Cambridge Carbonates Ltd
Expertise in carbonate and evaporite systems

CONFIDENTIAL

Multiclient report sold to:

XXX

2018

Julie Dewit, Pete Gutteridge, Jo Garland and Sarah Thompson

Hydrothermal, burial and fracture-related dolomites: insights into reservoirs and analogues

1. INTRODUCTION

Carbonate reservoirs are infamous for their complexity. The combination of depositional facies and early diagenesis related to local depositional environments and late diagenetic overprint result in highly heterogenous reservoirs. Diagenetic processes such as dolomitisation can have local to large scale positive or negative effects on the porosity and permeability of carbonate rocks. Although the general effect of dolomitisation on reservoir properties is often debated, many hydrocarbon reservoirs are found in dolomite rocks (Sun, 1995). In North America, 80 % of the recoverable oil and gas reservoirs are hosted by dolomites and up to 50 % of the world's carbonate reservoirs are dolomites (Zenger et al., 1980). This can partly be explained by the fact that dolomite is less susceptible to mechanical compaction and more brittle than limestone.

In this report, the focus lies on fracture-related dolomite reservoirs, i.e. dolomites formed as the result of the interaction of a limestone host rock with a fluid circulating through faults and fractures in shallow to intermediate burial conditions. These dolomites are generally coarse crystalline and characterised by well-connected intercrystalline pores, large vugs and fractures. Excellent fracture-related dolomite reservoirs occur in a variety of settings world wide, e.g. Albion-Scipio trend (USA); Ladyfern field (Canada); Arab-D reservoir of the Ghawar field (Saudi Arabia); Tawke field (Iraqi Kurdistan) and many more.

The definition of the fracture-related dolomites in this report is kept descriptive on purpose because it allows us to focus on the important characteristics of fracture-related dolomite resevoirs, such as their association with faults and fractures, their size, petrophysical characteristics and production history. Some fracture-related dolomites discussed in this report are also known as “hydrothermal dolomites”. Since this definition has a genetic connotation its interpretation may vary depending on the author. Davies & Smith (2006) define hydrothermal dolomite as “dolomite formed under burial conditions commonly at shallow depths by typically very saline fluids with temperatures and pressures higher than the ambient temperature and pressure of the host formation". Machel & Lonnee (2002) are more specific in their definition and define hydrothermal dolomites as dolomites formed by a fluid that is at least 5 – 10 °C hotter than the host rock at the moment of dolomitisation. In addition, the latter also define geothermal dolomites formed by a fluid that has the same temperature as the host rock at the moment of dolomitisation and hydrofrigid dolomites formed by a fluid which is cooler than the host rock at the moment of dolomitisation. The problem with the definition introduced by Machel & Lonnee (2002) is that it is often difficult to accurately define the ambient temperature of the host rock and of the dolomitising fluid at the time of dolomitisation. The fracture-related dolomites as defined in this report can, but are not necessarily, hydrothermal *sensu* Machel & Lonnee (2002), nevertheless, they are all characterised by a close association with faults or fractures and are relatively coarse crystalline.

The first commercial hydrocarbon discovery made in a carbonate reservoir was in fact in a fracture-related dolomite body. This field, known as the Lima-Indiana trend, was discovered in 1880. The fracture-related dolomite reservoirs of this trend developed in the Ordovician Trenton – Black River Group, which hosts many of the fracture-related dolomites of the USA (see also section 5.1). It took many years before the nature and characteristics of the dolomites of the Lima-Indiana trend were understood and more discoveries were made in the same play. Even after the link between structural elements and fracture-related dolomites was established fracture-related dolomites were considered too risky as exploration targets before 1980 because they were difficult to identify and image using seismic and other exploration techniques (Hurley & Budros, 1990). As exploration techniques improved, interest in the under-explored fracture-related dolomite reservoirs rose. Over the last two decades, they received renewed attention due to new discoveries including the Ladyfern field discovered in 2000 in British Columbia, which was the largest gas field found onshore Canada in 20 years (Slater & Smith, 2012), and successful enhanced recovery strategies applied to previously abandoned fields such as the Crystal and Vernon fields (Wood et al., 1997).

In order to be able to predict the location and characteristics of fracture-related dolomite bodies it is essential to understand the parameters controlling their development. As stated by Smith (2006), during exploration for fracture-related dolomite reservoirs some wells are geological successes, i.e. fracture-related dolomite is encountered, but economic failures, i.e. the dolomite is tight. The challenge with fracture-related dolomite bodies lies not only in predicting the stratigraphic and structural framework in which they occur, but also in the quality of the reservoir rocks which can vary across dolomite bodies. Not all dolomite bodies form in the same way and many factors such as depositional environment, heterogeneities in the host rock and tectonic regime can influence the flow path of dolomitising fluids. Therefore, dolomite bodies of different sizes, geometries and characteristics develop.

Understanding the occurrence of dolomite bodies is also important for reservoir management since fracture-related dolomites are more intensely fractured than limestones at the same burial depth or in the same structural setting. Some fracture-related dolomite reservoirs are classified as Type II fractured reservoirs according to Nelson (2001), e.g. the Qamchuqa Formation of the Taq Taq field (see section 6.1.4). In addition, high-permeability zones which can occur in fracture-related dolomite reservoirs or reservoir zones affected by fracture-related dolomitisation need to be taken into account during production to prevent early water break-through and during enhanced oil recovery. For example, dolomite will react less rapidly than limestone to an acid treatment which could result in uneven effect in mixed limestone-dolomite reservoirs (Cantrell et al., 2004).

Possessing a good understanding of fracture-related dolomites is important in current exploration strategies. Many recent discoveries in underexplored areas have been made in fracture-related dolomites (e.g. onshore SE Mexico) or consist of different reservoir units of which some are altered by fracture-related dolomitisation (e.g. Tawke, Iraqi Kurdistan). According to some, fracture-related reservoirs may even represent one of the largest untapped resources in mature basins because they are commonly contained in subtle diagenetic traps that are easily bypassed by drilling and fracture-related dolomitisation creates reservoirs where there would be none without the dolomitisation (Patchen et al., 2005).

Since the special volume published in the AAPG Bulletin and edited by Davies & Smith (2006) a lot of additional research has been carried out on fracture-related dolomites. In this report, we present an in-depth review of fracture-related dolomite reservoirs based on well-known analogues of North America and other analogues showcasing key characteristics of fracture-related dolomite reservoirs.

In this review we address:

- The **reservoir characteristics** of fracture –related dolomite, i.e. porosity-permeability ranges, dimensions of fracture-related dolomite bodies, reserves and production rates and how to detect the presence of burial and fracture-fed dolomite in reservoirs

- Where fracture-related dolomites form with respect to the **tectonic setting** and **host rock** in which they develop

- The elements required for fracture-related dolomites to form (**what is the recipe?**).

Because of the complexity of fracture-related dolomite reservoirs both field and outcrop data is highly valuable and is incorporated in this report.

This report is organised in different sections. First, an overview of relevant terms (section 2) and pore and texture classifications relevant for fracture-related dolomites (section 3). Subsequently, we present reservoir characteristics of fracture-related dolomites, i.e. porosity and permeability, effect of fracture-related dolomitisation on the porosity and permeability, reservoir dimensions, volumes, production rates (section 4). Then, fracture-related dolomite reservoirs and analogues are discussed as a function of tectonic setting, i.e. transtensional (section 5), compressional (section 6) and passive margin (section 9). An overview of the fracture-related dolomite cases detaied in this report is given in Figure 1. Finally, we discuss different parameters which have an influence on the fracture-related dolomitisation process (section 8).

Analogue	Reference	Section in report	Sample type	Tectonic regime	Host rock age	Burial depth
Crystal field	Atlas of Michigan Dundee Reservoirs (1997)	5.1.2	cores	transtensional	Devonian	725 m
Ramales Platform	Dewit (2012)	5.4	plug	transtensional	Cretaceous	outcrop
Anaran outcrop	Lapponi et al. (2011)	6.1.1	plug	compressional (FTB)	Cretaceous	outcrop
Subsurface example: Iraqi Kurdistan	in-house study	6.1.5	plug	compressional (FB)	Cretaceous	1400m
Rosevear	Saller et al. (2001)	6.2	cores	compressional (FB)	Devonian	3300 m
Jurassic onshore southern Mexico	in-house study	6.3	plug	compressional (FB)	Jurassic	4000 m
Monte Grappa anticline, Monte Zugna Fm	Ronchi et al. (2012)	6.4	plug	compressional (FB)	Triassic	outcrop
Monte Grappa anticline, Maiolica Fm	Ronchi et al. (2012)	6.4	plug	compressional (FB)	Triassic	outcrop
Reinecke field	Saller & Dickson (2011)	7.1	cores	passive margin	Carboniferous	1300 m
Jurassic Sorrento Peninsula	Galluccio (2009)	7.2	plug	passive margin	Jurassic	outcrop
Lima-Indiana trend	Keith & Wickstrom (1992)		cores	transtensional	Ordovician	400 m

Table 1 Overview of the sources of the porosity and permeability data discussed in this report. FB = Foreland Basin. FTB = Fold-and-Thrust Belt.

4.1.1. *Porosity and permeability range literature*

Porosity and permeability data from published papers, i.e. Keith & Wickstrom (1992), Atlas of Michigan Dundee Reservoirs (1997), Saller et al. (2001), Galluccio (2009), Lapponi et al. (2011), Ronchi et al. (2011), Saller & Dickson (2011) and Dewit (2012), and in-house studies relating to fracture-related dolomites are shown in Figure 7 (see also Table 1 for more details). Based on a total number of 1558 data points, a difference in porosity and permeability distribution for data obtained from plugs (2.5 cm diameter/1 inch) and whole cores (9 cm diameter) can be observed (Table 2). Plug porosity measurements rarely exceed 16 %, while whole core measurements have a much larger range and record datapoints up to 29 % (Figure 7). The difference in average porosity for plugs and cores is 2.8 %. The difference between porosity medians is 2.3 %. Plug permeability is rarely higher than 100 mD, while whole core measurements seem to hit a maximum level of 10 000 mD (Figure 7). On average, core permeability is one order of magnitude higher than plug permeability. The median (used in boxplots) is two orders of magnitude higher for cores compared to plugs. Moreover, the permeability associated with porosities <15 % is higher for whole cores than for plugs (see difference between permeability histograms Figure 7). Plugs characterised by homogenously distributted small pores (i.e. a couple of milimetres across) such as the fracture-related dolomites of the Jurassic Gulf of Mexico (see section 6.3 for more details) have a better overlap with the porosity and permeability of the whole cores. This shows the importance of the elementary representative of the dolomites is inferred to be higher due to fracturing, pore throat size increase and more uniform facies (Qing & Mountjoy, 1989).

Porosity and permeability increase

Many cases of fracture-related dolomites surrounded by tight limestones are known, see Michigan Basin reservoirs (see section 5.1.), Ladyfern field (see section 5.2), Rosevear field (see section 6.2), stratabound dolomite bodies of the Anaran anticline (see section 6.1.1), Ramales Platform (see 5.4), Jurassic onshore southern Mexico (see section 6.3). In these cases, it is fair to conclude that the good reservoir characteristics are due to the fracture-related dolomitisation. In the case of the Anaran anticline the porosity improvement is limited to the the fringes of the major dolomite bodies, but the permeability increase by vertically pervasive fractures is expected to be important (see section 6.1.1.). In the Venetian Alps (see section 6.4), fracture-related dolomites have a higher porosity (on average ~3 % higher) and permeability (on average x 5 as high) compared to the non-dolomitised limestone host rock.

