Examining the interplay of climate and low amplitude sea-level change on the distribution and volume of massive dolomitization: Zebbag Formation, Cretaceous, Southern Tunisia

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ABSTRACT
During the Cretaceous, a humid global climate, calcitic seas, high relative sea-level and low amplitude changes in relative sea-level largely prevented large-scale dolomitization in many carbonate successions. However, the well-exposed shallow-water carbonate sediments of the Upper Albian–Lower Turonian Zebbag Formation on the Jeffara Escarpment, southern Tunisia, are pervasively dolomitized. This study considers why dolomitization was so widespread in this region during a period of Earth history when platform-scale dolomitization is rare. Marine conditions were established in the Upper Albian, evidenced by stacked upward-shallowing packages of shallow subtidal to peritidal carbonate sediments in the basal Rhadouane Member. A gradual increase in the volume of subtidal sediments in the Cenomanian Kerker Member, culminated in deposition of laterally extensive marls, during maximum flooding of the platform in the Lower Turonian. The overlying Gattar Member was then deposited in shallower water as relative sea-level fell. The entire Zebbag Formation is pervasively replaced by stratabound, fabric-retentive, dolomite, except within the marl at the top of the Kerker Member, which is only partially dolomitized. Petrographic textures indicate dolomitization largely post-dated marine cementation and platform emergence but pre-dated chemical compaction. Slightly more positive oxygen isotope signatures, slightly elevated concentrations of Sr and a near-absence of evaporites are consistent with dolomitization by reflux of mesohaline sea water. An upward-decrease in major element concentrations and higher \(^{87}\text{Sr}/^{86}\text{Sr}\) compared to Upper Cretaceous sea water suggest that basal, Albian siliciclastic beds acted as aquifers facilitating dolomitization by fluxing fluids offshore. Dolomitization is interpreted to have resulted from multiple fluxes of sea water over periods of 0·5 to 2·5 Ma. The unusually high volume of dolostone for a platform of this age most probably reflects deposition within an arid climate belt, where an efficient reflux system was facilitated by basal, permeable siliciclastic strata.

INTRODUCTION
Despite numerous studies of the mechanisms, fluid sources, temporal and geographical distribution of dolomite in the Phanerozoic, there is still active discussion as to the primary controls on its distribution, which varies significantly in time and space. Several studies have related temporal variations in dolomite abundance to changes in Mg/Ca ratio, glacio-eustacy and atmospheric CO\(_2\) (Given & Wilkinson, 1987; Mackenzie & Morse, 1992; Sun, 1994; Burns et al., 2000; Wright & Oren, 2005). Greenhouse periods, characterized by warm climates, are interpreted to have a high abundance of dolomite, probably reflecting favourable conditions for
evaporite deposition and dolomitization via hypersaline reflux (Warren, 2000). While this is certainly true for the Afro-Arabian Plate during the Permo-Triassic and Jurassic, there was a more humid climate during the Cretaceous within the circum-Tethys region, and a transition to calcitic seas (Sandberg, 1983). This change in climate was coupled with the highest relative sea-level of the Phanerozoic (Haq et al., 1987), with atmospheric pCO₂ 3 to 12 times higher than present day (Kuyper et al., 1999). This led to an ice-free, hot and stable greenhouse climate by the middle Cretaceous (MacLeod et al., 2013; Bodin et al., 2015). The Upper Cretaceous has a low global abundance of dolomite (Given & Wilkinson, 1987; Sun, 1994), although massive dolomitization is observed in North Africa (Abdallah, 2003; Touir et al., 2009; Bodin et al., 2010) and southern Europe (Korbar et al., 2001; Husinec & Sokač, 2006; Benito & Mas, 2007; Iannace et al., 2013). This study considers why dolomitization was so widespread in this region, despite calcitic seas, low amplitude changes in relative sea-level and a humid global climate – none of which are conducive to dolomitization.

The Upper Albian to Middle Turonian Zebbag Formation is pervasively dolomitized and provides an excellent opportunity to study the processes and controls on massive dolomitization of marine carbonates on the northern margin of the Afro-Arabian Plate during the middle Cretaceous. Strata crop out along the laterally continuous Jeffara Escarpment located in the central part of southern Tunisia. The escarpment records an Upper Permian to Early Cretaceous succession, with excellent pseudo-3D exposure. It extends for over 200 km, from central southern Tunisia into north-western Libya separating the Ghadames Basin and Dahar uplift in the south-west from the Jeffara coastal plain in the north-east (Fig. 1). Dolomitization is observed along the length of the escarpment (Badalini et al., 2002; Bodin et al., 2010). The excellent exposure of the Zebbag Formation provides a high-quality outcrop analogue for hydrocarbon reservoirs in the region, including the Miskar gas field offshore Tunisia (Zappaterra, 1995) and the Arous Al-Bahar gas field within the offshore Sirt Basin (Belopolsky et al., 2012).

Previous studies document the diagenesis and dolomitization of Albian to Turonian strata in north-western Libya (Koehler, 1982; Chaabani et al., 2003; El-Bakai et al., 2010) and central Tunisia (M’rabet, 1981; Abdallah, 2003; Touir et al., 2009), but no previous work has been conducted on the Zebbag Formation of southern Tunisia. The origin of dolomitization within laterally equivalent strata has been variously attributed to reflux of hypersaline brines (M’rabet, 1981; Abdallah, 2003; Touir et al., 2009), normal marine fluids (Al-Aasm, 2005; Touir et al., 2009), mixed marine-meteoric fluids (Koehler, 1982; Abdallah, 2003; Al-Aasm, 2005) and deep phreatic fluids of continental origin (M’rabet, 1981). This study will present a multidisciplinary and multi-scale evaluation, using petrographical, geochemical and field evidence in order to fully evaluate the controls on dolomitization.

**GEOLOGICAL SETTING**

During the Late Cretaceous, southern Tunisia was located on the Saharan Platform, a passive margin. It was located around 12°N within a hot, arid climate belt (Fig. 2) (Chumakov et al., 1995; Scottese, 2001; Sellwood & Valdes, 2006). Prevailing trade winds moved in a south-westerly direction (Fig. 2; Fabre & Mainguet, 1991; Poulsen et al., 1998). Sea water temperature in the southern part of the Tethys is estimated to have been between 21°C and 36°C (Kolodyński & Raab, 1988; Pearson et al., 2001; Schouten et al., 2003; Steuber et al., 2005; Amiot et al., 2010; Linnert et al., 2014).

