Diagenetic Geobodies: Fracture-Controlled Burial Dolomite in Outcrops From Northern Oman

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Summary

Diagenetic heterogeneities are difficult to predict in the subsurface. Nevertheless, such heterogeneities can be crucial in hydrocarbon exploration. Diagenetic processes can significantly alter petrophysical properties of reservoir rocks, especially in carbonate rocks because of the reactive nature of the carbonate minerals. Dolomitization [i.e., the transformation of calcite (limestone: Lmst) into dolomite] is a common diagenetic process in carbonate rocks. Resulting dolomite bodies have a different pore network than the original Lmst and respond also differently to tectonic stress causing different fracture networks than in the original Lmst. The paper presents an overview of the learning outcomes gained by studying fracture-related dolomite in outcrops of Oman and subsequent laboratory analysis conducted over the last 4 years. A combined structural, petrographic, and geochemical approach was taken to study three dolomite systems occurring in different stratigraphic host-rock (HR) intervals. Structurally controlled dolomitization (i.e., dolomitization along faults and fractures) typically occurs in burial conditions, and the resulting strong permeability anisotropies caused by the dolomite textures can cause major challenges for hydrocarbon exploration.

Dolomite bodies in the Precambrian Khufai formation are related to N/S to NEE/SSW fractures, whereas dolomite bodies that mainly occur in the Jurassic HRs occur along reactivated WNW/ESE normal faults. These fracture-related dolomite bodies are generally less than 15 m wide, but can be up to a few hundred meters long. Late-diacastic dolomite bodies were also recognized in Permian HRs, where they occur at or close to the contact between Permain Lmst and early-diagenetic dolomite. This late-diagenetic dolomite system can be traced laterally for at least hundreds of meters and occurs in wadis that are approximately 40 km apart. Our data indicate that there were several dolomitization events in the geological history of the succession, generating dolomite bodies with different characteristics. This paper highlights the need to understand timing and structural setting of dolomite bodies in the subsurface to improve reservoir management.

Introduction

Reservoir heterogeneity refers to variations in porosity, permeability, and/or capillarity, laterally and/or vertically (Alpay 1972; Morad et al. 2010). Predicting the distribution of reservoir heterogeneities is important for the prediction of reservoir performance, because the heterogeneity controls fluid flow and recovery factors. The predicted reservoir performance greatly influences the planning of hydrocarbon production. A better understanding of how reservoir heterogeneity is controlled is thus of major economic importance. Heterogeneity in reservoirs is modeled by identifying geobodies in the subsurface. These geobodies are typically defined mainly by depositional facies (Barnaby and Ward 2007; Jung and Aigner 2012; Amour et al. 2013). The impact of diagenesis on reservoir heterogeneity was reported in siliciclastic rocks (Moraes and Srdam 1993; Bowen et al. 2007; Morad et al. 2010; Deschamps et al. 2012; Eugenia Arribas et al. 2012), as well as in carbonate rocks (Kerans 1988; Tyler et al. 1992; Eisenberg et al. 1994; Wang et al. 1998; Hulea and Nicholls 2012) and mixed siliciclastic/ carbonate settings (Borer and Harris 1991). Variations in diagenetic alteration may be linked to variations in depositional porosity and permeability, which led Morad et al. (2010) to propose a predicting tool by correlating the types and distribution of diagenetic processes to the depositional facies and sequence stratigraphic framework in clastic successions. Carbonates have more varied facies and diagenetic patterns than siliciclastics and may thus be more challenging for reservoir evaluation. Carbonate rocks are petrophysically very complex because of the wide diversity of pore types (Lucia 1995), partly caused by the relative instability of carbonate minerals and the impact of diagenetic overprint (Hulea and Nicholls 2012). In this respect, understanding the interplay of depositional and diagenetic controls on rock properties is essential for reservoir modeling (Hulea and Nicholls 2012). Previous work on diagenetic heterogeneities in carbonates found that petrophysical properties can be better grouped by rock fabrics than by strict depositional facies and that stacking of rock-fabric units within a high-frequency cycle can be used to approximate fluid flow and recovery efficiency (Kerans et al. 1994). Post-depositional diagenetic alteration, such as karst development and dolomitization, overprints depositional heterogeneity (controlled by facies composition and architecture), resulting in additional lateral and vertical heterogeneities (Tyler et al. 1992; Eisenberg et al. 1994) and significant reservoir compartmentalization (for example, related to localized karst collapse structures (Kerans 1988)).