No significant change in porosity and permeability

In general, fracture-related dolomitisation does not result in a significant increase in porosity and permeability when the precursor limestone host rock is very fine grained and/or tight. A small increase in the petrophysical properties can sometimes be observed as a result of the development of intercrystalline pores, but it is insufficient to make it a good reservoir based on matrix porosity. This was onserved by Ronchi et al. (2012) in the Maiolica Formation of the Venetian Alps (see section 6.4).

Negative effect on the reservoir properties

Close to the fluid feeders an "overdolomitisation" of the dolomite bodies can sometimes be observed. The term overdolomitisation refers to the recrystallisation and cementation of an originally porous dolomite by later dolomitisation phases. This negative effect is not observed in the entire dolomitised rock volume. On the scale of

Field	BOPD	MCFGPD	Gravity	Comment	Reference
Lima-Indiana	160 - 300	200 - 300			Keith & Wickstrom 1992
Albion-Scipio (TBR, Michigan Basin)			41 - 43		Hurley & Burdos 1990, Grammer 2007
Scipio discovery well - Houseknecht 1	140				
Confirmation well Scipio - Stephens 1		15000		blowout after hitting LCZ in Trenton	
Albion discovery well - Rosenau 1	200				
production 1958 - 1960	150	200			
production 1960 - 1961	125	165			
production 1961 - 2007≤	100 - 150	150			
Stoney Point (TBR, Michigan Basin)			45		Grammer 2007
Discovery well - Casler 1-30	220			tested at 2000 BOPD, put on production at 220 BOPD	
production	150	175			
Crystal (Dundee Fm, Michigan Basin) - discovery well	740		44		Atlas of Michigan Dundee Reservoirs 1997, Montgomery et al. 1998
production 1930 - 1940	1000 - 9000			high production rates led to rapid water breakthrough and abandonment of most wells within 10 years time	
production 1995	5				
EOR >1995 - horizontal side track wells	5 - 127				
Vernon (Dundee Fm, Michigan Basin)					
initial production <1935	≤5000				
EOR 1981 - 1985 - 16 horizontal sidetrack wells to recovering attick oil	25 - 200			on average each well recovered an additional 30000 bbls of oil	Wood & Quinlan 2003
Winterfield (Dundee Fm, Michigan Basin)	2000			initial production rates	Chittick et al. 1995
Goldsmith/Lakeshore (TBR, Appalachian Basin)	700	1000			Coulter & Waugh 2003
Ladyfern (Slave Point Fm, WCSB) - discovery well		100000			Davies & Smith 2006
40 wells producing in early 2002		785000			
40 wells producing in late 2002		400000			
wells producing from fracture-related dolomite		40000 - 100000			
wells producing from leached limestone		1000 - 20000			
Tawke (Bekhme, Qamchuca & Sarvak Fm, Zagros)	108000				Genel Energy 2017
Taq Taq field (Qamchuca Fm, Zagros)	17000		46 - 48	maximum production rate measured in the Qamchuca Fm	Garland et al 2010, Petroceltic 2011
Reinecke field, South Dome (Cisco Group, Midland Basin)	226	39	42	Wells penetrated top of reservoir to prevent water coning during primary recovery	Chevron 2015, Saller & Dickson 2011
Panuke field					Wierzbicki et al. 2006
discovery well		60000			
additional well encounterig low porosity, but fractured dolomite		53000			
well encountering porous and fractured dolomite		67000			
P6		>30000		production rate of wells associated with fracture-related dolomited which have been affected by a late dissolution phase	

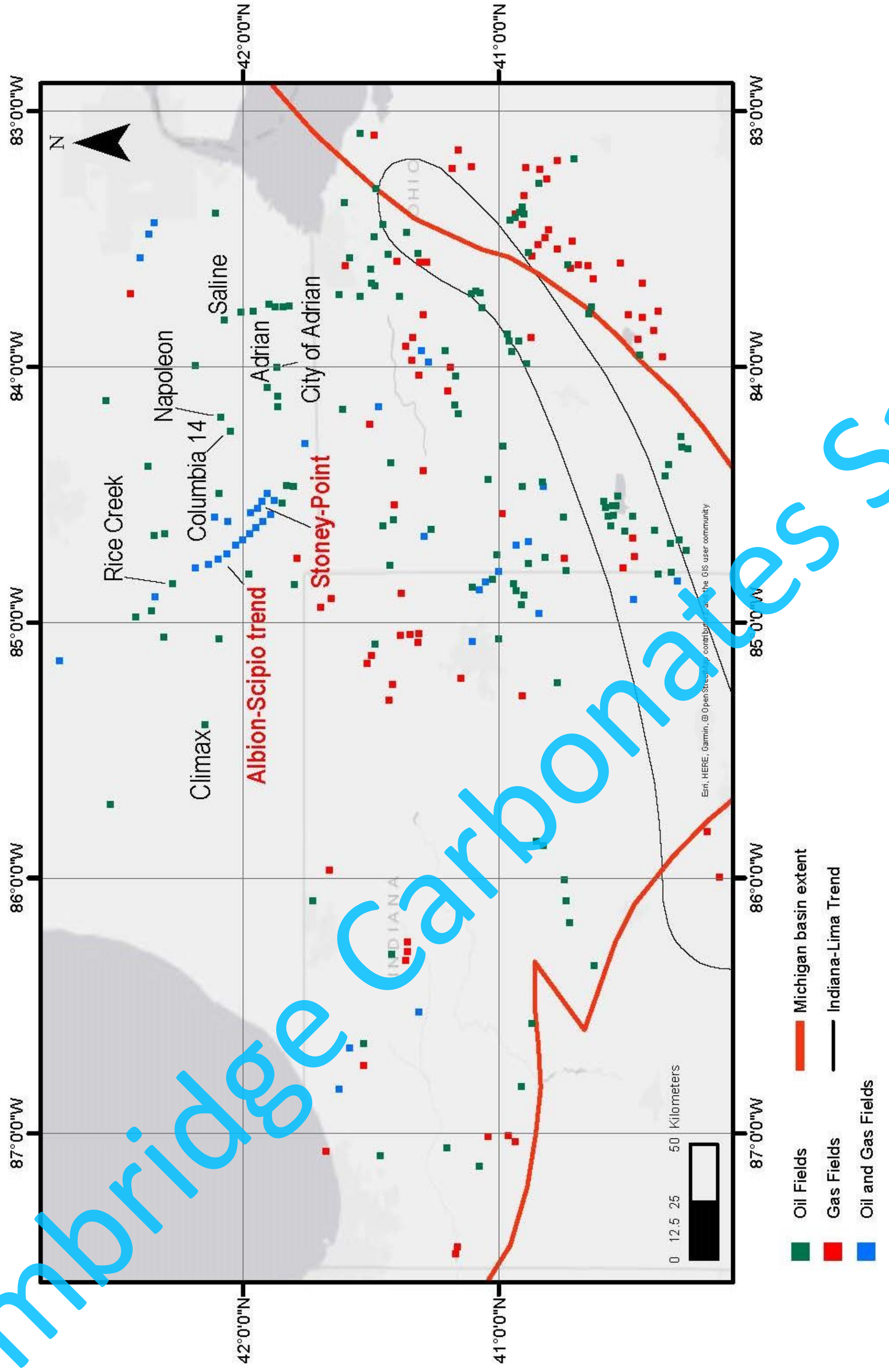


Figure 22 Map of the fields producing from the Trenton-Black-River Groups in the Michigan Basin (Modified from Swezey et al., 2015). The area shown in this map corresponds to the orange rectangle in Figure 21.

In the Albion-Scipio trend and Stoney Point field the reservoirs are present in partially to completely dolomitised Trenton and underlying Black River Groups which are up to 186 m thick in the fields' area (Taylor & Sibley, 1986). They consist of NW-SE oriented, low relief (~18 m) synclinal sag structures formed by the sinistral strike-slip reactivation of basement faults (Hurley & Budros, 1990) (Figure 26). The Albion-Scipio trend is 1.6 km wide and 56 km long (Figure 27). The total offset along the main fault in the Albion-Scipio trend is of ~4 km, but reactivation in the Paleozoic only accounts for ~1.6 km offset (Taylor & Sibley, 1986; Hurley & Budros, 1990). A set of *en-echelon* synclines separated by faults form the larger synclinal sag of the fields. The fields' trap is structural, stratigraphic and diagenetic as porosity only developed where pervasive dolomitisation occurred along faults and fracture zones and the transition from porous dolomite to tight limestone is sharp. The seal consists of non-dolomitised limestone, the fine crystalline and tight ferroan cap dolomite and the Utica shale (Hurley & Budros, 1990). In addition, to the structural control on the dolomitisation, impermeable shale beds in the Trenton-Black River Groups prevented upward flow of dolomitising fluids. Consequently, dolomitising fluids pooled below shale beds as thin as a couple of centimetres and dolomitisation took place preferentially below the low-permeability beds. This preferential dolomitisation is most clear under two of the most persistent shale beds known as "E shale" and "Black River Shale", which are bentonitic shales (Hurley & Budros, 1990). Originally, the Utica shale was believed to be the source rock of the Albion-Scipio trend and Stoney Point field, but TOC analysis revealed the Trenton and Black River Groups had higher hydrocarbon generation potential (Hurley & Budros, 1990). Thin organic material-rich shale laminae occurring within the Trenton and Black River Formations have TOC levels of 20 – 25 % in their insoluble residue (Swezey et al., 2015). Maturation of the organic matter is thought to have occurred during the Carboniferous and as indicated by the presence of hydrocarbon inclusions in the fracture-related dolomites hydrocarbon migration might have partly overlapped with dolomitisation. Fracture-related dolomitisation in the Albion-Scipio trend was the result of the interaction of hot fluids (115 °C < T_h < 160 °C) with the limestone host-rock along fractures opened during sinistral strike-slip fault activity (Figure 28) (Hurley & Budros, 1990; Grammer, 2007). The transtensional