During the late Albian, regional marine transgression established a broad and shallow, carbonate platform across much of the Saharan Platform of North Africa (Benton et al., 2000; Wood et al., 2014). The rise in relative sea-level is marked by a transition from siliciclastic sediments of the ‘Continental Intercalaire’ Ain El Guettar Formation (De Lapparent & Gorce, 1960) to the overlying marine carbonate sequence, which in the Jeffara Escarpment is represented by the Zebbag Formation (Lefranc & Guiraud, 1990; Bodin et al., 2010; Fig. 1). The Formation is divided into the Charenn, Radhouane, Kerker and the Gattar Members (Fig. 1). The Charenn and Radhouane Members are only found in the northernmost part of the Jeffara Escarpment, thinning towards the south (Bodin et al., 2010). The Charenn Member is a coarse-grained siliciclastic deposit which contains marine fauna (bryozoans and bivalves) and locally shows herringbone cross-bedding, indicating a tidal component. The Radhouane Member conformably overlies the Charenn Member or sits unconformably above the Lower Albian fluvial to marginal marine Ain El Guettar Formation (Bodin et al., 2010). It is characterized by bivalve and gastropod floatstones with abundant microbialites (Koehler, 1982; Bodin et al., 2010) and has been dated as Late Albian, based on the presence of the ammonite *Knemiceras* sp. (Abdallah et al., 1995).

Continued sea-level rise over a vast and flat area in the Cenomanian led to deposition of shallow-water peritidal and shallow subtidal facies with low diversity, salinity-tolerant fauna such as gastropod, and miliolid, wackestones to mudstones and a single evaporite horizon (Bodin et al., 2010). This suggests variable salinity levels with minimal circulation during deposition (Touir et al., 2009). The boundary between the Radhouane and Kerker
Members is gradual and defined by a transition from clay-free to clay rich marl-dominated facies (Bodin et al., 2010). The Kerker Formation resembles the Rhadouane Member, and the laterally equivalent Yifran Formation (Bodin et al., 2010), being composed of stacked peritidal cycles of gastropod and bivalve wackestones capped by microbialite beds (El-Bakai, 1997). The presence of bird tracks, mammal tracks and abundant tepee structures within the central part of the Kerker Member south of the study area (Contessi & Fantí, 2012a,b; Contessi, 2013) suggests periods of subaerial exposure, whereas lateralequivalent strata in the study area are dominated by subtidal facies.

The Cenomanian–Turonian boundary occurs within the uppermost part of the Kerker Member, with maximum flooding at ca 92.2 Ma (Lüning et al., 2004). It forms part of the second-order transgressive–regressive cycle of Marie et al. (1984). Other authors have correlated the Cenomanian–Turonian boundary to the third-order UZA 2.5 global sea-level cycle of Haq et al. (1987) (Tourir
& Soussi, 2003). Cenomanian sediments in this study contain abundant echinoid debris, pelagic foraminifera and oysters indicating a continued rise in relative sea-level and open marine conditions (Grosheny et al., 2013). The uppermost beds are the lateral equivalent of the upper Cenomanian to lower Turonian Bahloul Formation of Northern and Central Tunisia (Abdallah et al., 1995; Grosheny et al., 2013). As the rate of relative sea-level rise slowed, large rudist build-ups of the Gattar Member became established and prograded northwards. A fully upward-shallowing succession is seen within the Gattar Member, culminating with the development of tidal flats and deposition of evaporites within troughs in central Tunisia (Camoin, 1991; Abdallah, 2003). The Annaba marls, which directly overlie the Gattar Formation in northern central Tunisia, are not seen in the Jeffara Escarpment where the Gattar Formation is covered by the Beida Anhydrites (Touir et al., 2009).

**METHODS**

Six sections from around the town of Tataouine in Tunisia were logged using a Jacobs staff and traditional field methods. The carbonate rock textures were described using the Dunham (1962) classification. The GPS coordinates of logged sections are given in Table 1 and locations are shown on Fig. 1. Logged sections were systematically sampled to cover the full range of facies and textures observed within each member of the Zebbag Formation. Collected samples were prepared as 30 μm covered thin sections, impregnated with blue resin to highlight porosity. Sections were also stained with Alizarin Red S and potassium ferricyanide to determine carbonate mineralogy and iron content (Dickson, 1966). Petrographic description led to construction of a paragenetic sequence using transmitted light and cross-polarized light techniques. Dolomite textures were classified according to Sibley & Gregg (1987). Point counting of thin sections for mineralogy and porosity was undertaken using Petro© point counting software and stepper stage. For each section, 250 points were counted using an approximate stepping distance of 1-15 mm in the x direction and 1-14 mm in the y direction. A subset of samples was prepared as 30 μm uncovered, polished sections for cathodoluminescence, conducted using a Citel 8200 mark 2 luminoscope with an accelerating voltage of 6 to 8 kV, a vacuum of ca 0.2 mbar and a cathode current of between 310 to 335 μA.

The mineralogy of samples was analysed using X-ray diffraction (XRD) at the University of Manchester. Bulk samples were ground using a pestle and mortar and analysed using a Bruker D8 advanced instrument and a Cu Kα radiation. Data were collected over a range of 5° to 70° with a step size of 0.02°. Standards of known composition were run prior and post data collection to ensure accuracy. Quantification was determined using Siroquant software, which uses an area under the peak method of quantification.

Stable oxygen and carbon isotope (39 samples), major element and major element analysis (39 samples) were conducted at the Ruhr University, Bochum. Bulk rock powders were extracted from selected samples using a dentist drill. For stable isotope analysis, 0.30 mg ± 0.04 mg was weighed out and analysed using a Thermo 253 mass spectrometer attached to a Gasbench II and a PAL auto sampler. All values are reported relative to the Vienna-Pee Dee Formation belemnite (V-PDB) and standard deviations are 0.05 ‰ for carbon and 0.11 ‰ for oxygen. Where appropriate δ18O values calculated for fluids are reported relative to Standard Mean Ocean
Water (SMOW). For major element analysis, ca 0.15 mg of sample was weighed and dissolved in 3 M HNO₃. The solution was then diluted with 2 ml of deionized water (>18.2 MΩ cm⁻¹). The concentration of the elements Ca, Mg, Fe, Mn and Sr were analysed using a Thermo Scientific iCAP 6500 DUO inductively coupled plasma optical emission spectrometer. Eight reference samples were also analysed (BSC-CRM-512, dolomite and BSC-CRM-513, limestone) to ensure accuracy. The relative standard deviation, which is the ratio of the standard deviation to the mean, for all elements and all samples was <5%. All major element and isotope data presented are bulk samples with >80% dolomite based on XRD and point counting techniques.