Other than being linked to the depositional facies, diagenetic heterogeneities can also relate to structural heterogeneities (Davies and Smith 2006; Guidry et al. 2007; Vandeginste et al. 2013, 2014) that should be captured in realistic geological reservoir models. Generally, fracture networks originate early in the history of the host rock, suggesting that structurally related diagenetic heterogeneities can evolve during early diagenesis (Guidry et al. 2007) and can influence fluid flow for a large part of the burial history of the rock. A reservoir-productivity study on the Suban gas field in Indonesia has shown that bulk-reservoir performance relates to local stress acting on existing faults and fracture-damage zones (Hennings et al. 2012). The reservoir potential was shown to be most enhanced in areas that have a large amount of fractures with high ratios of shear-to-normal stress (Hennings et al. 2012). This paper discusses a type of diagenetic heterogeneity that is clearly templated by structures (i.e., structurally controlled dolomite geobodies). We investigate outcrop examples from several stratigraphic horizons in the central Oman

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Mountains, focusing thereby on the dimensions, the structural setting, and the origin of the fluids. All these factors are important in understanding the structurally controlled dolomitization process that causes diagenetic heterogeneities. Importantly, this type of dolomite body is generally characterized by high porosity (Davies and Smith 2006), and therefore is potentially filled with hydrocarbons (Sagan and Hart 2006; Smith 2006).

**Geological Setting**

The geological setting of fracture-controlled burial dolomite bodies is of key interest because it forms the main control on the dimensions of these bodies. The tectonic history determines several aspects of the fracture network that is associated with the burial dolomite bodies. Understanding the link between the diagenetic and the geological setting can help with predictions of analogous diagenetic heterogeneities in reservoirs. The study area is in the central section of the Al Hajar Mountains (or Oman Mountains), in the Jebel Akhdar tectonic window that is a geological structure in which erosion or normal faulting produced a hole in the Semail ophiolite and Hawasina nappes (i.e., large sheetlike bodies of rock that have been moved more than 5 km above a thrust fault from their original sites of formation), and thus the underlying autochthonous (i.e., nontransported) Precambrian to Mesozoic rocks crop out (Fig. 1). During Late Precambrian extension (i.e., tectonic stress associated with stretching of the crust or lithosphere) in the Arabian-Nubian Shield, Gondwana formed (Stern 1994) marking the Arabian plate by a passive continental margin on the southern side of the Paleothys Ocean for most of the Paleozoic (Stampfli et al. 1991). The breakup of Gondwana started in the Late Permian with the formation of the Neothys Ocean (Stampfli and Borel 2002; Stampfli and Kozur 2006). Northern Oman was on a NW-trending passive continental margin of the Arabian plate during most of the Mesozoic, but it evolved into a compressional margin during the Late Cretaceous as a result of Cenomanian intraoceanic subduction (i.e., part of oceanic plate moving under another part of oceanic plate) and Middle Turonian to Early Campanian SW-directed obduction (i.e., overthrusting of oceanic lithosphere onto continental lithosphere) of the adjacent oceanic crust of the Neothys during the convergence of Gondwana and Laurasia (Glennie et al. 1974; Hacker 1994; Stampfli and Borel 2002; Breton et al. 2004). This Alpine Phase I obduction led to regional downbending of the continental plate with NE/SW extensional strain and the formation of W- to NW-trending normal and transtensional faults (Loosveld et al. 1996; Filbrandt et al. 2006), but also led to Semail ophiolite obduction associated imbrication and predominantly SW-verging thrusting of the Arabian platform margin that peaked in the Early Campanian. The Alpine Phase II (Eocene to Pliocene), related to the separation of the Arabian from the African plate, involved NE/SW compression leading to overprinting of earlier extensional structures in the Oman Mountains by folding and thrusting (Loosveld et al. 1996). Doming of Jebel Akhdar may have started early after the emplacement of the Hawasina and Semail nappes during latest Cretaceous and Paleocene time and was probably enhanced by later Tertiary compression (Searle 1985; Michard et al. 1994).