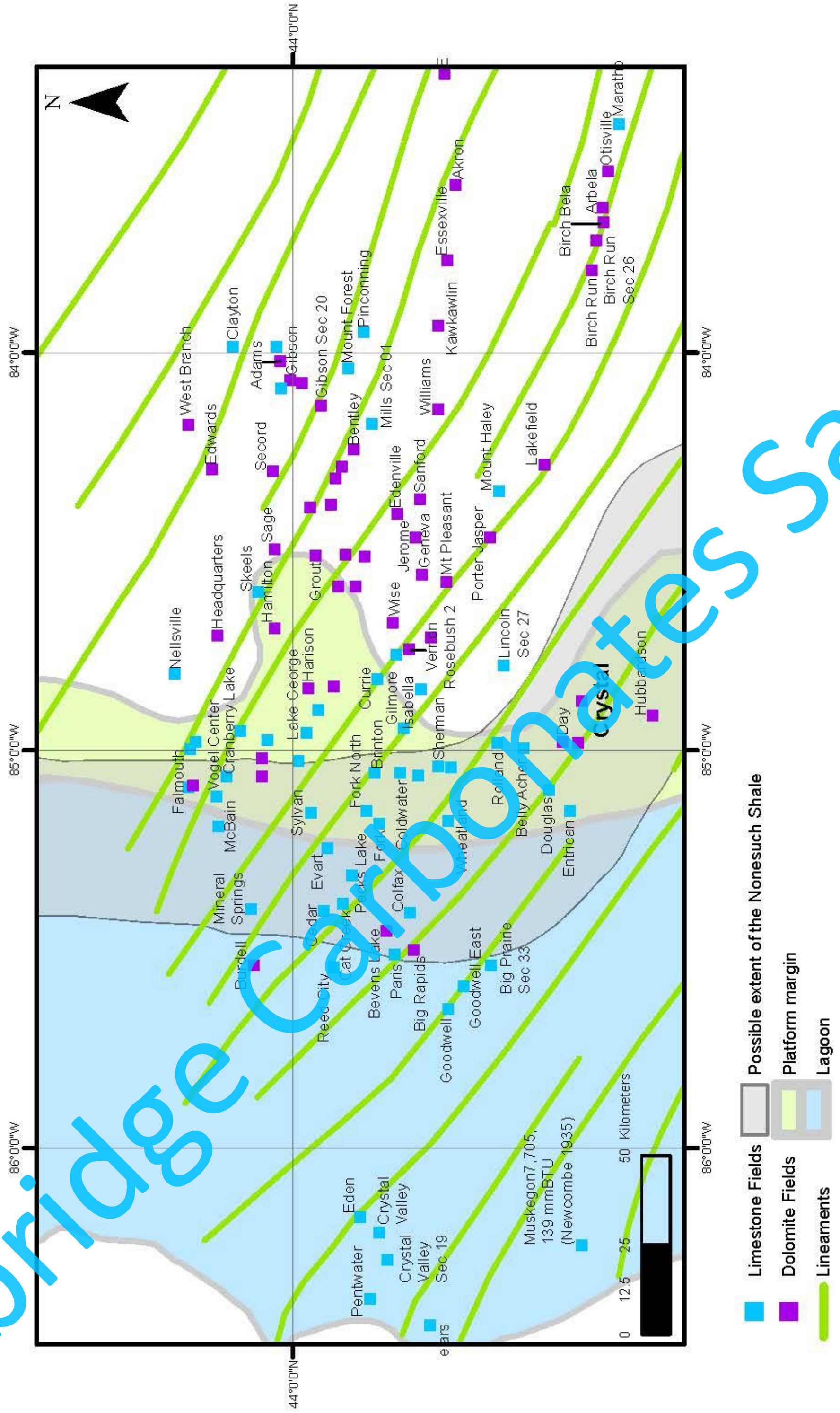


Figure 34 Map of hydrocarbon fields hosted by the Dundee Formation (modified after Atlas of Michigan Dundee Reservoirs, 1997; Luczaj et al., 2006; Van Sickel, 2017). The Nonesuch Shale was deposited in a rift lake. Its areal extent is interpreted to reflect the extent of the Mid-Continent rift of the Michigan Basin (Swezey et al., 2015).

recovery rates in the Crystal field (Montgomery et al., 1992). Since the production strategy of most Dundee fields developed during the 1930s and 1940s in the Michigan Basin was similar, horizontal wells could improve recovery in other Dundee reservoirs. Wood (1997) estimates that 80 MMBO could be recovered by redeveloping those abandoned fields.

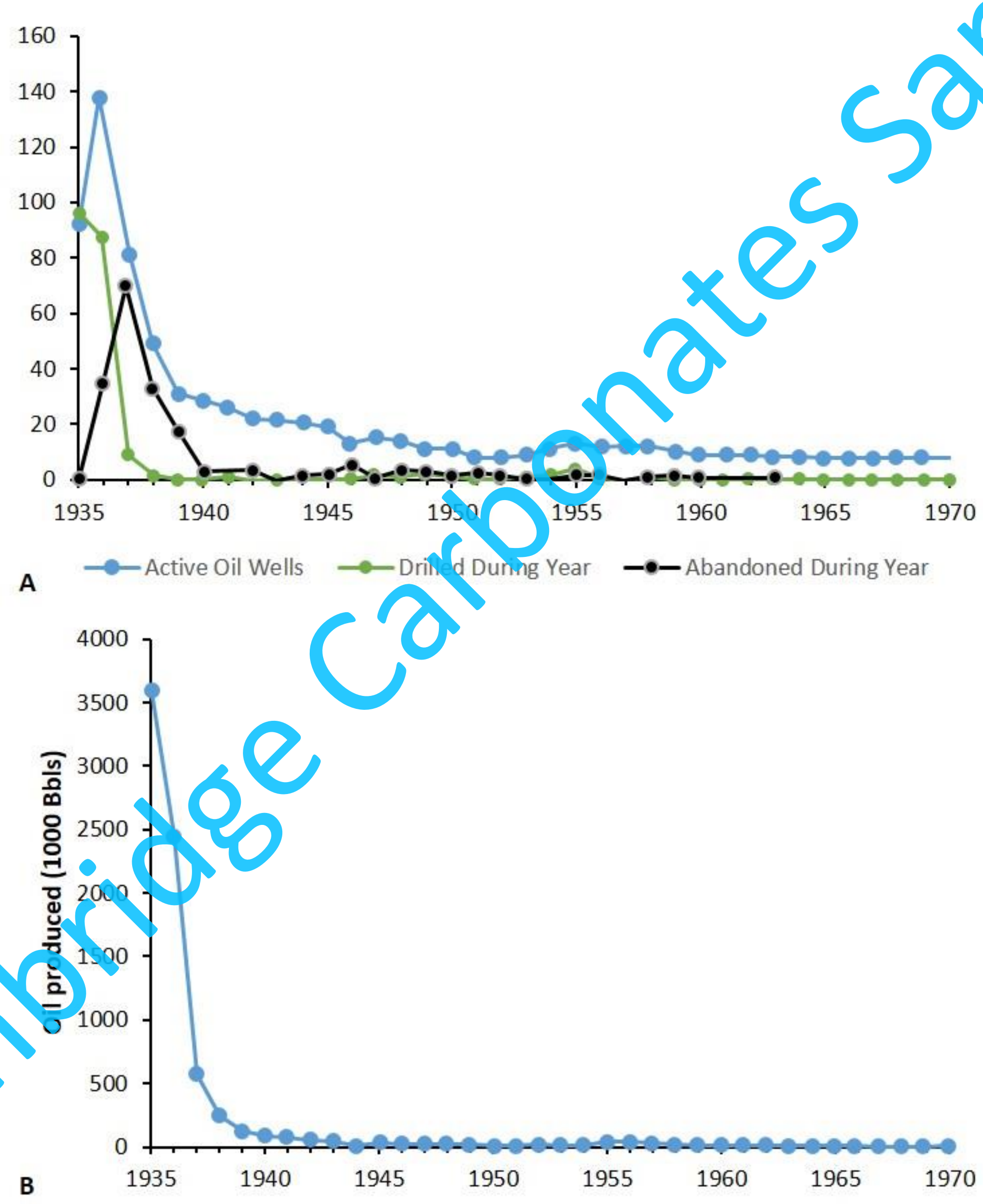


Figure 39 Development (A) and production (B) of the Crystal field up to 1970 (modified after Montgomery et al., 1998).

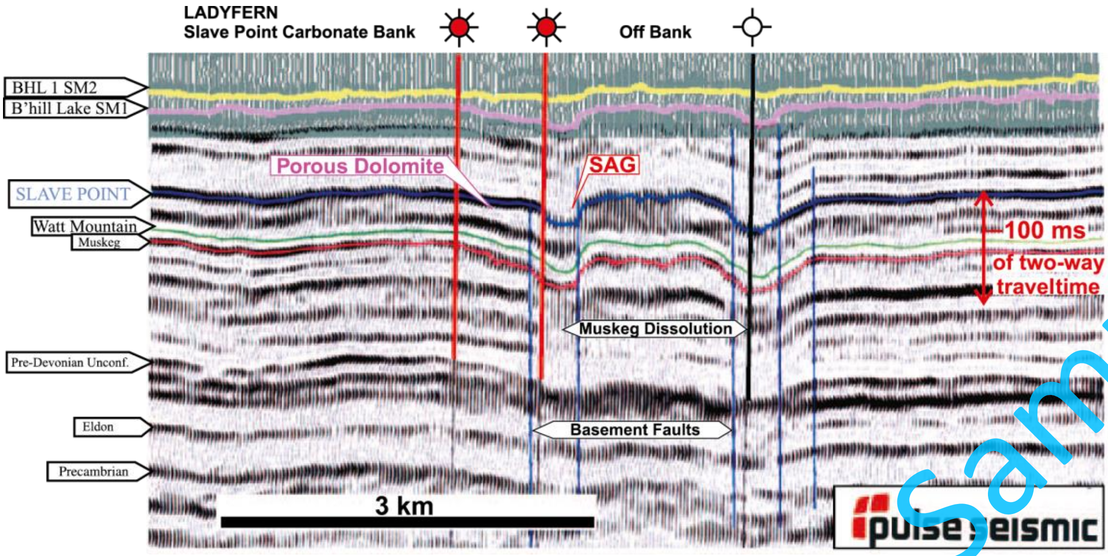


Figure 46 Seismic line across the Ladyfern field showing sags occuring in the Slave Point Formation extending down into the basement. The sag is levelled out at the Beaverhill Lake Marker 2 (BHL SM 2) which is equivalent to the earliest Late Devonian. The Muskeg Formation is less thick in the sags which is interpreted as fault-focalised dissolution of evaporites in the formation. The discovery wells projected on the seismic line are the Ladyfern a-97-H and 94-H-1 (Davies & Smith, 2006). Reprinted with permission of the AAPG whose permission is required for further use.

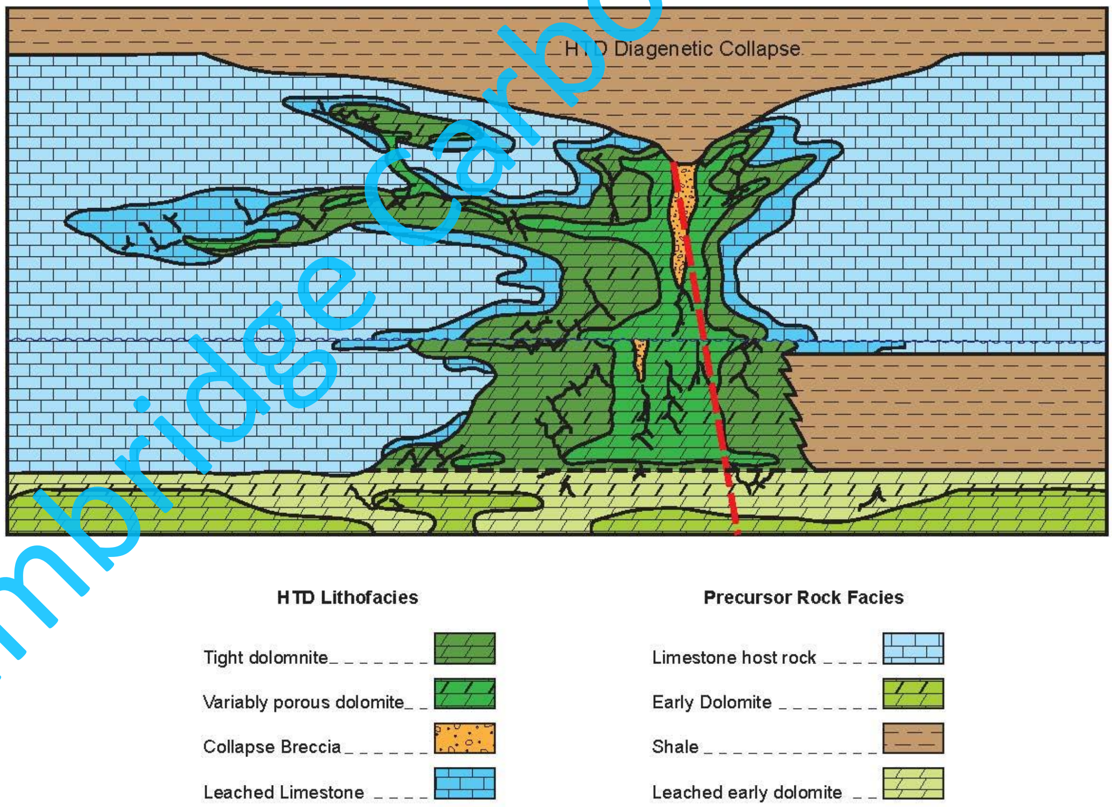


Figure 47 Conceptual model of the dissolution pipes (sags), fracture-related dolomite and leached limestone halo in the Ladyfern field (redrafted after Reimer et al., 2001).

saddle dolomite (A) with large vuggy pores parallel to the ABBA-bands) and coarse crystalline dolomite (coarse crystalline, white-pink, fabric destructive, saddle dolomites with large vuggy and intercrystalline pores) (Figure 54). Matrix dolomites make up 12 % of all dolomite samples, while coarse crystalline dolomites represent 32 %. The major part of the dolomite samples (56%) has zebra dolomite features.