The Sr isotope measurements (six samples) were carried out at the SGiker-Geochronology and Isotopic Geochemistry facility of the University of the Basque Country UPV/EHU (Spain). The procedure for sample treatment and extraction of Sr was carried out according to the method of Pin & Bassin (1992) and Pin et al. (1994). The ⁸⁷Sr/⁸⁶Sr ratios were measured by MC-ICP-MS using a high-resolution Thermo Fisher Scientific Neptune instrument in static multicollection mode. Values were corrected for mass fractionation by normalizing to ⁸⁸Sr/⁸⁶Sr = 8.375209 (Steiger & Jäger, 1977). The uncertainty for individual measurements of ⁸⁷Sr/⁸⁶Sr isotopes and average ratio under the same conditions for NBS-987 standard over the period of analyses was 0.710269 ± 0.000015 (2 SD). The full analytical details can be found in Newport (2014).

RESULTS

Sedimentology and petrography

A composite log of the Zebbag Formation and field photographs are shown in Figs 3 and 4–6, respectively. The detailed sedimentology of each member is described in detail below.

Rhadouane member

The average thickness of the Rhadouane Member in the field area is 13 m (Fig. 3) but reaches a maximum of 35 m in the northernmost part of the escarpment (Bodin et al., 2010). The base of the Rhadouane Member is defined by a thin, yellow marl bed which rests unconformably above the Ain el Guettar Formation. The transition between the Rhadouane and Kerker Members is gradual and defined by the progressive loss of siliciclastic sediments.
sand and an increase in the thickness and frequency of carbonate marl units (Fig. 3). The Rhadouane Member is characterized by an upward-decrease in clay content and pervasively dolomitized, metre-scale, upward-shallowing successions, as follows (Fig. 4B):

1 Basal unit of highly bioturbated (by *Thalassonoides*) beds of skeletal (gastropod and benthic foraminiferal) peloidal wackestones to packstones with abundant rounded to sub-rounded, moderately sorted detrital quartz grains. No original shell material is present and skeletal composition is only recorded by the presence of biomouldic porosity or ghosts of grains. The presence of marine fauna and relatively muddy textures suggest deposition in a moderate-energy to low-energy lagoonal environment.

2 Central unit of skeletal peloidal wackestone to grainstone.

3 Uppermost planar-crinkly algal laminites with rare, low amplitude stromatolites with ca 5 cm relief and a crinkly to ridge morphology (Fig. 4C). These beds are commonly overprinted by laterally discontinuous breccia and calcrete horizons, composed of abundant dolomitized intraclasts, within a dolomitized matrix, cutting into underlying beds (Fig. 4D). The matrix-replacive dolomite is very finely crystalline (ca 15 μm) with very dull orange luminescence, whereas clasts are composed of dolomite which is often coarser (ca 50 μm) than the matrix, with a dull orange core and brighter orange rim under CL. Truncated dolomite

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**Fig. 4.** (A) A field panorama showing the three studied members (Rhadouane, Kerker and Gattar) of the Zebbag Formation. (B) Stacked peritidal cycles with three separate units (described in text). Red lines separate units and yellow lines represent top/base of different cycles. (C) Stromatolites with tepee structures. (D) Laterally discontinuous breccias with dolomite clasts (cl) and calcrete horizons (10 cm increments on Jacob staff) ca 2 m above base of Rhadouane Member. (E) CL image of breccia clast and matrix within Rhadouane Member. Note truncated rhombs at edge of clast (arrowed).
rhomboids within clasts and abraded detrital dolomite rhombs are also observed (Fig. 4E).

Kerker member

The thickness of the Kerker Member in the field area is 56 m (Fig. 3) but can reach a total thickness of 140 m further to the north (Bodin et al., 2010). The Kerker Member shows similar stacked, upward-shallowing facies to that observed in the Rhadouane Member, albeit separated by decimetre-scale marl beds. Bioturbated skeletal peloidal pack/wackestones are overlain by peloidal wackestones to grainstones that, in the middle part of the Kerker Member, are in part substituted by lenticular beds of cross-bedded oolitic or skeletal grainstones up to 30 cm thick (Fig. 5A). These are capped by planar-crinkly algal laminites and common domal stromatolites with ca 2 to 10 cm relief. Other important differences compared to the Rhadouane Member include:

1. In the lower Kerker Member, there is a prominent gypsum horizon, the only evidence for evaporite deposition within the Zebbag Formation in the study area.
2. The middle part of the Kerker Member has a thin (ca 50 cm) dedolomitized, brecciated algal laminit bed that is highly deformed. Dedolomitization of this bed is laterally continuous over the length of the outcrops at several locations.
3. In the upper part of the Kerker Member, there is a gradual loss in the number and thickness of algal laminites, and in the uppermost ca 20 m, none are observed. This is coupled with an upwards-increase in the limestone–marl ratio and thickness of gastropod and shelly wackestones to grainstones units.
4. The uppermost Kerker Member is defined by a ca 6 m thick marl horizon which contains open marine fauna including bivalves, echinoids and oysters, showing that this member gradually becomes more subtidal, upwards (Fig. 5C). This marl unit is only partially dolomitized.

Gattar member

The Gattar Member is 30 m thick in the field area (Figs 3 and 6A) and has a relatively constant thickness across the escarpment (Bodin et al., 2010). Due to intense dolomitization in the study area, detailed facies analysis of the Gattar Member is challenging; however, some general trends and facies are noted. The lowermost part of the Gattar Member is characterized by poorly defined low-relief (ca 5 m) rudist colonies measuring up to 40 m in diameter (Fig. 6A). Rudists are rarely preserved (Fig. 6B) and generally only recognizable from calcite-cemented biomolds, in some rare cases, ghost rudist grainstone fabrics are seen in proximity to the rudist
moulds. Rarely, towards the base of the Gattar Member, beds contain ghosts of peloids and ooids. Dolomitization is mostly fabric-destructive and so these beds cannot be traced laterally or correlated between outcrops. In the upper parts of the Gattar Member, algal laminated beds and stromatolites, with \( ca \) \( 2 \) m radii and 50 cm of relief

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**Fig. 6.** Field photographs from the Gattar Member showing (A) low-relief rudist build-ups seen at the base of the Gattar Member, (B) rarely preserved rudist moulds and casts, (C) geopetal structures filled with sediment (red outline), cement and sediments (white outline with boundary shown by black line) and cement (yellow outline) seen within the upper parts of the Gattar Member.

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**Fig. 7.** Dolomite petrotypes in the Zebbag Formation. (A) PPL photomicrograph of Dol-R-1 replacing ooids and isopachous fringing cements. (B) Same image as in (A) but taken under CL. (C) PPL photomicrograph of zoned dolomite cement lining intergranular porosity. (D) Same image as (C) but taken under CL. do, dolomite; ca, calcite cement.
become common, and geopetal structures are observed (Fig. 6C). The Gattar Member is therefore interpreted to have been deposited under dominantly subtidal conditions in its lower part with more common peritidal facies higher in the succession. This member is overlain by an evaporitic succession of the Beida Formation, further to the north of the study area; however, evaporites were not noted in these outcrops. Fractures lined by calcite and subsequently filled with sediments cut through the Gattar Member.