**Methodology**

We explored the whole of the Jebel Akhdar tectonic window for the occurrence of late-diagenetic dolomite bodies, mainly by driving through all wadis and mountain roads and observing cliffs, as well as by hiking the mountain flanks. Although early-diagenetic, stratabound dolomite bodies were also recognized, these geobodies are not discussed in detail in this paper, because our focus is on late-diagenetic, structurally controlled dolomite geobodies. The latter were identified in the field, and their dimensions were measured on the accessible outcrops with a surveyor’s tape. Their occurrence was mapped by recording their global-positioning-satellite locations. In addition, late-diagenetic dolomite geobodies on inaccessible outcrops were recorded on photopanoramas, and for cliff faces less than 1 km away, dimensions were calculated from angle and distance measurements with a tripod, compass, and Swarvoski 8 × 30 monocular rangefinder. Several fracture analyses were carried out by measuring strike and dip of each fracture along scan lines with a Brunton geological compass. Additional information, such as the width, infilling, geometry of the fracture, and distance between fractures, was recorded also. Limestone (Lmst) and dolomite samples were collected in beds of Neoproterozoic age in Wadi Bani Awf, of Permian age in both Wadi Sahlan and Wadi Mistal, and of Jurassic age in Wadi Mistal, as indicated in Fig. 1. Hand samples were cut, finely polished, etched with 1-M hydrochloric acid, and stained with Alizarin Red S and potassium ferricyanide to distinguish calcite and dolomite and their ferroan equivalents (Dickson 1966). Thin sections were prepared, halves were stained, and they were studied with a Zeiss Axioskop 40 polarization microscope and a CITL Cathodoluminescence MMK-2 stage mounted on a Nikon Eclipse 50 microscope. Dolomite and Lmst samples were also investigated for their geochemical elemental composition and stable carbon, oxygen, and strontium isotopic composition, following procedures explained in Vandeginste et al. (2013).
Results

Dolomite Geobody Types and Dimensions. Three different types of dolomite bodies were recognized. The first type (Type 1) has a dark-reddish weathering color and is hosted in the Neoproterozoic Khufai formation in Wadi Bani Awf (Fig. 2a). These dolomite bodies, which are high angle to perpendicular to bedding, follow NNE-trending fractures along hundreds of meters and are up to approximately 15 m wide. The second type (Type 2) has a brownish-red weathering color and occurs typically at the contact between limestone (Lmst) and overlying early-diagenetic dolomite in the lower part of the Khuff equivalent formation (Lower Permian). This type was observed in Wadi Mistal, Wadi Sahtan (Fig. 2b), and in several smaller wadis. These dolomite bodies are laterally more extensive (one can trace them for nearly a kilometer in outcrops) and are up to approximately 60 m thick (vertically). The third type (Type 3) of dolomite body was identified in both Permian and Jurassic host rock (HR) in Wadi Mistal (Fig. 2c). This type is characterized by a reddish-to-rusty weathering color and is strongly affected by dedolomitization (Vandeginste and John 2012). This dolomite type occurs along WSW-trending fractures and normal faults (Fig. 3). These geobodies are up to approximately 100 m long and a few meters wide. The dolomite body is several meters wide where it has replaced Lmst HR, whereas its lateral extent is very limited where it cuts early-

Fig. 2—Field outcrop photographs. Trees (2 to 3 m high) for scale. Late-diagenetic dolomite bodies are outlined by white transparent line on the pictures. (a) DT1 in Lmst HR of the Neoproterozoic Khufai formation in Wadi Bani Awf. (b) DT2 at the contact between Lmst and overlying ED dolomite HR of Early Permian age, unconformably overlying Precambrian siliciclastic host rock (PHR) in Wadi Sahtan. (c) DT3 in Lmst and stratabound ED dolomite HR of Jurassic age in Wadi Mistal.

Fig. 3—Rose diagrams of strike of fractures analyzed in transects along stratigraphic beds crosscutting both Lmst and dolomite in the Neoproterozoic Khufai Formation in Wadi Bani Awf, in the Lower Permian Khuff equivalent formation in Wadi Mistal, and in the Jurassic Sahtan Group in Wadi Mistal.
diagenetic (ED) dolomite HR beds; in the latter case, the late-diagenetic dolomite occurs in small veins rather than meter-scale replacement bodies. Dolomite-to-Lmst contacts are sharp for all types. However, the Type-2 dolomite contact with ED dolomite in Permian HR is gradational.