In general, a clustering of dolomite types occurs in the fault-controlled dolomite body (Figure 53 B & C). Zebra dolomites are mainly present in the central part of the dolomite body and matrix dolomite occurs in the extremities of the dolomite body (Figure 53 C). Coarse crystalline dolomites preferentially occur in the vicinity of the fault zone and along the platform edge. This distribution of dolomite types indicates a general trend that can be explained by the migration of the dolomitising fluids in the Pozalagua dolomite body. Zebra dolomites are present in the Pozalagua Fault Zone and west of it. It is generally accepted that zebra dolomites are the result of focussed and high pressure fluid flow through nearby faults in low permeability host rocks (Nielsen et al., 1998; Vandeginste et al., 2005, Davies & Smith, 2006). In contrast, matrix dolomite, which is fine crystalline, replacive and not linked to fault activity occurs far away from the fault zone and represents a gradual transition to the limestone host rock. Coarse crystalline dolomites are fabric destructive and commonly originated from the second non-ferroan dolomite phase. Therefore, the coarse crystalline dolomites are interpreted as the recrystallization product of the first dolomitisation phase.

Indicator semivariograms computed based on the mapped dolomite types data reveal directional anisotropy of the dolomite types consistent with the previous fluid flow interpretation. The directions of anisotropy N30W and N 60E respectively correspond to the strike of the feeder fault and the orientation of the platform margin and a set of joints. Discontinuities between clinoforms of the platform margin could thus have been utilised by dolomitising fluids as a pathway from the basin to the carbonate platform. This is supported by the occurrence of a small dolomite body in the clinoforms at Ranero and the occurrence of coarse crystalline dolomite along the southern side of the Pozalagua dolomite body (Figure 53 C).

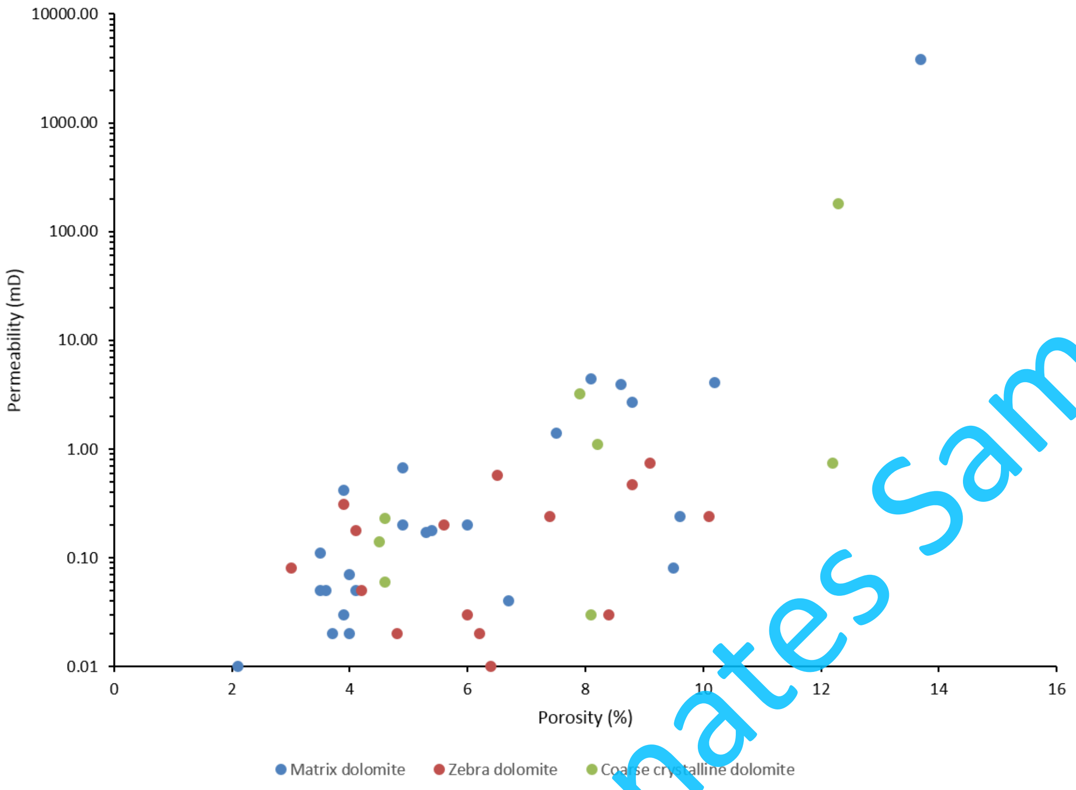


Figure 60 Porosity-permeabilty cross plot of the different dolomite types of Matienzo (modified after Dewit et al., 2014).

In Matienzo, no relationship between precursor limestone facies and occurrence of dolomites could be observed, i.e. grainstones and packstones are not dolomitised to a greater extent or more frequently than wackestones. As stated by Murray and Lucia (1967) "the nature of the original sediment only influences the dolomite distribution to the extent that no secondary changes occurred". At Matienzo, compaction and cementation changed the characteristics of the precursor limestone early on. Primary porosity and permeability of the limestone facies was thus perhaps only partly or not preserved at the moment of dolomitisation. Thick limestone beds are, however, efficient barriers to dolomitising fluids in Matienzo, i.e. a massive limestone unit seals the dolomite body and some dolomite "fingers" occur below massive limestone beds. Therefore, in Matienzo bed thickness might be of greater importance than original limestone facies in governing fluid flow patterns. The influence of the bed thickness on fracture development (i.e. its mechanical behaviour) has been described in literature (Ladeira & Price, 1981; Van Noten & Sintubin, 2010; Jacquemyn et al., 2012).

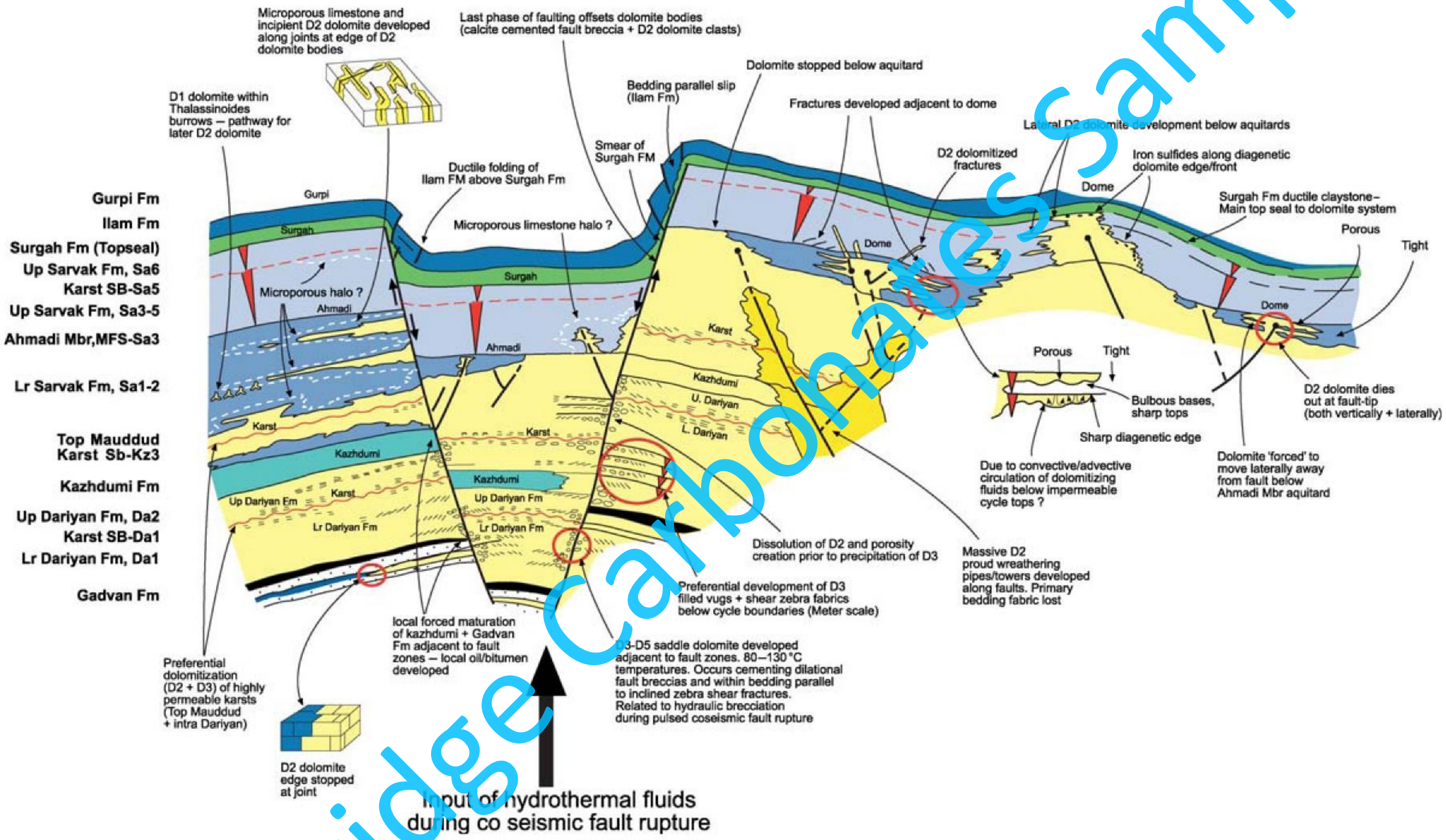


Figure 66 Conceptual summary figure of the dolomite field relationships based on outcrops in the Anaran Anticline. Vertical section is c. 1 km, and cross section is c. 3 km. D2, D3–D5 dolomites are spatially linked to fault zones (fracture fed vertically), and follow below aquitards or within permeable facies (karst, HST units) laterally. Top seal to the whole system is the clay-rich and ductile Surgah Formation. Sharp et al. (2010). Figure reprinted with permission of the Geological Society of London.