Petrography of diagenetic phases

There are two main types of dolomite, Dol-R-1 and Dol-R-2, and their distribution varies throughout the studied succession.

The entire Rhadouane, the lower-middle parts of the Kerker Member and the upper Gattar Member are completely replaced by finely crystalline (20 μm to 50 μm diameter), partially fabric-preserving dolomite with planar-e to planar-s textures (Fig. 7A and B). Isopachous marine cements coating ooids within oolitic grainstones are also dolomitized (Fig. 7A). This phase is classified as Dol-R-1 and is the most common dolomite type within the Zebbag Formation. Under CL, Dol-R-1 has a homogeneous dull orange-yellow luminescence (Fig. 7B). Rarely, bright to dull luminescent, finely zoned dolomite cements line intergranular porosity (Fig. 7A and B). Residual porosity is often occluded by non-luminescent, non-ferroan calcite cement. Dol-R-1 is cross-cut by both calcite-cemented fractures and very weakly formed bed-parallel dissolution seams and stylolites.

The lower parts of the Gattar Member are pervasively dolomitized by fabric-destructive, coarsely crystalline dolomite (ca 250 μm) with planar-e to planar-s textures and a cloudy core-clear rim morphology (Dol-R-2). Some crystals show sutured contacts with adjacent rhombs. Only rare ghosts of rudist fragments, undifferentiated molluscs and ooids are preserved. On the boundary between the cloudy core and the clear rim, there is often partial dissolution and cementation by non-luminescent calcite, while there is common etching and partial dissolution within the clear rim (Fig. 8A and B). Under CL, cloudy (inclusion rich) cores are dull orange luminescent with slight mottling, while the clear rims exhibit slightly duller orange luminescence with no mottling (Fig. 8B). Rhombs of Dol-R-2 typically exhibit serrated contacts with other rhombs, but no pressure dissolution is noted in intercrystalline calcite cements (Fig. 8A). There is no spatial variability in the dolomite phases observed either along strike or along depositional dip.

Calcite cement

Throughout the Zebbag Formation, intercrystalline, mouldic, fracture, intragranular and vuggy porosity is lined, and usually filled, by calcite cement. Two different luminescence patterns were observed under CL; (ii) non-luminescent calcite and (ii) fine, sharp oscillatory zonation alternating between bright, dull and non-luminescent (Fig. 9A and B).

Dedolomite

Stratabound dedolomitization is observed at the base of the Gattar Member, and ca 15 m above the base of the Kerker Member. These horizons have ghost dolomite textures, are non-luminescent under CL, excepting minor, localized, dull orange luminescence that probably reflect the presence of minor inclusions of dolomite (Fig. 9C and D).

Geochemistry

Stable isotope analysis, major element concentrations and strontium isotope analysis were used to constrain the
Fig. 9. Photomicrographs of (A) sharply zoned calcite cement filling fracture and mouldic pore space, (B) same photograph as in A but taken under CL, (C) coarse dedolomite crystals with minor inclusions of dolomite (black outline) and (D) dedolomite with remnant and ghost dolomite rhombs (black outline).

Fig. 10. Oxygen and carbon stable isotope cross plot of dolomite samples from the Zebbag Formation. Black box represents marine limestone signature and grey box represents expected marine dolomite signature based on an +3 per mil difference between co-precipitated limestone and dolomite (based on data from Budd (1997).
source of dolomitizing fluids and data are summarized in Fig. 3.

**Carbon, oxygen and strontium isotopes**

Isotopic analysis of pristine oyster shells from the upper parts of the Kerker Member have $\delta^{13}C = 1.54\%_o$ and $\delta^{18}O = -4.13\%_o$ (Fig. 10). There is a clear distinction in the oxygen and carbon isotopic signature between each formation as shown in Fig. 3. The $\delta^{18}O$ signature of dolomite within the Rhadouane Member has a mean value of $-0.63\%_o$ ($-1.47$ to $-0.33\%_o$) and $\delta^{13}C$ values of $1.30\%_o$ (0.87 to 1.66\%_o). The oxygen isotope signature of dolomite within the Kerker Member is slightly more negative compared to the Rhadouane Member, with a much narrower range (mean $= -0.80\%_o$, 0.88 to $-0.70\%_o$). Carbon isotope ratios of dolomite in the Kerker Member average $2.02\%_o$ (1.29 to 2.72\%_o). The Gattar Member shows the most negative and the widest ranging oxygen isotope signature for the whole of the Zebbag Formation (mean $= -1.15\%_o$, $-2.57$ to $-0.15\%_o$) but slightly more positive $\delta^{13}C$ values (mean $= 2.89\%_o$, 0.83 to 4.95\%_o) (Fig. 10).

Given the presence of calcite cement and the difficulty in obtaining samples of pure dolomite for isotope analysis, an ‘endmember’ isotopic composition was estimated. This was carried out by measuring the C and O isotopic composition of mixtures of calcite cement and dolomite. The proportions of each phase in each sample were measured by point counting and mineralogy verified using XRD (Newport, 2014). Figure 11 shows the results of this analysis, and demonstrates a linear relationship between samples with ca 100% calcite and samples with ca 100% dolomite. Based on these data, an ‘endmember’ isotopic composition can be interpreted using simple linear regression (Fig. 11 and Table 2). The $\delta^{18}O$ value of precipitating fluids for each member was calculated (1-1 to 2.0\%o; Table 2) based on a sea surface temperature of 35°C and the dolomite fractionation factor of Matthews & Katz (1977). This fractionation factor was chosen in line with the recommendation of Murray & Swart (2017).

Dolomite from the Rhadouane and Kerker members has a mean $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.707739 (0.707685 to 0.707785; Fig. 12), while dolomite in the Gattar Member shows a much wider range of $^{87}\text{Sr}/^{86}\text{Sr}$ values (mean $= 0.707676$, 0.707538 to 0.707908; Fig. 12).