Dolomite bodies of both the second and third type occur in Permian HR in Wadi Mistal. On the basis of field observations, it is clear that the third dolomite type (i.e., reddish-to-rusty WNW-trending dolomite) crosscuts the second dolomite type (i.e., laterally extensive brownish-red dolomite).

Fractures. Fracture-density histograms are presented for transects across late-diagenetic dolomite Type 1 (DT1) and Type 3 (DT3) and their HR (Fig. 4). The majority of the fractures are less than 0.5 cm wide, and most are completely cemented with calcite, dolomite, or both. The fractures are up to several meters or tens of meters long (laterally), and they generally do not extend vertically beyond the thickness of the bed and are thus bed-bound. The results of the fracture analyses show that the highest density of fractures occurs close to the main fracture within the late-diagenetic dolomite Type 1. The majority of fractures are less than 0.5 cm wide, and most are completely cemented with calcite, dolomite, or both. The fractures are up to several meters or tens of meters long (laterally), and they generally do not extend vertically beyond the thickness of the bed and are thus bed-bound. The results of the fracture analyses show that the highest density of fractures occurs close to the main fracture within the late-diagenetic dolomite Type 1. There is no clear trend in terms of fracture width along this transect in Type 1 dolomite and its HR. A higher abundance of open fractures (as well as wider fractures) close to the main fracture is also observed in DT3 in Permian HR, but this is not confirmed for the same dolomite type in Jurassic HR. For DT3, a higher density of fractures occurs at the edges of the dolomite body rather than in the center, as was the case for Type 1. The most-significant difference in fracture density is measured in Jurassic HR with a higher density of fractures (approximately six times more) in stratabound ED dolomite than in Lmst [i.e., approximately 15 to 95 fractures/m in stratabound dolomite vs. 1 to approximately 15 fractures/m in Lmst (for scanlines of the same orientation in Jurassic HR)]. In all cases, the strike and dip of the open fractures are similar to those of the cemented fractures. The main fracture set of the open fractures has an orientation similar to that of the main dolomite body, and an additional minor fracture set could also be separated. Details of the statistical analysis of the structural orientation of the open fractures are presented in Table 1.

Lmst and Dolomite Textures. The Lmst HR and the respective dolomitized equivalent are presented as pairs in Fig. 5 [i.e., Precambrian HR and dolomitized equivalent (Fig. 5a, 5b), Permian HR, and dolomitized equivalent (Fig. 5c, 5d)].
HR and dolomitized equivalent (Fig. 5c, 5d), and Jurassic HR and dolomitized equivalent (Fig. 5e, 5f). The Lmst texture varies between stratigraphic beds, but is generally difficult to recognize because of microsparitization. The original texture of the Precambrian HR is particularly faint because of thick (up to 25 μm) cleavage twin planes, but is identified as a peloidal grainstone (Fig. 5a). The Permian HR is a bioclastic packstone with benthic foraminifera, small gastropods, shell and coral fragments (Fig. 5c). The Jurassic HR consists of mudstone, wackestone, and packstone with one or more of the following components: shell fragments, crinoids, gastropods, sponge fragments, benthic foraminifera, or peloids (Fig. 5e). There are also a few siliciclastic beds and some stratabound dolomite beds in the Jurassic outcrop.

Both the first dolomite type (NNE-trending dark-reddish weathered dolomite bodies in Precambrian HR) and the third type (WSW-trending reddish-to-rusty dolomite bodies in Permian and Jurassic HR) are mainly composed of fabric-destructive zebra dolomite in which gray medium-crystalline (150 to 400 μm) and white coarse-crystalline (500 to 2000 μm) dolomite bands alternate (Fig. 5b, 5f). In the center of white bands, calcite cement occupies former pore space on top of saddle dolomite crystals. Also, the second dolomite type (laterally extensive dolomite bodies at the Lmst-to-ED dolomite contact in Permian HR) contains zebra dolomite at several sites. However, zebra dolomite is not predominant in this case, but gray medium-crystalline dolomite prevails and both fabric-destructive (Fig. 5d) and fabric-preserving textures are recognized.

