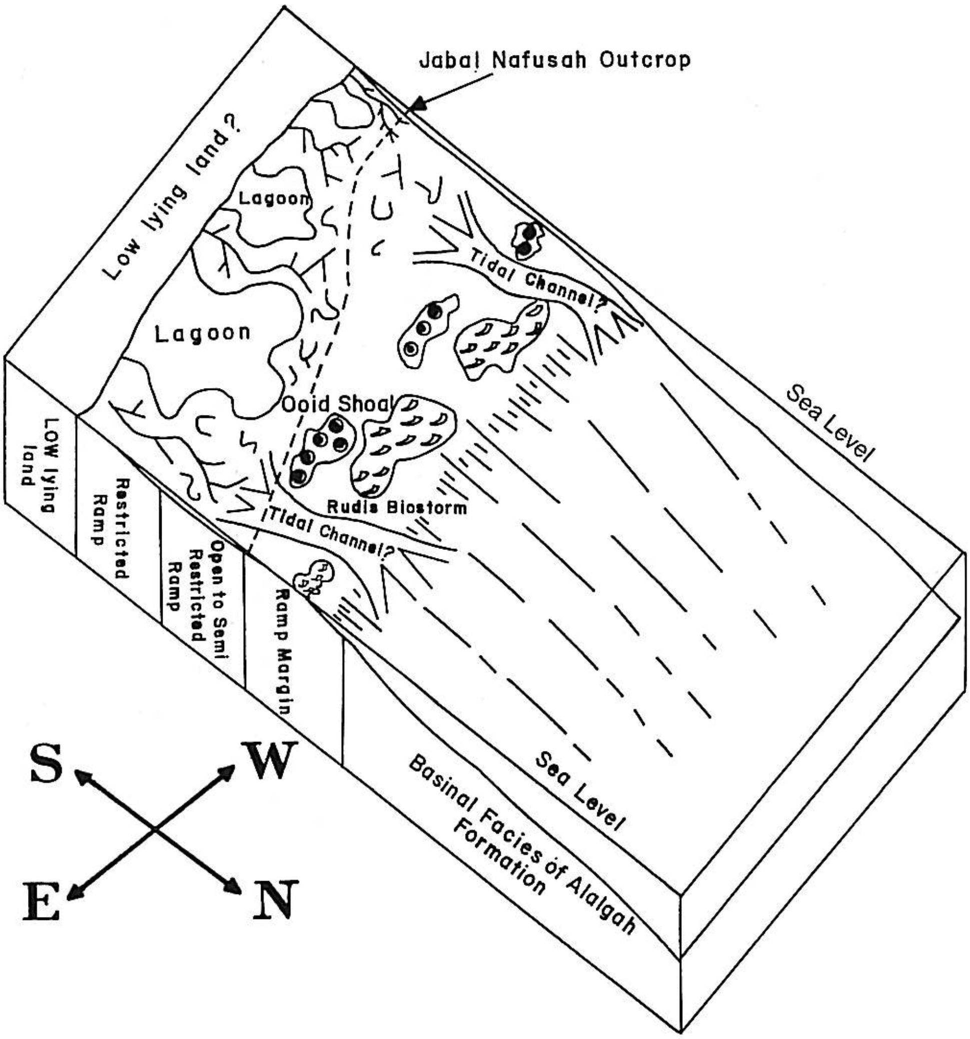

Fig. 9. Schematic block diagram of proposed Cenomanian sedimentary environment in NW Libya.

and Yifran members) regressive megasequence conditions could be more evaporitic south of Jabal Nafusah, with better development of sabkha sequences could be expected.

Mid-Ramp or Ramp Margin:

Stratigraphic sequences in wells drilled on the Jifarah Plain north of Jabal Nafusah indicate that post-Cretaceous erosion has removed the Sidi as Sid and the remainder of the Cenomanian in at least part of that area. The open to semi-restricted ramp environment probably graded northwards into mid-ramp or ramp margin environment. The margin is thought to occupy a narrow band in the subsurface that parallels the present coastline.

The presence of ramp margin is inferred on the basis of Cenomanian rudist debris in the Ain Tobi Member of the Jabal Nafusah, from oyster debris found at a point southeast of Tarabulus in Jabal Nafusah where its orientation changes from north-south to east-west, and from oyster packstones and grainstones of the Sidi as Sid's equivalent (Zebbag Formation) in Tunisia (Pedley *et al.*, 1982). This deposition environment probably also contains cross-bedded carbonate bodies and bioturbated units such as those found in the Ain Tobi Member in the Nafusah Escarpment. The presence of the *Ichthyosarcolites* Band as a series of buildups and the absence of a visible shelf-slope break on seismic lines implies that this is a ramp margin. The extensive post-Cretaceous erosion which removed the Cretaceous deposits along the coast may have resulted in obliteration of any ramp margin that was present.