**Major element concentrations**

Overall, there is a clear decrease in the concentration of major elements from top to base of the Zebbag Formation (Fig. 3), with the dolomitized limestone of each member of the Zebbag Formation showing distinctive elemental concentrations. Iron concentrations in the Rhadouane Member are the highest for the entire Zebbag Formation, with mean $= 4205$ p.p.m. (2757 to 6772 p.p.m.) compared to mean values of 1042 p.p.m. in the Kerker Member (1042 to 4261 p.p.m.) and 271 p.p.m. in the Gattar Member (76 to 696 p.p.m.) (Fig. 3). The Rhadouane Member also has the highest Mn (mean $= 363$ p.p.m., 308 to 441 p.p.m.) and Sr concentration for the whole Zebbag Formation (mean $= 383$ p.p.m., 170 to 1011 p.p.m.) compared to the Kerker Member (mean $= 274$ p.p.m., 103 to

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**Fig. 11.** Isotopic signature of known mixtures of calcite and dolomite from the Zebbag Formation to determine endmember isotopic signatures. Top row shows values of $^{13}C$ and bottom row shows values of $^{18}O$. $R^2$ values are also shown. See text for details.
Table 2. Table of average major element composition and endmember stable isotope signatures for the Zebbag Formation, arranged in stratigraphic order. Isotopic signatures are calculated using a reverse linear regression. The $\delta^{18}O$ is calculated for water at 35$^\circ$C using the equation by Matthews & Katz (1977).

| Member    | Sr (p.p.m.) | Fe (p.p.m.) | Mn (p.p.m.) | $\delta^{13}C_{\text{IW}}$ | $\delta^{18}O_{\text{IW}}$ | $\delta^{18}O_{\text{water}}$ |
|-----------|-------------|-------------|-------------|---------------------------|---------------------------|-------------------------------|
| Gattar    | 93          | 271         | 55          | 3-80                      | -0-80                     | 1-1                           |
| Kerker    | 132         | 1876        | 274         | 2-10                      | -0-40                     | 1-5                           |
| Rhadouane | 383         | 4205        | 363         | 2-10                      | 0-10                      | 2-0                           |

Fig. 12. A chart showing the $^{87}\text{Sr}/^{86}\text{Sr}$ signature for dolomite types Dol-R-1 and Dol-R-3 compared to sea water signature for the Upper Cretaceous. Grid and sea water curve adapted from McAthur et al. (2001). H, Hauterivian; Ba, Barremian; Ce, Cenomanian; Tu, Turonian; Co, Coniacian; S, Santonian; Ca, Campanian; Ma, Maastrichtian; D, Danian.

DISCUSSION

**Sedimentology and stratigraphy**

The progressive transition from clastic to carbonate deposition during deposition of the Rhadouane Member is consistent with global sea-level rise and associated global climate change, influencing drainage patterns and limiting siliciclastic sediment supply. The dominance of stacked, upward-cleaning cycles is suggestive of sedimentation within a subtidal lagoonal to peritidal setting bounded by oolitic sand bars. The presence of ooids, the single horizon of gypsum and the microbial facies that occur towards the top of cycles implies stressed, saline conditions, while the low relief of the crinkly laminites and stromatolites indicates water depths were very shallow. Nevertheless, the near-absence of evaporites suggests that salinity rarely reached gypsum saturation.
Discontinuous calcrete and breccia horizons indicate that the top of upward-shallowing cycles became emergent during deposition of the Rhadouane Formation. These are not interpreted as evaporite-removal breccias as there is no clear indication of collapse structures, which would indicate the removal of evaporites, nor any petrographical evidence of evaporite crystal moulds, evaporite pseudomorphs or ghosts. The identification of higher relief, domal stromatolites up-section suggests a gradual increase in water depth, culminating with deposition of a thick marl with an open marine skeletal assemblage in the uppermost Kerker Member. These observations are in line with regional interpretations of rising sea-level to a maximum flooding event in the lowermost Turonian (Lüning et al., 2004; Fig. 3).

The base of the Gattar Member in the study area is dominated by rudist bioherms and ooid shoals, marking a return to relatively shallower water and higher energy conditions. It is possible that these facies define a low-relief shelf break, but pervasive dolomitization has hindered identification of detailed stratral relationships. Within the uppermost part of the member, an increased abundance and frequency of algal laminites beds and stromatolites suggests upward-shallowing and progradation of peritidal facies. A continued basinward shift in facies led to the development of supratidal conditions and deposition of the overlying Beida Anhydrite as part of the Abiod Formation, which are not seen in the field area, and eventually exposure of the platform (Camoin, 1991; Touir et al., 2009).

**Timing of dolomitization**

The replacement of marine isopachous fringing cements by dolomite indicates that dolomitization occurred after marine cementation. Dolomite Dol-R-1 is cross-cut by stylolites. As well-developed stylolites need at least convex–concave grain contacts in ooid grainstones, indicating that dolomitization pre-dated compaction. Calcrete horizons within the Rhadouane Member are dolomitized and reworked as clasts (Fig. 4C), and truncated dolomite rhombs occur within brecciated clasts that form above calcretes (Fig. 4D), while single dolomite rhombs occur within the matrix. This suggests that dolomitization occurred immediately prior to, and immediately following platform emergence. The subtle difference in texture and luminescence of dolomite between clasts and matrix in breccias at exposure surfaces (Fig. 4D) also implies that the Rhadouane Member was affected by multiple pulses of dolomitizing fluids.

Dolomite phase Dol-R-2 shows sutured crystal contacts between adjacent rhombs but lacks clear, well-formed stylolites. As well-developed stylolites need at least ca 500 m of overburden to form in dolomitized sediments (Mountjoy et al., 1999), replacement by Dol-R-2 must have occurred prior to significant burial. We interpret Dol-R-2 to have formed during shallow burial, prior to any significant chemical compaction.

**Origin of dolomite**

**Stratigraphic observations and dolomite texture**

Dolomitization in the Zebbag Formation occurs as stratabound dolomite bodies, replacing all limestone within a single escarpment that extends over a distance of 200 km (Bodin et al., 2010). This stratabound geometry and spatial extent of dolomitization rules out the possibility of dolomitization via mixed meteoric-marine fluids as proposed by previous authors (Koehler, 1982; Abdallah, 2003), a conceptual model that is anyway widely questioned (Warren, 2000). As well as its wide extent, the lack of spatial variability in dolomite texture and geochemistry within each member of the Zebbag Formation is notable. Overall, the planar texture of dolomite phases Dol-R-1 and Dol-R-2 imply dolomitization at temperatures below the crystal roughening temperature of 50°C (Sibley & Gregg, 1987). However, texture does vary stratigraphically. Within the Rhadouane, Kerker and upper parts of the Gattar members, which are dominated by peritidal facies, dolomite is finely crystalline and partially fabric-preserving (Dol-R-1). Here, muddy sediment in packstones and wackestones provided a high reactive surface area for dolomitization and nucleation rates outpaced growth rates (Sibley & Gregg, 1987). In the lower parts of the Gattar Member, replacive dolomite is coarsely crystalline and exhibits a cloudy core, clear rim morphology (Dol-R-2). Coarse sediments in rudist grainstones have a lower reactive surface area leading to growth of coarser dolomite rhombs. This strongly suggests that dolomite texture is, at least in part, facies controlled.