Geochemical Signature. Each of the three dolomite types has a distinctive iron (Fe) vs. manganese (Mn) content (Fig. 6). The Fe content is lowest (up to approximately 2%) in Type 2 dolomite, slightly higher (2 to 4%) in Type 1, and highest (3 to 9%) in Type 3 dolomite. Despite the differences in Fe content, the Mn content is more similar in the three types and ranges from approximately...
Fig. 6—Iron (Fe) vs. manganese (Mn) crossplot of dolomite types. Dashed lines indicate trendlines representing the Fe vs. Mn ratio in each of the three different dolomite types. The Fe/Mn ratio decreases from Type 3 to Type 1 to Type 2 dolomite. Data from Type 3 dolomite in Jurassic HR are from Vandeginste et al. (2013).

All three dolomite types have a δ13C signature that is similar to that of original marine Lmst of the respective HR age (Fig. 7). In contrast, the δ18O signature of Type 1 dolomite is approximately 10% more depleted than the original signature of the Neoproterozoic marine Lmst, and also Type 3 dolomite has a more-depleted δ18O signature than the original Permian and Jurassic HRs in which they occur (Fig. 7). However, Type 2 dolomite has a δ18O signature similar to that of Permian marine Lmst, and lower δ13C values seem to correlate with lower δ18O values within this range for marine Lmst.

The 87Sr/86Sr isotopic signatures in all three dolomite types display a 87Sr enrichment compared with the signature expected for marine Lmst of their respective HR age. Nevertheless, there are clear discrepancies in the significance of this enrichment between the different dolomite types. Type 1 dolomite shows an increase of approximately 0.001 for the 87Sr/86Sr ratio and Type 2 dolomite an increase of approximately 0.002, whereas Type 3 dolomite shows an increase of 0.005 up to 0.012 (Fig. 8). It is clear that Type 3 dolomite follows a 87Sr/86Sr vs. δ18O trend that does not change with the formation in which it occurs (i.e., Permian or Jurassic strata).

**Discussion**

**Dolomite Types and Spatial Distribution.** Detailed fieldwork led us to distinguish three types of late diagenetic dolomite in the Jebel Akhdar tectonic window in northern Oman. These dolomite types differ in dimension or structural orientation and have a slightly different weathering color. The fracture-related dolomite type in Neoproterozoic host rock (HR), defined as Type 1, has NNE-trending bodies that are hundreds of meters long and up to approximately 15 m wide. The dolomite bodies, which we defined as Type 3, occurring in both Permian and Jurassic HR, are up to approximately 100 m long and a few meters wide. Type 3 dolomite bodies are also mainly controlled by structures, such as a reactivated normal fault (Vandeginste et al. 2013), and their orientation is WNW, approximately perpendicular to the Type 1 dolomite trend. For dolomite Types 1 (DT1) and DT3, it is thus clear that dolomitization took place mainly along the faults or fractures, forming a dolomitization halo around the respective structure, and that the length of the dolomite body along the structure is at least five times greater than the width for the majority of these bodies. This indicates that fluid flow focused along the fault without much penetration into the HR matrix, which, in turn, may suggest that the matrix had a low permeability at the time of dolomitization. High length/width ratios are typical for dimensions of structurally controlled hydrothermal dolomite bodies. Most of the...
documented hydrothermal dolomites reservoirs have larger dimensions than Type 1 and Type 3 dolomite bodies in northern Oman, though. Some of the largest, the Albion-Scipio reservoir in the Orдовician Trenton-Black River formation and the Clarke Lake reservoir in the Devonian Slave Point formation, are 45 and 35 km long and up to 1 and 7 km wide, respectively (Davies and Smith 2006). The Albion-Scipio hydrothermal dolomite field is localized at sags linked to a major strike-slip fault, and dolomitization was mainly constrained by the damage zone of this fault because fluids did not penetrate the HR matrix much (Davis and Smith 2006). The location and dimension of the hydrothermal dolomite bodies thus give information on paleofluid pathways, which one could extrapolate to extract reservoir implications. In a similar way, because paleoconditions generated massive fluid flow resulting in dolomitization, current stress fields and structures can cause major wellbore instability and a loss of drilling-fluid circulation in the annulus. Natural fractures can be “stress-sensitive” when they are hydraulically conductive because of their suitable orientation for failure (shear or tensile) in the present-day stress tensor (Finkbeiner et al. 1997). A study by Haghi et al. (2013) concluded that both stress-sensitive and stress-insensitive fracture sets have significant influence on hydraulic conductivity.