Outer Ramp:

The Gabes–Tarabulus–Misratah Basin lies to the north of the ramp margin (Fig. 10). The Cenomanian

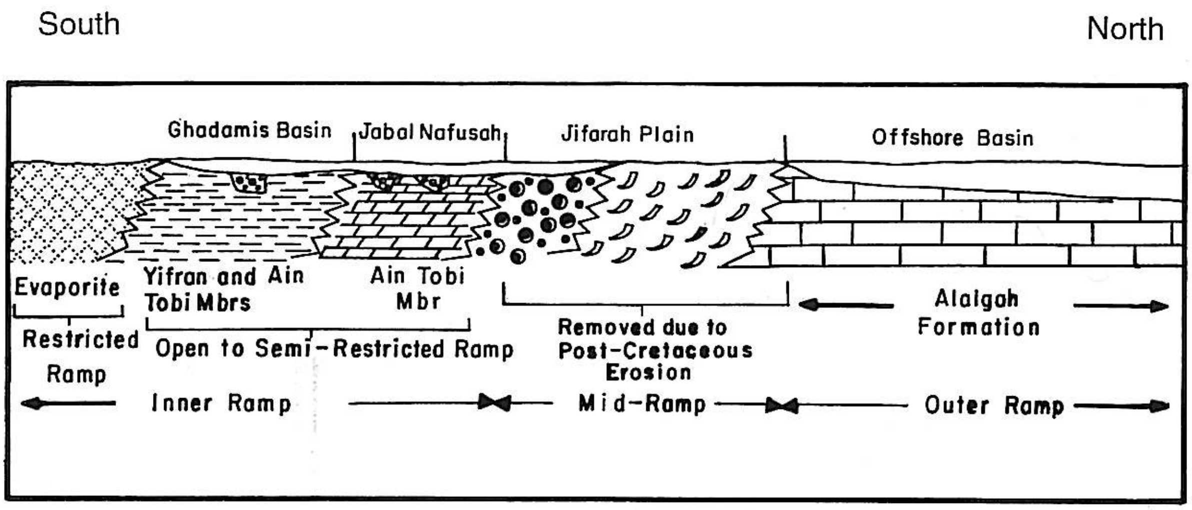

Fig. 10. Postulated changes in Cenomanian lithofacies in onshore and offshore NW Libya.

strata in this basin is represented by the Alalgah Formation (Hammuda *et al.*, 1985). The outer ramp environment is only known from the description of completion logs which reached the Cretaceous in offshore Libya (e.g. K1-137, H1-137, L1-137 and J1-NC35A wells).

Cenomanian sediments of the Alalgah Formation consist of laminated dolomitic marls containing miliolid and pelagic foraminifera and rudist material. The miliolid and rudist are thought to be derived from higher up the slope near the crest of the uplift. The pelagic foraminifera represent normal sediment accumulations for this environment.

Because of the paucity of the Upper Cretateous subsurface data, and absence of surface data in the northwestern Libyan offshore region, elaboration upon the basinal and slope environments is not possible.

Conclusion

1. The Sidi as Sid Formation includes two members. They are the Ain Tobi Dolostone Member which previously describe as dolomitic limestone and the Yifran Marl Member.

2. Bioturbation, lamination and cross-bedding structures are the most common form of structures found in units of the Ain Tobi Member. Units interpreted as solution breccias occurred in small intervals in most of the measured sections.

3. *Ichthyosarcolites* Band of Christie (1955) found in the lower and middle part of the Ain Tobi Member and vary the thickness from 3 to 18 m. The band is a marker bed across the whole Jabal Nafusah. The *Ichthyosarcolites* Band makes a gross change from the dominance of thicker bioturbated beds below to thinner beds above.

4. The Ain Tobi sediments have completely been dolomitized and five diagenetic types are identified. Dolomite Type-1 as early, fine, subhedral and non-ferroan. Cores of crystals of this dolomite type are selectively dissolved leaving intrapores. Crystals of dolomite Type-1 have homogeneous luminescence pattern. Dolomite Type-2 is early, very fine, and anhedral to subhedral replacing packstone/grainstone facies, Crystals of dolomite Type-2 have bright orange-yellow luminescent pattern. Dolomite Type-3 occurs in the lower part of the Ain Tobi sequence in all measured sections and interbedded with quartz sandstone. Its crystals are fine to medium, subhedral probably formed post-compaction. Type-3 dolomite is characterized by dirty orange luminescent cores and very thin bright luninescent rims. Type-4 dolomite is medium to coarse, euhedral to subhedral and characterized by cloudy cores and clean rims. Crystals of this type have orange luminescent cores and dull rims. Dolomite Type-5 (baroque dolomite) found only in the eastern part of the study area. Crystals of this type are coarse to very coarse with cloudy cores and clean rims and characterized by curved faces. Dolomite Type-5 has orange luminescent cores, dull rims and bright cleavage lines. Early calcitization or replacement of dolomite by early calcite occurs close to the unconformity surface and show complex zonation. However, replacement of dolomite by late calcite occurs in the top of the sequence and show dull to no luminescence.

5. The Sidì as Sid Formation represents part of inner ramp sequence, which ranged from open to semi-restricted ramp and restricted or lagoon ramp. The restricted ramp environment is represented by the Yifran Marl Member, the open to semi-restricted ramp environment is represented by the Ain Tobi Member in Jabal Nafusah areas and in the subsurface Ghadamis Basin. The open to semi-restricted ramp probably graded northwards into mid-ramp or ramp margin environment which are removed by post-Cretaceous erosion from the Jifarah Plain. The outer ramp environment is represened by the Alalgah Formation in the offshore Gabes–Tarabulus–Misratah Basin. It consists of laminated dolomitic marls containing miliolid and pelagic forminifera.

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