**Fluid chemistry**

The carbon and oxygen isotopic composition of carbonate precipitated from Cretaceous sea water has been estimated to vary between $\delta^{13}C = 0.00_{\%o}$ and $4.00_{\%o}$ and $\delta^{18}O = -5.0$ to $-3.5_{\%o}$ (Scholle & Arthur, 1980; Bogoch et al., 1994). The composition of pristine oyster shells ($\delta^{13}C = 1.54_{\%o}$, $\delta^{18}O = -4.1_{\%o}$) from the Kerker member is consistent with this. All three Members of the Zebbag formation also show normal marine $\delta^{13}C$ signatures ($\delta^{13}C = 1.29$ to $4.95_{\%o}$), probably due to buffering of the carbon isotopic composition by Upper Cretaceous limestone during recrystallization (Land, 1980; Rott & Qing, 2013). Marine dolomites are expected to have more positive $\delta^{18}O$ values ($+3.00_{\%o}$) (Land, 1980; Budd, 1997).
compared to stratigraphically age-equivalent limestone, such that δ18O values between −2.00‰ and 0.50‰ would be anticipated for the Zebbag formation if dolomitization was from penecontemporaneous sea water. The endmember measured δ18O value, based on known mixtures of calcite and dolomite for the Rhadouane member is slightly more positive (δ18O = −1.47 to −0.33‰). This apparent increase is less marked for the Kerker (δ18O = −0.88 to −0.70‰) and Gattar members (δ18O = −2.57 to −0.15‰).

Based on measured isotopic values, and a sea surface temperature of 35°C, the composition of the dolomitizing fluid has been calculated using the equation of Matthews & Katz (1977) as δ18Owater = 2‰water1.5‰ and 1‰water respectively, for the Rhadouane, Kerker and Gattar members (Table 2). These values are all more positive compared to Cenomanian sea water (δ18Owater = −1.9‰) (Wilson et al., 2002; Voigt et al., 2004), but more negative values would be calculated at lower temperatures. It is highly probable that the oxygen isotopic composition of sea water became more positive as a result of evaporation, although rarely did fluids reach gypsum saturation; only one gypsum bed was identified within the study area. This suggests that although evaporation was only temporarily high enough to reach gypsum saturation, brine pools were extensively developed across the peritidal zone. This is supported by the presence of peritidal facies, with a low diversity faunal assemblage, within the Rhadouane and lower Kerker members and the uppermost Gattar Member. The slight increase in the δ18O values of brines in the Rhadouane Member compared to the Kerker and Gattar members is consistent with deposition of these facies within very shallow water, implying a closer spatial proximity to the brine pool. The presence of the Beida Anhydrites (Touir et al., 2009) above the Gattar Member suggests that hypersaline fluids would have been available to the platform later in the Turonian.

Further evidence for elevated fluid salinity can be interpreted from concentrations of Sr (e.g. M´rabet, 1981; Touir et al., 2009). The K0 of Sr with respect to water and gypsum is <1 (Veizer, 1983), so strontium will be preferentially concentrated into the fluid phase, and removal of Ca by gypsum will increase Sr/Ca ratios (Swart et al., 2005). Stoichiometric dolomite precipitated from fluids with typical sea water ratios of Sr/Ca should have Sr concentrations of 100 p.p.m. (Vahrenkamp & Swart, 1990). The upper Rhadouane Member shows the highest concentration of Sr, below the evaporite marker horizon (mean = 384 p.p.m.), suggesting that dolomitizing fluids had elevated Sr/Ca ratios and absolute concentrations of this element. The Kerker and Gattar members have average Sr concentrations of 133 p.p.m. and 94 p.p.m., respectively, more typical of normal sea water. In conclusion, oxygen isotope ratios and facies analysis suggests that dolomite precipitated from sea water that was slightly above normal salinity, but a lack of evidence for thick evaporate beds and an absence of Sr-enrichment suggests fluids rarely reached gypsum saturation.

The concentration of Fe and Mn within dolomite can be used to interpret the redox state of precipitating fluids; the K0 of Fe and Mn is >1 and so both of these elements are preferentially incorporated into the dolomite crystal under reducing conditions (Machel, 1988). Holocene dolomites associated with marine fluids and evaporites have Fe values ranging between 10 p.p.m. and 2000 p.p.m. and Mn values ranging between 5 p.p.m. and 275 p.p.m. (Gregg et al., 1992; Montanez & Read, 1992b). The measured values of Fe (76 to 2338 p.p.m.) and Mn (36 to 276 p.p.m.) for the Gattar Member and for the middle and upper Kerker Member are consistent with these values. In all cases, this implies precipitation under at least moderately reducing conditions, consistent with the dull luminescence under CL.

The lowermost Kerker and Rhadouane members have much higher concentrations of Fe (2757 to 6772 p.p.m.) and Mn (308 to 714 p.p.m.) than the overlying strata. This could in part be due to leaching of Fe from Fe-oxides that are commonly associated with exposure surfaces (Montanez & Read, 1992b; Christ et al., 2012; Vandeginste & John, 2012), which are common in the lower Rhadouane Member. It cannot, however, explain the increased Fe concentration in the upper Rhadouane and lower Kerker members, where there is little evidence for emergence. While the presence of peritidal facies suggests there could be short-lived exposure events, we propose an alternative interpretation.

The nearest reservoir of Fe and Mn would be the underlying Ain el Guettar Formation, which comprises marginal marine siliciclastic sediments. If dolomitizing fluids had used this sandstone as an aquifer, then water–rock interaction could have enriched fluids in Fe and Mn. Further support for this interpretation comes from measured 87Sr/86Sr. Carbonates precipitated from Cenomanian sea water should have 87Sr/86Sr values of 0.707400 to 0.707420, while measured values for the Rhadouane and Kerker members are enriched (mean 0.707739; Fig. 12). Such enrichment could have also occurred by fluid–rock interaction during brine migration (Fig. 13A). As such, it is possible that the enriched Sr concentrations and oxygen isotopic ratios ascribed previously to increased brine salinity could also reflect fluid interaction with siliciclastic sediments. Such a model has significant implications for the distribution of dolomitization, as migration of refluxed brines offshore within the basal sandstone aquifer provides a mechanism for fluid transport over tens of kilometres to distal locations on the carbonate platform. Given that the peritidal sediments that dominate the Rhadouane and Kerker members would have a low initial permeability, such a model
provides an efficient mechanism for dolomitizing the platform to a wide extent.

Turonian sea water should precipitate carbonate with $^{87}$Sr/$^{86}$Sr between 0.707290 and 0.707350 (Fig. 12; McAthur et al., 2001), and the Gattar Member shows an enrichment above this range (mean 0.707676). This is less easy to explain hydrogeologically by interaction with the Ain el Guettar Formation. An alternative explanation is that recrystallization of the Gattar Member took place during interaction with younger fluids, responsible for precipitation of calcite cements in fractures. These fluids could have interacted with the overlying Miocene Beglia
Formation, which is now observed as a fracture-filling phase in the Gattar Member. Further support for this assertion comes from the pervasive dedolomitization and calcite cementation observed within the basal Gattar Member. The presence of Miocene-aged sandstones filling fractures that are lined by meteoric calcite and associated with dedolomitization supports a model for dedolomitization in the Miocene (Al-Aasm, 2005).