The late-diagenetic dolomite occurred mainly at the contact between limestone (Lmst) and overlying early-diagenetic (ED) dolomite in Lower Permian HR, which we defined as Type 2 dolomite, is laterally extensive along at least approximately 1 km and seems to be more controlled by lithology or ED contact, whereas the control by fractures is less clear in this case. This implies that dolomitizing fluid flow for this Type 2 dolomite did explore a matrix that must have been permeable enough to allow sufficient fluid flow and input of magnesium for dolomitization to take place. We hypothesize here that, given a source of dolomitizing fluids and a driving mechanism for fluid flow, it is permeability that plays a key role in determining the sites where late-diagenetic dolomite bodies form. However, in the case of ED dolomite, dolomitization at low temperature is more prone to kinetic inhibition, the grain size and organic content in the Lmst may play an important role as well, in addition to permeability. The impact of organic matter was demonstrated for dolomite-type-experiments at low temperature (Roberts et al. 2013), and also the impact of the crystal size of the reactant was shown in laboratory experiments (Sibley et al. 1987).

**Origin of Dolomite Types and Timing of Dolomitization Events.** The distinction between the three dolomite types is also clear on the basis of their geochemical signature, because each dolomite type shows a distinct signature in δ13C, δ18O, δ34S, and 87Sr/86Sr (Figs. 6 through 8). This indicates that each of the dolomite types was formed by different dolomitizing fluids, and thus likely formed at a different time. Crosscutting relationships showed that dolomite Type 3 (DT3) is younger than DT2. DT1 is interpreted to be the earliest phase, and certainly predates DT3, because (1) it was found in Precambrian HRs and thus has the potential to be the oldest phase; (2) the fracture-related dolomite bodies are folded, and thus dolomitization must have preceded some folding; (3) dolomitization occurred in between the onset and termination of bedding-parallel stylolitization, and hence, most likely before the deep burial related to the Alpine Orogeny; (4) DT1 was observed only in Precambrian rocks, and these rocks were affected by intense deformation related to the Hercynian Orogeny during Carboniferous time (in contrast to the Permian and Jurassic HRs) (Vandeginste et al. 2014). The 87Sr/86Sr ratios show that DT1 is least enriched in 87Sr, whereas DT3 shows very high 87Sr/86Sr ratios (Fig. 8). Assuming that the derived chronology of the three dolomite types is correct, this shows then an increasing 87Sr enrichment in the dolomitizing fluids through geologic time (i.e., more interaction of the dolomitizing fluids with siliciclastic units or Precambrian basement). However, this trend is not confirmed by the iron content, which is lower in Type 2 than in Type 1 dolomite (Fig. 6). The average δ13C signature decreases from Type 1 to Type 2 to Type 3, but these signatures relate to the δ13C signature of the original marine limestone (Lmst) of the respective HR age (Fig. 7), and thus indicate HR buffering for the stable carbon isotope signature recorded in the dolomite. In contrast, the δ18O values measured in DT1 and DT3 are much more depleted than the signature of marine Lmst of the respective HR age (Fig. 7). This is most likely related to dolomitization at high temperature, but also the δ18O signature of the dolomitizing fluid will affect the δ18O signature measured in the dolomite. Most of the stable oxygen isotopic values of DT2 plot within the signature for Lower Permian age (Fig. 7). On the basis of the different mineralogy and thus different fractionation of oxygen isotopes between seawater and carbonate, the dolomite δ18O values are still more depleted than the expected marine dolomite signature of Lower Permian age, which would be approximately 3% higher than that of Lmst, on the basis of equations from Kim and O’Neil (1997) for calcite and Vasconcelos et al. (2005) for dolomite. Thus, even for DT2, formation at slightly elevated temperature is expected assuming a seawater-derived formation fluid.