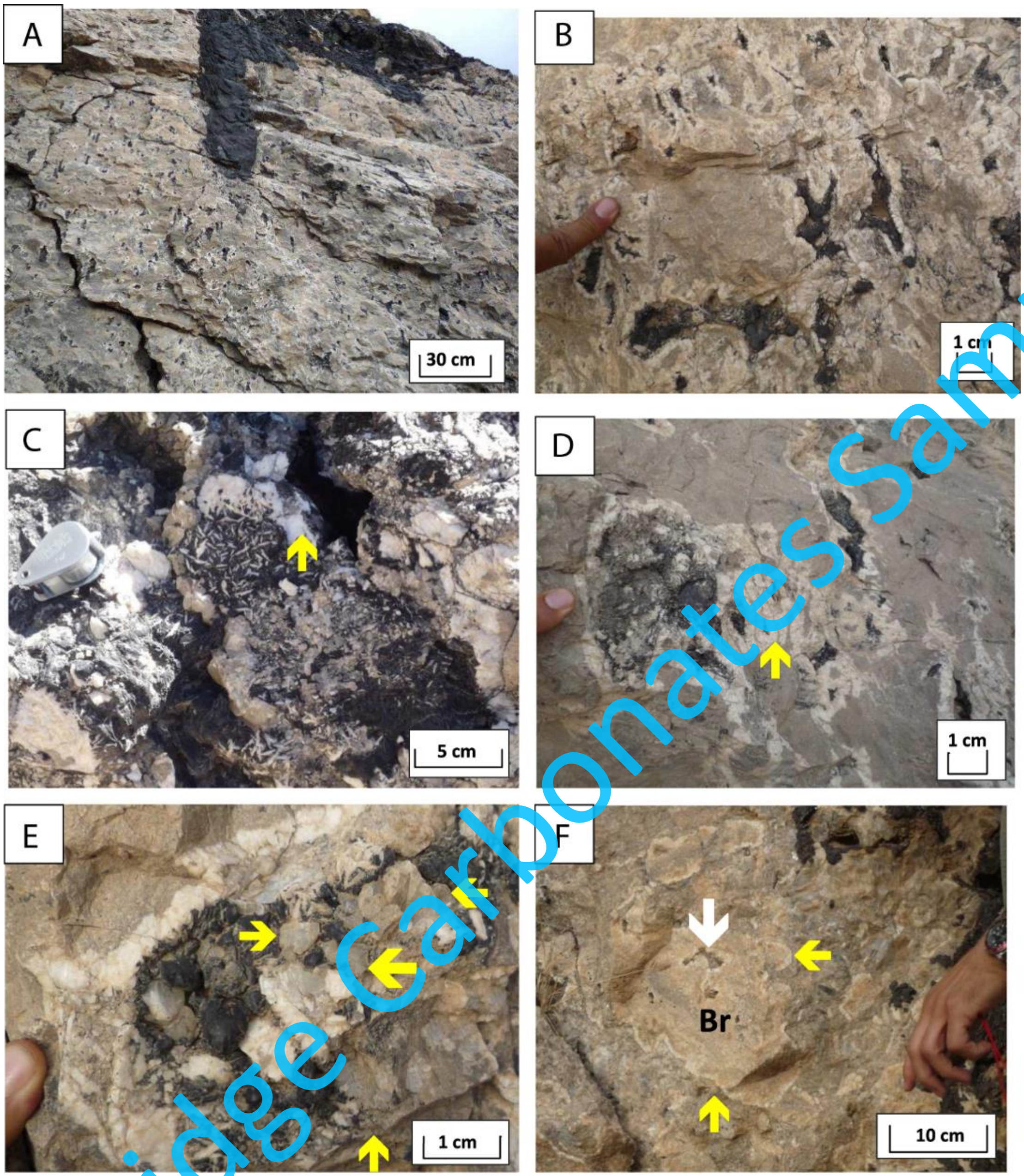
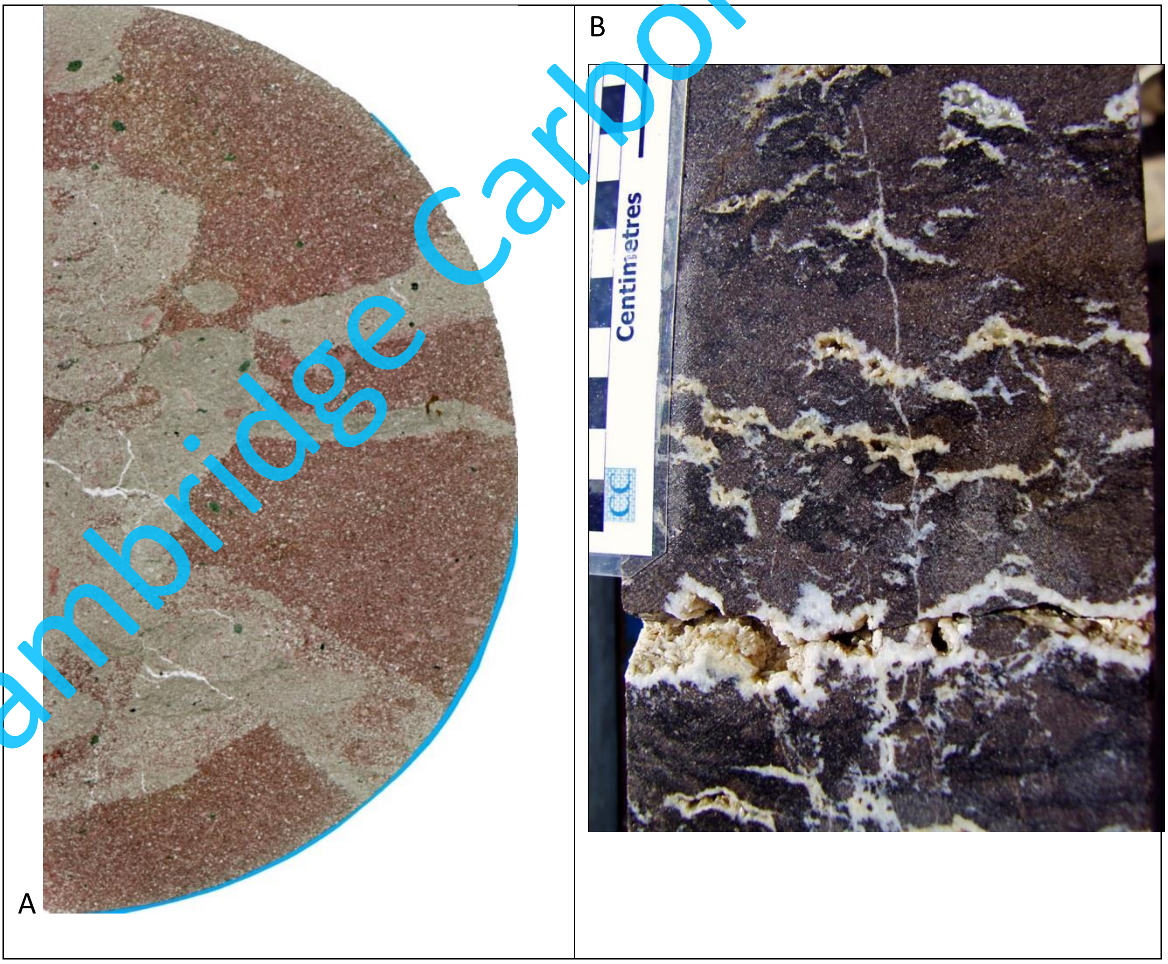


Figure 75 Field photographs (Mansurbeg et al., 2016) showing: A. Parallel-aligned tension gashes/vugs lined with saddle dolomite, calcite, bitumen and, in some cases, anhydrite. The tension gashes are arranged perpendicular to the thrust plane. Note the thick bitumen seepage from the thrust plane at top of the photograph. B. Close up view of the tension gashes showing that the saddle dolomite (whitish) lines the gashes and related vugs, which are filled with bitumen (black). C. Top view of a vug lined by saddle dolomite engulfed by coarse crystalline equant calcite (arrow); note that bitumen (black) fills the intercrystalline space between the saddle dolomite. D. Saddle dolomite lines and nearly completely fills some of the narrow, parallel-aligned tension gashes (arrows). E. A vug lined by saddle dolomite and partly filled by calcite, which cements saddle dolomite (arrows); note that bitumen covers saddle dolomite, whereas the calcite covers bitumen. F. A brownish-stained area (Br), which is composed of rhombic and saddle dolomite and lined by saddle dolomite (yellow arrows). Note the presence of a small vug partly filled with saddle dolomite in themiddle of the brownish area (white arrow).

inclusion analyses indicated that these dolomites precipitated from pore waters that had temperatures as high as 150 °C, with very variable salinities. These temperatures are significantly higher than the expected burial temperature, and are thus considered hydrothermal in nature.

Plug data demonstrates that dolomites clearly have enhanced reservoir quality compared to coeval limestones (Figure 84). There is, however, a rather wide range in poroperm data for the dolomites. Dolomites with the best reservoir properties exhibit well-preserved intercrystalline pore space, and a sucrosic texture (i.e. Figure 83 F). On the other hand, those high temperature dolomites which have relatively poor matrix properties exhibit a closely interlocking crystal geometry (Figure 83 G). It should be noted that plug data is not always representative of reservoir quality in these dual porosity systems, since the vuggy and fracture components of the pore-size distribution are not sampled.



Facies	AVG porosity (%)	AVG permeability (mD)	n	percentage of facies (%)
stromatolitic Mudstone/wackestone/pakstone	2.34	26.3		
dolomite	4.51	76.8	10	21
limestone	1.53	11.2	32	67
difference in porosity/permeability factor	2.98	7		
amphipora wackstone/packstone	2.20	55.8		
dolomite	4.89	76.8	24	25
limestone	1.08	47.1	72	75
difference in porosity/permeability factor	3.81	2		
peloid Amphipora packstones/grainstones	8.24	159.5		
dolomite	8.6	169.6	158	94
limestone	3.24	15.3	7	4
difference in porosity/permeability factor	5.36	11		
bioclastic and Amphipora packstones/grainstones	8.29	365.1		
dolomite	9.72	479.6	158	95
limestone	2.58	7.66	7	2
difference in porosity/permeability factor	7.14	63		
stromatoporoid packstones/grainstones	7.67	208		
dolomite	9.94	292.9	269	73
limestone	2.09	6.2	5	24
difference in porosity/permeability factor	7.85	47		
large stromatoporoid wackstone/packstone	3.23	192.4		
dolomite	6.58	673.8	147	28
limestone	1.97	13.5	48	67
difference in porosity/permeability factor	4.61	50		
current-layered stachyodes packstone/grainstone	1.57	2.4		
dolomite	3.66	3	29	15
limestone	1.30	1.9	69	74
difference in porosity/permeability factor	2.36	2		
brachiopod wacksetone/mudstone (all limestone)	0.37	35.2	34	100

Table 12 Porosity and permeability of the depositional (dolomitised) facies (modified after Saller et al., 2001). Partially dolomitised limestones (20 – 80 % dolomite) are not taken into account here. Many stromatolitic mudstone/wackestone/packstone samples had anomalously high permeability given their porosity, these were most likely damaged during coring resulting in artificially high permeabilities.