**MODEL OF DOLOMITIZATION**

Overall, dolomite texture, distribution and geochemistry is consistent with dolomitization from low temperature (<50°C), slightly reduced, mesosaline fluids. Although conceptual models of reflux dolomitization commonly invoke penehaline fluids, close to gypsum saturation, there is good theoretical evidence that pervasive dolomitization can occur from mesosaline brines, given sufficient time for reflux and large enough fluid volumes (Jones & Xiao, 2005).

Using the method presented by Frazer et al. (2014), the total number of moles of Mg required for dolomitization can be calculated. The total volume of dolomite is estimated to be $1,800,000 \text{ km}^3$ based on dimensions of 200 km $\times$ 125 km $\times$ 0.1 km (Bodin et al., 2010) and an estimated initial porosity of 40%. This gives a total mass of $5.14 \times 10^{18} \text{ kg}$ of dolomite based on a mineral density of $2.86 \text{ g cm}^{-3}$. Using a molar mass of dolomite of $0.184 \text{ kg mol}^{-1}$, a total of $2.80 \times 10^{19} \text{ mol}$ of Mg would be needed to completely dolomitize the Zebbag Formation.

Fluid inclusion analysis of marine halite suggests a Cretaceous sea water concentration of Mg of $0.034 \text{ mol L}^{-1}$ (Timofeeff et al., 2006), so a total volume of $8.24 \times 10^{20} \text{ l}$ of Cretaceous sea water would have been required to completely dolomitize the Zebbag Formation assuming 100% efficiency. More realistically, the system would not have been 100% efficient, so this provides a minimum required volume. Biostatigraphic data and the age of sequence boundaries observed at the base of the Rhadouane Member and top of the Gattar Member, indicates that dolomitization must have occurred during a 9 Myr period. This requires at least $91.5 \times 10^{12} \text{ l}$ of sea water to flow through the Zebbag Formation per year. Montanez & Read (1992a) estimated that a flow rate of $5 \times 10^{12} \text{ l}$ could be fluxed through a single peritidal cycle each year in the Devonian Knox Group using measured flow rates through modern day sabkhas (McKenzie et al., 1980). Both the Zebbag Formation and the Knox Group have similar areas (both estimated to be 25,000 km²), and consist of cycles of upward-shallowing peritidal sediments of comparable thickness. This estimates brine flux to be $3.7 \text{ m year}^{-1}$, a reasonable estimate given the modelling work of García-Fresca et al. (2012) and García-Fresca & Jones (2011).

Climate within the study area during the Cenomanian–Turonian at has been modelled as hot and arid (Fig. 2). Sea surface temperatures are predicted to have been between 30°C and 36°C (Schouten et al., 2003; Steuber et al., 2005); an optimum temperature for dolomitization to take place, without precipitation of anhydrite cements. Above this temperature, the amount of anhydrite that is precipitated, even from mesohaline brines increases, potentially creating significant barriers to dolomitizing fluid flux (Jones & Xiao, 2005; Al-Helal et al., 2012). Further support for appropriate climate conditions comes from global circulation modelling, which indicates that wind direction was towards the south-west, forcing waves and currents onto the Saharan shield, thereby maintaining a constant supply of sea water (Poulsen et al., 1998; Ufnar et al., 2008).

**Rhadouane and Kerker members**

The Rhadouane and Kerker members comprise stacked cycles capped by peritidal facies, and the upward-increase in ooids and microbialites until the middle of the Kerker Member suggests that salinity was increasing until sea level began to rise during deposition of the uppermost Kerker Member. Texturally distinct dolomitized clasts and dolomitized matrix within brecias formed at emergent surfaces suggests dolomitization took place prior to and immediately following exposure. Each cycle is therefore interpreted to have been dolomitized as a result of individual pulses of dolomitizing fluids supplied during deposition of the shallowest part of small-scale upward-shallowing cycles (Fig. 13A). Refluxing brines can cause dolomitization of the uppermost part of upward-shallowing cycles (Montanez & Read, 1992a) as a result of sinking of brines through peritidal cycles, although recent work has also shown that the more porous and permeable beds within the lowermost part of cycles can become preferentially dolomitized while the upper parts of cycles act as permeability barriers and remain undolomitized (Iannace et al., 2013). In the case of the Rhadouane and Kerker members, repeated fluxing of brines is interpreted to have led to complete dolomitization of the sediment stack as shown by numerical models (García-Fresca & Jones, 2011; García-Fresca et al., 2012). The very shallow, broad and very low angle dip of the carbonate platform, with laterally extensive facies belts, probably meant that brine pools formed and underwent evaporation over a vast peritidal area. Combined with migration of the brine pool during changes in relative sea-level, this may in part explain the lack of spatial variation in dolomite fabric and geochemistry.

In the Rhadouane Member, there are few permeability barriers separating individual cycles. Dolomitization is
therefore interpreted to have occurred as dense brines sank through the platform causing 'top-down' dolomitization. Each pulse of dolomitizing fluids would probably penetrate to depths greater than the previous sedimentary cycle, particularly as most cycles are less than ca 1 m thick, anhydrite cements are absent and dolomitization would modify porosity in such a way that permeability would be increased, up to a porosity optimum (Saller & Henderson, 1998). In the Kerker Member, the high vertical layering of the succession, imparted by marls at the base of upward-shallowing cycles, could have imparted some lateral flow on dolomitizing fluids. Multiple pulses of dolomitizing fluid would need to occur for pervasive dolomitization to occur; hydrogeologic and reactive transport models have shown that repeated pulses of dolomitizing fluids can cause pervasive dolomitization of a sediment stack given sufficient time, porosity and permeability (Garcia-Fresca & Jones, 2011; Garcia-Fresca et al., 2012). The fine-grained texture of many facies in the Rhadouane and Kerker members would have permitted rapid nucleation and dolomitization (Gabbellone & Whitaker, 2016), resulting in very finely crystalline dolomite textures. One dimensional modelling of stacked peritidal cycles indicate that pervasive dolomitization can occur within 1-5 kyr as a result of multiple reflux fronts, although the modelled brines were evaporated to 4× the concentration of sea water (Garcia-Fresca & Jones, 2011). The estimated duration of between 48 and 207 kyr for metre-scale peritidal cycles (Montanez & Read, 1992a; García et al., 1996) suggests that there was sufficient time for brine reflux to cause pervasive dolomitization of the Zebbag Formation. Furthermore, the repeated stacking of similar facies throughout the Rhadouane and Kerker members suggests low amplitude relative sea-level changes, consistent with the greenhouse climate and tectonic stability of the Arabian-Saharan Shield. Many authors have proposed that dolomitization is associated with relative sea-level fall (Mutti & Simo, 1994; Touir et al., 2009). This study clearly shows that within a greenhouse climate, when amplitude of sea-level change is relatively small, dolomitization can still occur during sea-level rise, terminating only during periods of maximum flood.