In terms of absolute timing, DT3 formed around Santonian time (Late Cretaceous) during tectonic compression before Cambodian obduction of the Semail ophiolite, as proposed by Vandeginste (2013). Type 3 dolomitization fluids were warm and show evidence of interaction with Precambrian sandstone or the crystalline basement, mainly on the basis of their high 87Sr enrichment and iron and manganese content. These fluids exploited normal faults that developed because of extensive forces in the subducting slab; these faults thus trend parallel to the continental margin (Vandeginste et al. 2013). Type 2 dolomitization occurred between Triassic ED dolomitization and Santonian Type 3 dolomitization, on the basis of crosscutting relationships. Type 1 dolomitization is most likely associated with the Hercynian Orogeny during Carboniferous time.

**Dolomitization and Implications for Reservoir Properties.** Good reservoir properties in dolomite bodies of burial origin are mainly linked to two factors. First, it was shown that burial dolomite is more prone to fracturing than its Lmst equivalent because of its crystalline nature that enhances a brittle behavior during deformation (Sinclair 1980). It was reported that dolostone reservoirs commonly have lower matrix porosities and permeabilities than Lmst reservoirs but higher fracture porosities and permeabilities (Schmoker et al. 1985). Amthor et al. (1994) suggested that permeability of Lmst vs. dolostone depends on depth and that dolostone is more permeable than Lmst at depths of more than 2 km. The trend of more fractures in dolomite than in Lmst is also confirmed by our results. The ED dolomite has a fracture density that is approximately six times higher than the Lmst in the Jurassic beds studied. Also the late-diagenetic dolomite Type 1 (DT1) and DT3 contain a higher density of fractures and of open fractures than their Neoproterozoic and Permian Lmst HR, respectively. These results thus show the importance of defining dolomite bodies as geobodies that can contribute to the heterogeneity in reservoirs, because open fractures will influence permeability. Second, the influence of hydrothermal fluids seems to be important for the generation of the late-diagenetic dolomite bodies. In this case, hydrothermal dolomitizing fluids migrated along faults or fractures in Lmst. Several dolomitized carbonates of hydrothermal origin have good reservoir characteristics (Davies and Smith 2006; Sugar and Hart 2006; Wiesbicki et al. 2006). In these examples, the development of good reservoir properties is generally associated with the reactivation of faults or migration of corrosive fluids. Typical textures in these hydrothermal dolomites show vuggy porosity, zebra dolomite, and breccia textures. However, porosity in these dolomitized zones could be occluded by extensive dolomite cementation (i.e., overdolomitization). The key to create or preserve good reservoir quality seems to be to maintain a balance between porosity generation by dilational fracturing and/or carbonate dissolution, and a lesser degree of dolomite cementation (and potentially later, calcite or quartz cementation). These features are intrinsic to the dolomitization
process itself (i.e., the tectonic stress fields and amount, duration, and chemical composition of the fluids exploiting the structures). This shows that understanding the tectonics or structural development and potential reactivation as well as the chemical composition, temperature, and migration of basinal fluids is critical in predicting the reservoir properties of burial dolomites, and that thus a good geological insight is important in well planning and engineering of hydrocarbon-production plans.

To understand the dolomitization process in the context of tectonics and fluid flow, an additional challenge with outcrop analog studies is reconstructing the subsurface equivalent (i.e., stripping the nonrelevant uplift and surface-weathering history from the resulting outcrops). For example, if calcite occludes pore space in the center of zebra-dolomite bands, it is of major importance to determine the origin of this calcite (i.e., whether this calcite formed in deep burial conditions or by meteoric fluids in the near-surface environment upon uplift). Impact of surface weathering on DT3 is reported in Vandeginste and John (2012). The latter study demonstrated significant dedolomitization related to near-surface conditions and resulting instability of the iron-rich dolomite, and a clear control of climate on dedolomitization. Even regions that experience a high degree of aridity today, such as Oman, could have experienced a much more active hydrological cycle in the past, and this needs to be taken into account when looking at outcrop analogs. Similarly, other studies developed a “Standard Property Calculator” to strip back all late-diagenetic changes from outcrop analogs, to approximate conditions that are specific for the reservoirs and thus only taking into account the (early) diagenetic processes until the burial reservoir conditions (Benson et al. 2014).