	Monte Zugna Fm - peritidal platform					
	limestone (n = 5)		dolomite - Grappa (n = 21)		dolomite - Valsugana (n = 11)	
	porosity	permeability	porosity	permeability	porosity	permeability
MIN	0.40	0.04	1.40	0.01	0.98	0.13
MAX	3.95	1.00	10.86	12.74	4.68	1.78
AVERAGE	1.25	0.24	4.57	1.33	2.36	0.53

DIFFERENCE BETWEEN LIMESTONE AND DOLOMITE	porosity: Grappa dolo - lmst	permeability Grappa dolo/lmst	porosity Valsugana dolo - lmst	permeability Valsugana dolo/lmst
	1.00	0.25	0.94	3.25
	6.91	12.74	3.68	1.78
	3.31	5.53	2.12	2.19

Table 13 Porosity and permeability data of the Monte Zugna Fm (modified after Ronchi et al., 2012).

The Ammonitico Rosso Formation which caps the Monte Zugna Formation consists of tight deep water deposits. Only meter size fracture-related dolomite bodies were observed in these pelagic limestones (Ronchi et al., 2012). The Ammonitico Rosso Formation is interpreted to have acted as a seal for the dolomitising fluids.

The Maiolica Formation, which is separated from the Monte Zugna Formation by the Ammonitico Rosso Formation consists of basinal mudstones and wackestones (Ronchi et al., 2012). Fracture-related dolomite occurs only in neptunian dikes that connect the Maiolica Formation with the Monte Zugna Formation and provided a permeable pathway in the otherwise tight formation (Figure 92). In the Maiolica Formation the increase in porosity is small, i.e. 1.11 % (less than the increase noted for the Monte Zugna Formation). The permeability increased with a factor 3.39, but on average the permeability of the dolomitised Maiolica Formation is still only 0.33 mD (Figure 91 & Table 14). The porosity and permeability increase in this formation is attributed to the development of intercrystalline pores. The hydrothermal dolomitisation does have an influence on the reservoir characteristics of the Maiolica Formation, but it is insufficient to make it an interesting reservoir rock.

The good porosity and permeability dataset acquired was used to populate the static reservoir model of the South Dome of the Reinecke field. The 3D distribution of dolomite, porosity and permeabity was extrapolated from well data using 3D seismic lines and and the transform relation between porosity and permeability (Figure 100).

	Dolomite		Mixed limestone & dolomite		Limestone	
	Porosity (%)	Permeability (mD)	Porosity (%)	Permeability (mD)	Porosity (%)	Permeability (mD)
Min	0.9	0.0	1.1	0.0	0.3	0.0
Max	28.7	9302.5	17.2	997.6	21.8	8458.6
Avg	8.7	937.8	10.6	45.2	10.8	264.7

Table 15 Standard porosity and permeability of whole cores of dolomite, mixed limestone and dolomite and limestone (modified after Saller & Dickson, 2011).

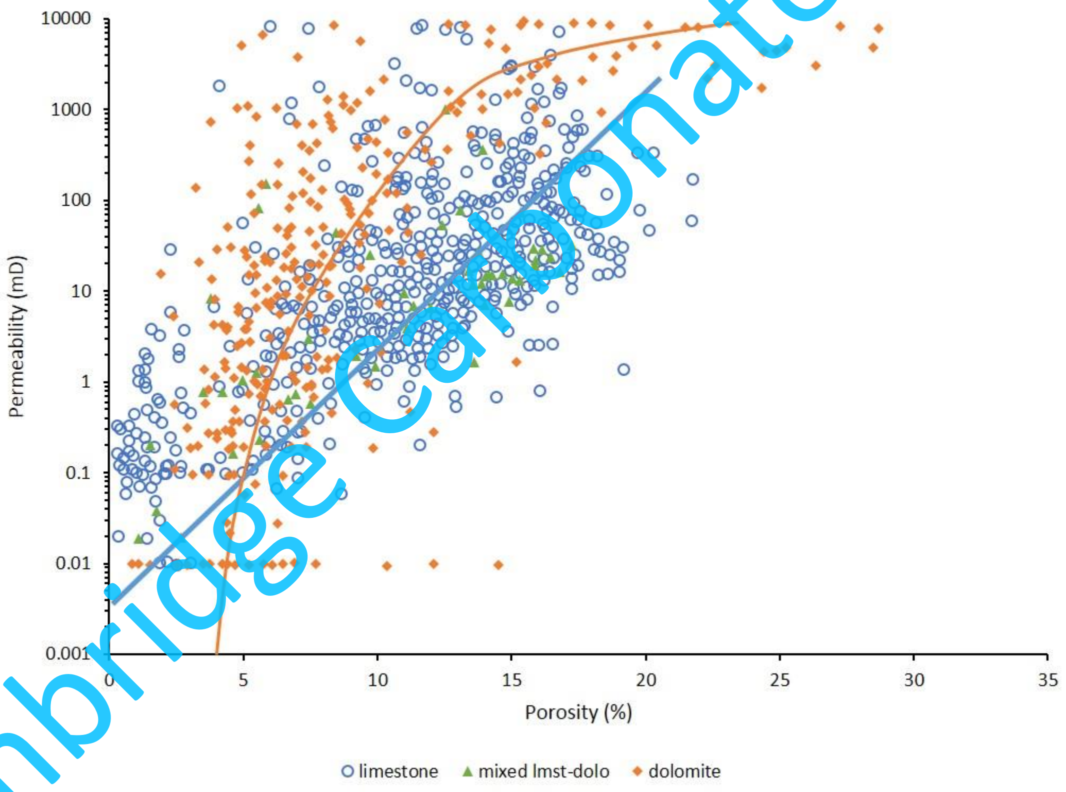


Figure 98 Plot of porosity versus horizontal permeability (whole core data) for Reinecke limestones and dolomites in the South Dome. Lines represent regressions of porosity vs. permeability for limestones and dolomites in Reinecke field (modified after Saller et al. (2004) and Saller & Dickson (2011)).

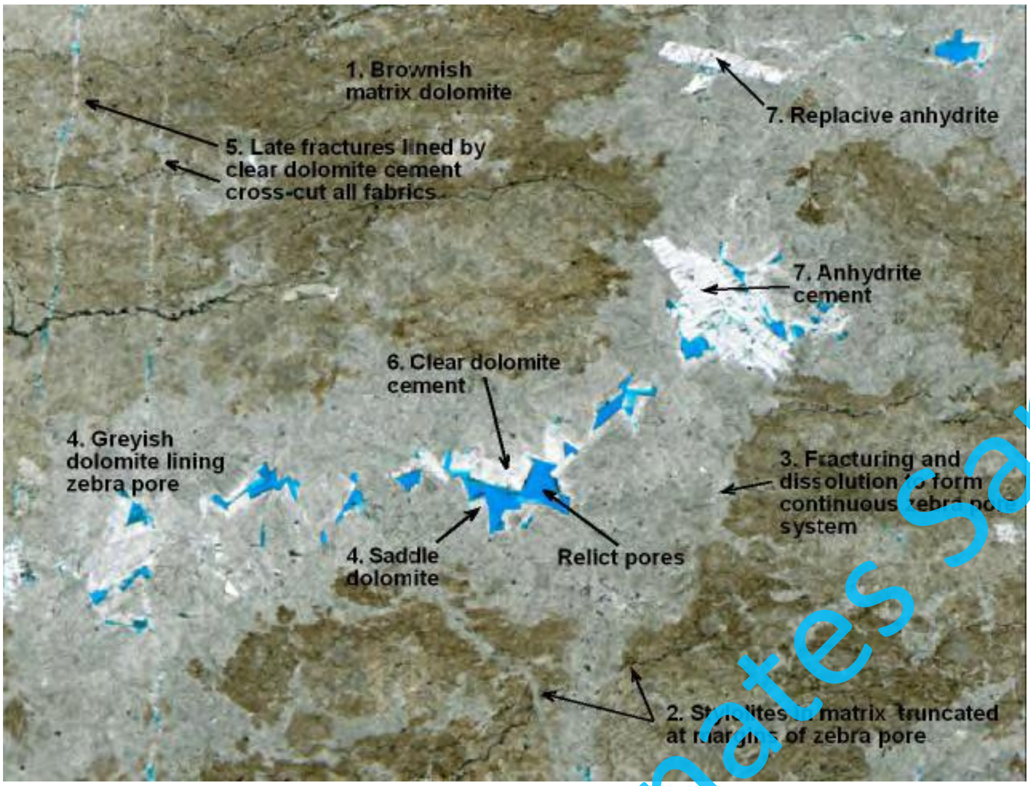


Figure 103 Scanned thin sections of fracture-related dolomite of the Ash Shaer field. Grey inclusion-rich dolomite cement lining late stage fracture and vuggy pore in brown dolomite matrix. Secondary porosity is infilled with clear anhydrite cement. Relict porosity is filled with blue epoxy resin. The FOV (field of view) is 3 cm.

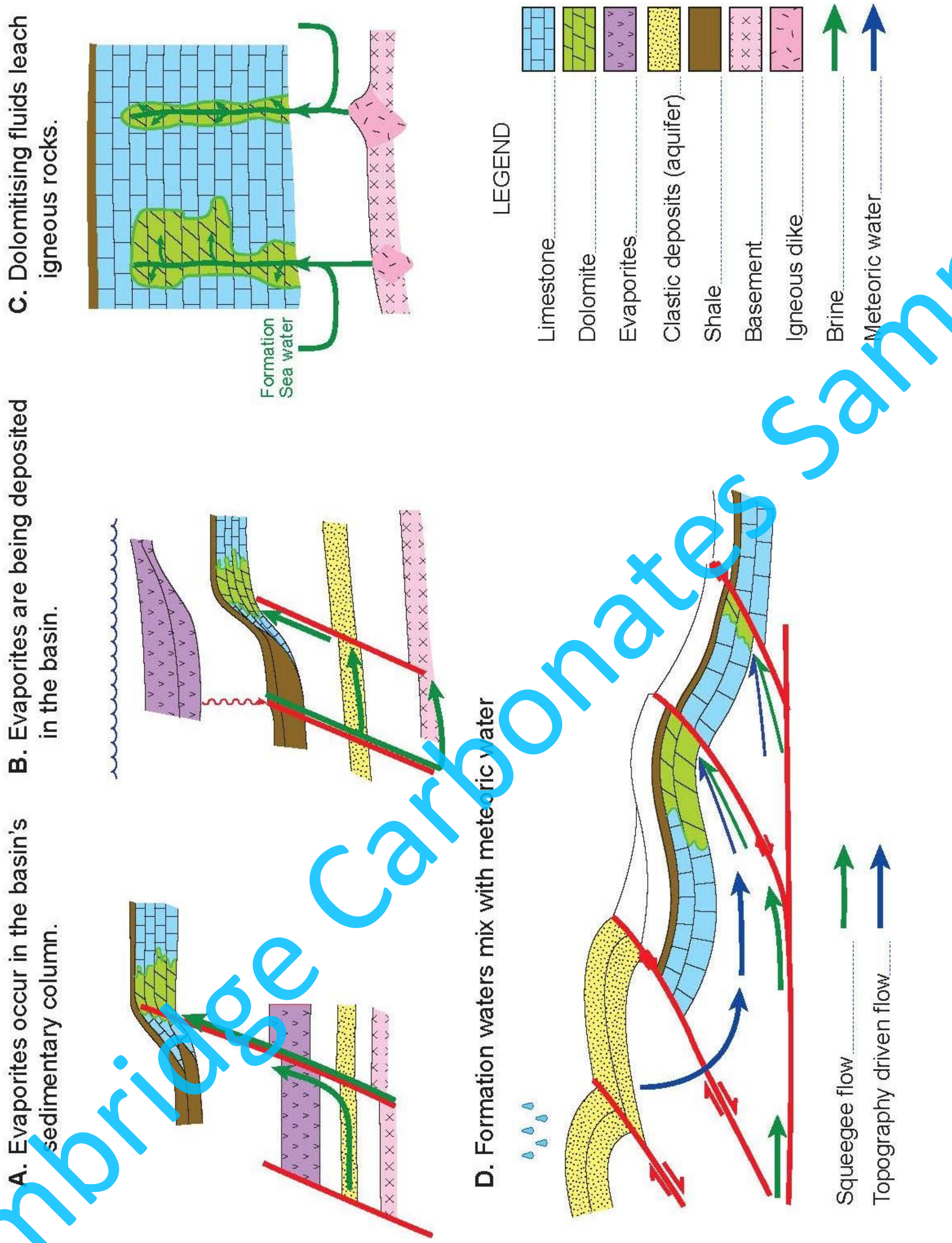


Figure 105 Schematic representation of different fluid source and flow models for fracture-related dolomitisation. A. Evaporites occur in basinal deposits. The overpressurised fluids escape along faults before interacting with carbonates capped by an impermeable seal. B. Evaporites are being deposited actively at the basin's surface. The dense brines percolate to deeper parts of the basin and geothermally rise via aquifers and/or pre-existing fractures and faults. C. Formation/sea waters interact with igneous rocks and form dolomite halos around the igneous bodies. D. Meteoric fluid is recharged from the high fold-and-thrust belt into frontal thrust sheets where it mixes with basinal fluids to form low-salinity dolomitising fluids.