It has been argued that elevated concentrations of Fe, Mn and enriched \( ^{87}\text{Sr}/^{86}\text{Sr} \) signatures within the Rhadouane Member derive from the interaction of dolomitizing fluids with underlying clastic strata. In this model, downward refluxing dolomitizing fluids would sink through carbonate strata and into the underlying Ain el Guettar Formation. Prominent clay horizons capping the Chennini Member of the Ain el Guettar Formation could have facilitated the lateral flux of brines, and provided a source of Fe and Mn. The decrease in Fe and Mn concentrations in the Kerker Member could reflect a decrease in the concentration of Fe and Mn in the fluid as the flow path extended laterally, as a result of relative sea-level rise, and with distance above the base Zebbag Formation. However, such a model would need to be tested by hydrogeological modelling.

The relatively close proximity of cycles to the brine source and the fine-grained, high reactive surface area of finer sediments that characterize the Rhadouane and Kerker members means sediments could dolomitize quickly (Jones & Xiao, 2005; Al-Helal et al., 2012; Gabbellone & Whitaker, 2016). Two-dimensional modelling of pene- saline reflux and subsurface studies has shown that the amount of dolomitization decreases with distance away from brine source (Saller & Henderson, 1998; Jones & Xiao, 2005; Al-Helal et al., 2012), and so duration of flux must be sufficient to cause dolomitization over a geographically wide area. Reactive transport modelling of mesohaline brines has shown that ca 50% of calcium carbonate can be replaced over distances of up to 6 km and to a depth of ca 500 m over 1 Myr (Jones & Xiao, 2005). Given the estimated duration of ca 2-4 Myr during depo- sition of the Rhadouane and Kerker members, dolomitization would be expected to extend further than 6 km and deeper than 500 m. Within each upward-shallowing succession, the reflux zone would have prograded north- wards, such that the total lateral extent of dolomitization would be significantly more than 6 km. Brine reflux con- tinued until the platform top became completely flooded in the Uppermost Cenomanian. At this point, evaporation was insufficient to form refluxing fluids and so dolomitization via active reflux was shut off (Fig. 13B). This agrees with modelling work conducted on the San Andres Formation (Garcia-Fresca et al., 2012).

**Gattar member**

In the Lower Turonian, rudist bioherms of the Gattar Member were deposited above the Kerker Member, with facies passing southwards into tidal flat deposits (Camoin, 1991; Touir & Soussi, 2003). This platform geometry would have restarted the flux of dolomitizing fluids, from south to north along depositional dip. The lack of evap- orites within the basal Gattar Member, normal marine dolomite major element signatures and only slightly more positive oxygen isotope values, suggests that dolomitization occurred from mesosaline fluids. The uppermost marl bed in the Kerker Member probably acted as a permeability barrier to dolomitizing fluids, focusing fluids laterally and downdip. Furthermore, the grainer sediments at the base of the Gattar Member would have excellent permeability, facilitating the flux of dolomitizing fluids offshore (Fig. 13C). Layered sequences of grainy and muddy layers have been shown to provide an effective
mechanism for driving dolomitizing fluids to a greater distance from source (Al-Helal et al., 2012) despite them becoming less saturated with respect to Mg as a result of dolomite precipitation along the flow path. This, coupled with the coarse-grained sediment texture, resulted in fewer nucleation sites and growth rates of crystals effectively outpaced nucleation rates forming coarsely crystalline Dol-R-2.

Facies progradation within the Gattar Member suggests that the source of dolomitizing fluid moved basinward through time, leading to pervasive dolomitization of the entire Gattar Member (Fig. 13C). A similar situation has been modelled in the San Andres Formation of Texas (Garcia-Fresca et al., 2012). The presence of the Beida Anhydrite facies above the Gattar Member, to the north of the study area, indicates that sea water salinity gradually increased, potentially leading to more effective dolomitization of the platform. Given the poor resolution of biostratigraphy in the Gattar Member, it is difficult to estimate how long reflux was maintained. However, using the maximum flooding event at 92.2 Ma (Lüning et al., 2004) and sequence boundary at 91.7 Ma (Camoin, 1991), a period of 500 kyr is estimated. This prolonged period of fluid flow, coupled with facies progradation, would have been sufficient for massive dolomitization over the distance observed, particularly given the hypothesized lateral component to the flow. This is supported by the sharp contact between pervasively dolomitized strata in the Gattar Member and partial dolomitization in the top Kerker Member.

**CONCLUSIONS AND IMPLICATIONS**

Integration of field, petrographical and geochemical data of the Upper Cretaceous Zebbag Formation in southern Tunisia have shown that dolomitization occurred as a result of near surface mesosaline reflux of dolomitizing fluids over a period of less than 9 Myr, during the Cenomanian and Turonian. Despite an apparent global scarcity of platform-scale dolomitization during the Upper Cretaceous, the Jeffara Escarpment of southern Tunisia shows extensive and pervasive dolomitization. This is interpreted to primarily reflect the regional climate. The studied interval of the Zebbag Formation was located within a hot and arid climate belt that resulted in sufficient evaporation of sea water to create mesosaline brines. This occurred along a discrete climate zone north of the hot, humid equatorial conditions that presided across the Arabian Plate, and explains the abundance of dolomitized platforms restricted to the circum-Mediterranean region at this time.

The Saharan Platform was tectonically stable during the Cenomanian–Turonian such that reflux was maintained for prolonged periods of time allowing strata to become pervasively dolomitized. This probably occurred by numerous passes of penecontemporaneous sea water that was slightly evaporated, but rarely to the point of gypsum saturation. Laterally extensive dolomitization was probably further facilitated during the Upper Albian and Cenomanian (Rhodouane and Kerker members) by fluid flux along an underlying Albian sandstone aquifer. Dolomitization was much less pervasive at the Cenomanian–Turonian boundary, when sea-level rise associated with a second-order maximum flooding event resulted in deposition of relatively deep water marls that were probably located far from the source of dolomitizing fluids. Subsequently, during the Turonian, growth and progradation of the carbonate platform and basinward migration of brine pools ensured pervasive dolomitization over distances of several hundred kilometres was re-established. Deposition of the Beida Anhydrites in the uppermost Turonian, which are not seen in the study area, indicates the penecontemporaneous brines may have led to more efficient dolomitization of the uppermost Gattar Member.

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