The Role of Fractures in Reservoir Heterogeneity. As shown previously, fractures and faults play an essential role with respect to reservoir quality of dolostones; both predolomitization and post-dolomitization fractures are important. Larger structures and preferentially faults rather than fractures are of interest for channeling dolomitizing fluids in the early stages of dolomitization, because fault activity can trigger fluid flow (Sibson 1992) needed for the delivery of magnesium (Mg) to the site of dolomitization. Hydrothermal dolomite bodies testify to hydrothermal fluid flow in fractures, synchronous structural features, fluid-flow channeling, and dolomitization linked to a tectonic control (Iriarte et al. 2012). Hereby, fluid circulation concentrated preferentially in more-fractured areas with increased permeability and in extensional chimneys for the Asón Valley dolomite bodies (Iriarte et al. 2012). Diagenetic dolomitization reactions resulting from fluid interaction with the host Lmst along the fault result in dolomite bodies with different petrophysical properties than the host Lmst (Lucia 1995). Within these bodies, the diagenetic textures and chemical composition may be different closer to the fault than away from the fault, with a gradual change in diagenetic textures (Wilson et al. 2007; Sharp et al. 2010). This gradual change in textures may be present in large (hundreds of meters to kilometer size) dolomite bodies, but may be minimal in smaller (meter-scale wide) dolomite bodies that are mainly defined by a halo along the main structure (fault or fracture). Characteristics of predolomitization faults and fractures, such as orientation and transmissivity, can thus act as a template for structurally controlled dolomite bodies. Understanding the predolomitization fracture network thus provides information on paleofluid-flow processes, from which we can then derive insight into current fluid-flow processes. A significant challenge in this workflow is some obliteration of the original (predolomitization) fracture network by the generally fabric-destructive replacement process of hydrothermal dolomitization.

The second type of fractures (i.e., post-dolomitization fractures) can affect the reservoir heterogeneity because dolomite bodies can react differently to applied stress than the surrounding Lmst. The crystalline nature of dolostone links to its brittle behavior, and it will generally fracture more rapidly than Lmst under a certain applied stress (Sinclair 1980). Our results have clearly demonstrated this in the comparison between Jurassic ED dolomite vs. Lmst beds, with a fracture density that was approximately six times higher. In this case, the dolomite bodies will act as a template for fracture patterns, which help define reservoir heterogeneity. Also, late-diagenetic dolomite showed a higher fracture density than the Neoproterozoic and Permian HR counterparts. This trend was not confirmed though by the late-diagenetic dolomite in Jurassic HR. We interpret this difference to be linked to the timing of late-diagenetic dolomitization, and hence, the post-dolomitization history. The late-diagenetic dolomite Type 1 (DT1) formed much earlier than the late-diagenetic DT3, and thus underwent a longer burial and tectonic history after dolomitization. DT3 occurs both in Permian and Jurassic HRs; in this case, the fracture pattern in the dolomite bodies in the stratigraphically lower Permian host rock may reflect the impact of the deeper burial compared with that in the Jurassic beds.

Conclusions

The prediction of reservoir heterogeneity is of major importance in the planning of hydrocarbon production (Hamilton et al. 1998; Barton et al. 2004; Sech et al. 2009). This heterogeneity has three main components (i.e., depositional, diagenetic, and fracture heterogeneity). Although the depositional lithology forms the foundation and is defined from deposition onwards, both diagenesis and fracturing can affect these depositional layers throughout the geological history of the rocks. Moreover, there is an important interplay between fractures and diagenetic products, with multiple feedback mechanisms between fracturing and dolomitization and likely several dolomitization “cycles” related to larger regional tectonics and fluid-flow migration. A thorough understanding of the region by a multidisciplinary approach is key to a better prediction of reservoir heterogeneity.

This study has illustrated how different diagenetic dolomite geobodies can be distinguished by their link with structures and their geochemical signature. This information helps in the reconstruction of paleofluid migration. The insights gained from this and similar studies can then be extrapolated to derive more-global information on the interplay between depositional facies, fractures, and diagenetic products. Moreover, this study has shown the clear impact of dolomitization on fracture distribution, and provided quantitative data on these outcrops that may be analogs to subsurface reservoirs.

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References


Barton, M.D., Tyler, N., and Angle, E.S. 2004. Facies Architecture and Permeability Structure of Valley-Fill Sandstone Bodies, Cretaceous Ferron Sandstone, Utah. In Regional to Wellbore Analog for Fluvial-


Sinclair, S.W. 1980. *Analysis of Macroscopic Fractures on Teton Anticline, Northwestern Montana,* Texas A&M University, College Station, Texas.


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