km and assuming a hydrostatic regime the depth of dolomitisation is inferred to have been 3.9 ±1 km of depth (Gasparrini et al., 2006 A). Dolomitisation is assumed to have taken place during the Early Permian in a **complex** tectonic setting, i.e. post-thrusting relaxation (Gasparrini et al., 2006 B).

8.5. Host rock and seal of the fracture related dolomite body

Basinal and slope deposits versus shallow-water platform

In general, shallow-water carbonate deposits are typically dolomitised because porosity and permeability is required to allow dolomitising fluid circulation. In the case of a predating synsedimentary dolomitisation, an additional reason for the preferential dolomitisation of the shallow-water carbonates compared to basinal carbonates potentially lies in the mineralogy, pore and fracture network. Basinal carbonates consist mainly of stable low-Mg calcite, whilst shallow-water carbonates are composed of a mix of low-Mg and high-Mg calcite and aragonite, with the latter two being less stable. As a consequence dolomitised slope and basin deposits are rare. Moreover, dolomitisation of fine grained deposits has never been reported to have resulted in dolomite bodies with reservoir qualities. Porosity and permeability is improved locally as a result of faulting or brecciation (e.g. Ronchi et al. 2011). In SE Mexico, burial dolomitisation affected Cretaceous basinal deposits. For example in the Jacinto, Teotleco and Sen fields the dolomitisation improved the porosity and permeability marginally, however, hydrocarbons can be produced from these dolomitised basinal deposits via fractures.

The following examples illustrate the circumstances under which dolomitisation occurred in slope and basinal deposits and the characteristics of such dolomite bodies:

- In the Hammam Faraun fault block slope deposits have been dolomitised in an extensional tectonic setting. Fracture-related-dolomitisation only occurred where the precursor limestone is grainy such as in debrites and foraminiferal grainstone turbidites. Stratiform dolomite bodies (up to 300 m long) formed in these grainy microcrystalline chert occurs which precipitated simultaneously with the fracture-related dolomite from high temperature fluids. The hydrothermal fluids are interpreted to have leached silica from the granite wash deposited around the Peace River Arch and to have been hotter than usual due to the basement structure and high geothermal gradient (Packard et al., 2001). It is unlikely that the granitic basement itself had an influence on the saturation of hydrothermal fluids with respect to carbonate minerals, but the crustal faults delimiting the basement high may have leaked CO_2 and as a result the hydrothermal fluids may have been more acidic. In addition, as the hydrothermal fluids cooled during their ascent they may have become more undersaturated with calcite which is characterised by retrograde solubility.

The Deep Panuke field (see section 5.3) is also known to have some leached limestone associated with fracture-related dolomites, but most of the porosity is present in the fracture-related dolomites. In this case, however, the dissolution phase that resulted in the leached limestone halo also affected the dolomites and is a separate diagenetic event, post-dating the dolomitisation (Wierzbicki et al., 2006). Wierzbicki et al. (2006) suggest CO_2 and H_2S (gasses also present in the Deep Panuke field) may have been responsible for the acidity of the late diagenetic fluids dissolving the fracture-related dolomites and their limestone host rock. The H_2S may have been the result of thermal sulphate reduction (TSR). The presence of helium gas (<0.03 %) in the field is evidence for the fact that deep seated faults cross cut the fracture-controlled dolomite and leached limestone bodies since helium is derived from the radiogenic decay of granitic basement rocks (Wierzbicki et al., 2006). It is possible that other gasses, such as CO_2, might have been sourced from the deep basement/crust too.

Corrosion of fracture-related dolomites can also occur in between two phases of dolomitisation. Martín-Martín et al. (2015) report the dissolution of fabric-preserving, stratabound dolomites along fractures, faults, intercrystalline pores and bed-parallel stylolites prior to the precipitation of coarse crystalline saddle dolomite, hydrothermal calcite and associated MVT ores. The late acidic fluids are interpreted to have circulated through the stratabound dolomites following the reactivation of basement faults (Martín-Martín et al., 2015).

9. REFERENCES

Atlas of Michigan Dundee Reservoirs, 1997. [Online] Available at: http://www.geo.mtu.edu/svl/michproj/fldsplash.htm

Al-Qayim, B. & Rashid, F., 2012. Reservoir characteristics of the Albian Upper Qamchuqa Formation Carbonates , Taq Taq oil field Kurdistan, Iraq, Journal of Petroleum Geology, 35, 4, 317 – 342.

Aqrawi, A. A. M., Horbury, A. D., Goff, J. & Sadooni, F. N., 2010. The Petroleum Geology of Iraq, Scientific Press, p. 424.

Awdal, A. H., Braathen, A. Wennberg, O. P. & Sherwani, G. H., 2013. The characteristics of fracture networks in the Shiranish Formation of the Bina Bawi Anticline; comparison with the Taq Taq Field, Zagros, Kurdistan, NE Iraq, Petroleum Geoscience, 19, 139 – 155.

Baird, A., Kelly, J. & Symonds, R., 1993. The reservoir potential of the Zechstein-3 carbonate member (Platten), offshore Netherlands, AAPG International Conference and Exhibition, The Hague, Netherlands, October 17-20, 1993, AAPG Search and Discovery Article #90990.

Barnes & Harrison, 2001. Hydrothermal Dolomite Reservoir Facies (HTDRF) in the Dundee Limestone, Central Michigan Basin, USA. AAPG Search and Discovery, Eastern section meeting, Kalamazoo, Michigan, #90900.

Barnes, D. A., Parris T. M. & Grammer, G. M., 2008. Hydrothermal dolomitization of fluid reservoirs in the Michigan Basin, USA. AAPG Annual Convention, San Antonio, Texas, April 20 – 23. Search and Discovery Article #50087.

Boreen, T. D. & Colquhoun, K., 2003. The Ladyfern Gas Field – Canada is still hiding Mammoths, AAPG Annual convention Salt Lake City, Utah, May 11 – 14, 2003.

Boreen, T. D. & Colquhoun, K., 2001. Ladyfern, N.E.B.C.: Major Gas Discovery in the Devonian Slave Point Formation. Rock the Foundation Convention, June 18-22, 2001, Canadian Society of Petroleum Geologists, number 112.

Boreen, T. D., Colquhoun, K. & Harrington, J., 2001. Ladyfern, N.E.B.C.: Major Gas Discovery in the Devonian Slave Point Formation. Rock the Foundation Convention, June 18-22, 2001, Canadian Society of Petroleum Geologists, number 094.

Cantrell, D., Swart, P. K. & Hagerty, R. M., 2004. Genesis and characterization of dolomite, Arab-D reservoir, Ghawar field, Saudi Arabia, GeoArabia, 9, 2, 11 – 36.

Capuano, R.M. 1993. Evidence of fluid flow in microfractures. American Association of Petroleum Geologists Bulletin 77, 1303-1314.

Cervato, C., 1990. Hydrothermal dolomitization of Jurassic-Cretaceous limestones in the southern Alps (Italy): Relation to tectonics and volcanism, Geology, 18, 458 – 461.

Chen, D., Qing, H. & Yang, C., 2004. Multistage hydrothermal dolomites in the Middle Devonian (Givetian) carbonates from the Guilin area, South China, Sedimentology, 51, 1029 - 1051.

Choquette, P.W. and L.C. Pray, 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates, AAPG Bulletin, v. 54/2, p. 207-244.

Chittick, S., Salotti, C., Wood, J., Pennington, W., McDowell, S., Huntoon, J., Harrison W. 1995. Characterization of the Dundee Formation, Winterfield Field, Clare County, Michigan. AAPG Search and Discovery Article, 90954.

Collins, J. F., Kenter, J. A. M., Harris, P. M., Kuanysheva, G., Fischer, D. J. & Steffen, K. L., 2006. Facies and reservoir-quality variations in the late Visean to Bashkirian Outer Platform, Rim, and flank of the Tengiz Buildup, Precaspian Basin, Kazakhstan. In: P. M. Harris and L. J. Weber (eds.), Giant hydrocarbon reservoirs of the world: From rocks to reservoir characterization and modeling: AAPG Memoir 88/SEPM Special Publication, 55 – 95.

Colquhoun, I., 2004. Middle Ordovician Trenton-Black River Group Carbonate Play. Ontario Oil & Gas, 15 – 19.

Copp, I., 2008. Hydrothermal dolomite (HTD) reservoirs – new Australian carbonate play, PESA News, April/May 2018, 86 – 95.

Curran, B. C. & Hurley, N. F., 1992. Geology of the Devonian Dundee Reservoir, West Branch Field, Michigan, AAPG Bulletin, 76, 9, 1363 – 1383.

Davies, G.R. & Smith, L.B. 2006. Structurally-controlled hydrothermal dolomite reservoir facies: An overview. American Association of Petroleum Geologists Bulletin 90, 1641-1690.

Dewit, J., Huysmans, M., Muchez, Ph., Hunt, D.W., Thurmond, J.B., Verges, J., Saura, E., Fernandez, N., Romaire, I., Esestime. P. and Swennen, R. 2012. Reservoir characteristics of fault-controlled hydrothermal dolomite bodies: Ramales Platform case study. In: Garland, J.G., Neilson, J.E., Laubach, S.E. and Whidden, K.J. (eds.) Advances in carbonate exploration and reservoir analysis. Geological Society of London Special Publication, 370, 83-110.

Dewit, J., Foubert, A., El Desouky, H. A., Muchez, Ph., Hunt, D., F. Vamhaecke & Swennen, R., 2014. Characteristics, genesis and parameters controlling the development of a large stratabound HTD body at Matienzo (Ramales Platform, Basque-Cantabrian Basin, northern Spain), Marine and Petroleum Geology, 55, 6 – 25.

Dewit, J., 2012. Genesis and reservoir properties of hydrothermal dolomites (HTD), Ramales Platform (northern Spain). PhD thesis KULeuven, Aardkundige Mededelingen, 35, p. 183.

Dickson, J. A. D. & Saller, A. H., 2006. Carbon isotope excursion and crinoid dissolution at exposure surfaces in carbonates, West Texas, U.S.A., Journal of Sedimentary Research, 76, 404 – 410.

Diehl, S. F., Hofstra, A. H., Koenig, A. E., Emsbo, P., Christiansen, W. & Johnson, C., 2010. Hydrothermal zebra dolomite in the Great Basin, Nevada – Attributes and relation to Paleozoic stratigraphy, Tectonics, and ore deposits, Geospherem 6, 5, 663 – 690.

Dravis, J.J. & Muir, I.D. 1993. Deep burial brecciation in the Devonian Upper Elk Point Group, Rainbow Basin, Alberta, western Canada. In: Fritz, R.D., Wilson, J.L. & Yurewicz, D.A. (eds.) Palaeokarst related hydrocarbon reservoirs. SEPM Core workshop 18, 119-166.

Duggan, J. P. Mountjoy, E. W. & Staiuk, L. D., 2001. Fault-controlled dolomitization at Swan Hills Simonette oil field (Devonian), deep basin west-central Alberta, Canada, Sedimentology, 48, 301 – 323.

Esteban, M. & Taberner, C., 2003. Secondary porosity development during late burial in carbonates reservoirs as a result of mixing and/or cooling of brines, Journal of Geochemical Exploration, 78 – 79, 355 – 359.

Gabellone, T., Iannace, A., Invernizzi, C., Mazzoli, S. & D'Antonio, M., 2013. Fluid channeling along thrust zones: the Lagonegro case history, southern Apennines, Italy, Geofluids, 13, 2, 140 – 158.

Galluccio, L., 2009. Dolomites within the Mesozoic carbonates of Sorrento Peninsula (southern Apennines – Italy): Genetic models and reservoir implications. PhD Thesis, University of Naples "Federico II", p. 217.

Garland, C. R., Abalioglu, I., Acka, L., Cassisy, A., Chiffoleau, Y., Godail, L., Grace, M. A. S., Kader, H. J., Khalek, F., Legarre, H., Nazhat, H. B. & Sallier, B., 2010. Appraisal and development of the Taq Taq field, Kurdistan region, Iraq. In: Vinning, B. A. &Pickering, S. C. (eds.) Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference, 801–810.

Gasparrini, M., Bakker, R. J., Bechstädt, T., Boni, M., 2003. Hot dolomites in a Variscan foreland belt: hydrothermal flow in the Cantabrian Zone (NW Spain), Journal of Geochemical Exploration, 78 – 79, 501 – 507.

Gasparrini, M., Bakker, R. & Bechstädt, 2006 A. Characterization of the dolomitizing fluids in the Carboniferous of the Cantabrian Zone (NW Spain): A fluid-inclusion study with cryo-Raman spectroscopy, Journal of Sedimentary Research, 76, 12, 1304 -1322.

Gasparrini, M., Bechstädt, T., Boni, M., 2006 B. Massive hydrothermal dolomites in the southwestern Cantabrian Zone (Spain) and their relation to the Late Variscan evolution, Marine and Petroleum Geology, 23, 543 – 568.

Gomez-Rivas, E., Corbella, M., Martín-Martín, J., Stafford, S. Griera, A. & Teixell, A., 2001. Origin and Timing of Stratabound Dolomitization in the Cretaceous Carbonate Ramp of Benicassim, Revista de la sociedad española de mineralogía, 15, 103 – 104.

Grammer, G. M., 2007. Summary of Research through Phase II/Year 2 of initially approved 3 Phase/3 Year Project – Establishing the Relationship between Fracture-Related Dolomite and Primary Rock Fabric on the Distribution of Reservoirs in the Michigan Basin, p. 307.

Grammer, G. M. & Harrison, W. B., 2013. Evaluation and Modeling of Stratigraphic Control on the Distribution of Hydrothermal Dolomite away from Major Fault Planes, RPSEA Technical report, 08123.12, p. 284.

Guo, C., Chen, D., Qing, H. Dong, S., Li, G., Wang, D., Qian, Y & Liu, C., 2016. Multiple dolomitization and later hydrothermal alteration on the Upper Cambrian-Lower Ordovician carbonates in the northern Tarim Basin, China, Marine and Petroleum Geology, 72, 295 – 316.

Harrison, W. B., 2017 A. History and development of oil and gas plays of the Michigan Basin, OPI conference and trade show, May 24 – 26, 2017 Presentation.

Harrison, W. B., 2017 B. Devonian oil and gas plays of the Michigan Basin, OPI conference and trade show, May 24 – 26, 2017, Presentation [Online] Available at: http://www.ogsrlibrary.com/downloads/OPI-2017_Devonian-oil-play-in-Ontario-and-Michigan_Harrison.pdf.

Hart, B. S., Sagan, J, A. & Ogiesoba, O. C., 2009. Lessons Learned from 3-D Seismic Attribute Studies of Hydrothermal Dolomite Reservoirs, CSEG Recorder, May 2009, 18 – 24.

Hickman, R. G., Kent, W. N., Odegard, M., Henshaw, N. & Martin, J., 2003. Hydrothermal Dolomite Reservoirs--A Play Whose Time Has Come, AAPG Annual Meeting, May 11-14, 2003, Salt Lake City, Utah, AAPG Search and Discovery Article #90013.

Hinks, A. W., Hinks, V. A. & Sullivan, 2014. Support for a Deep Fault Related Hydrothermal Dolomite Model for Some Michigan Basin Dundee Formation Reservoirs, Eastern Section Meeting, London, Ontario, Canada, September 27-30, 2014, Search and Discovery Article #9019.

Hips, K., J. Haas & Győi, O., 2016. Hydrothermal dolomitization of basinal deposits controlled by a synsedimentary fault system in Triassic extensional setting, Hungary, International Journal of Earth Sciences, 105, 1215 – 1231.

Hollis, H., Bastesen, E., Boyce, A., Corlett, H., Gawthorpe, R., Hirani, J., Rotevatn, A., Whitaker, F., 2017. Fault-controlled dolomitization in a rift basin, Geology, 45, 3, 219 – 222.

Horbury, A., 2012. Understanding the Zagros, GEO ExPro, p. 11.

Hurley, N. F. & Budros, R., 1990. Albion-Scipio and Stoney Point Fields-USA. In: AAPG Treatise Reprint Stratigraphic Traps, I, 1 – 37.

Jacquemyn, C., Swennen, R. & Ronchi, P., 2012. Mechanical stratigraphy and (paleo-) karstification of the Murge area (Apulia, southern Italy). In: Garland, J., Neilson, J., Whidden, K. Laubach, S. (eds.), Geological Society, London, Special Publications, 370, 169 – 186.

Jacquemyn, C., 2013. Diagenesis and application of LIDAR in reservoir analogue studies: karstification in the Cretaceous Apulia carbonate platform & dolomitization in the Triassic Latemar carbonate buildup. Published PhD study, p. 192.

Kareem, H. K., Al-Aasm, I. & Mansurbed, H., 2016. Structurally-controlled hydrothermal dolomitization: A case study of the Cretaceous Qamchuqa Formation, Zagros Basin, Kurdistan, Iraq, AAPG Education Directorate, Geoscience Technology Workshop, Carbonate Reservoirs of the Middle East, Abu Dabi, UAE, November, 23 – 24, 2015, Search and Discovery Article #51253.

Kara, D., R. & Keith, 1988. Depositional facies and diagenetic history of the Trenton Limestone in northern Indiana, In: B. D. Keith (ed.), The Trenton Group (Upper Ordovician Series) of eastern North America-deposition, diagenesis, and petroleum: AAPG Studies in Geology 29, p. 277-298.

Kaufman, J., Meyers, W.J. & Hanson, G. N., 1991. Burial cementation in the Swan Hills Formation (Devonian), Rosevear field, Alberta, Canada, Journal of Sedimentary Petrology, 60, 6, 918 – 939.

Keith, B. D. & Wickstrom, L. H., 1992. Lime-Indiana Trend – USA Cincinnati and Findlay Arches, Ohio and Indiana, In: Treatise of Petroleum geology, Atlas of oil and gas fields, Stratigraphy Traps III, Foster, N. H. & Beaumont, E. A., The American Association of Petroleum geologists, Tulsa, Oaklahoma, USA, 347 – 367.

Ladeira, F.L., Price, N.J., 1981. Relationship between fracture spacing and bed thickness, Journal of Structural Geology, 13, 179–183.

Lapponi, F., Casini, G., Sharp, I., Blendinger, W., Fernández, N., Romaire, I. & Hunt, D., 2011. From outcrop to 3D modelling: a case study of a dolomitized carbonate reservoir, Zagros Mountains, Iran, Petroleum Geoscience, 17, 283 – 307.

Lavoie, D. & Morin, C., 2004. Hydrothermal dolomitization in the Lower Silurian Sayabec Formation in northern Gaspé – Matapédia (Québec): constraint on timing of porosity and regional significance for hydrocarbon reservoirs, Bulletin of Canadian Petroleum Geology, 52, 3, 256 – 269.

Lavoie, D., Chi, G., Urbatsch, M. & Davis, J., 2010. Massive dolomitization of a pinnacle reef in the Lower Devonian West Point Formation (Gaspé Peninsula, Quebec): An extreme case of hydrothermal dolomitization through fault-focused circulation of magmatic fluids, AAPG Bulletin, 94, 513 – 531.

Logan, P., Binnie, J., Garland, J. & Yildizel, A., 2013. Complex, two-phase dolomitisation in the Miran West anticline, Kurdistan, Hydrocarbon exploration in the Zagros Mountains of Iraqi Kurdistas and Iran, Conference proceedings, London, 23-25 January.

Lu, P. & Cantrell, D., 2016. Reactive transport modelling of reflux dolomitization in the Arab-D reservoir, Ghawar field, Saoudi Arabia, Sedimentology, 63, 865 – 892.

Luczaj, J. A., Harrison, W. B. III. & Williams, N. S. 2006. Fractured hydrothermal dolomite reservoirs in the Devonian Dundee Formation of the central Michigan Basin. American Association of Petroleum Geologists Bulletin 90, 1787-1801.

Machel, H. G. and Lonnee, J. 2002. Hydrothermal dolomite, a product of poor definition and imagination. Sedimentary Geology, v.152, 163-171.

Machel, H. G., 2004. Concepts of dolomitization: a critical reappraisal. In: The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs, Braithwaite, C. J. R., Rizzi, G. & Darke, G. (eds.), Geological Society, London, Special Publications, 25, 7 – 63.

Malone, M., Baker, P. A. & Burns, S., 1996. Hydrothermal dolomitization and recrystallization of dolomite breccias from the Miocene Monterey Formation, Tepusquet area, California, Journal of Sedimentary Research, 66, 5, 976 – 990.

Mansurbeg, H., Morad, D., Othman, R., Morad, S., Ceriani, A., Al-Aasm, I., Kolo, K., Proust, J. N., Preat, A. & Koyi, H., 2016. Fault-controlled dolomitization of Upper Cretaceous Reservoirs, Zagros Basin, Kurdistan Region of Iraq: implications for hydrocarbon migration and degradation, AAPG Education Directorate, Geoscience Technology Workshop, Carbonate Reservoirs of the Middle East, Abu Dabi, UAE, November, 23 – 24, 2015, Search and Discovery Article #51249.

Martín-Martín, J., Travé, A., Gomez-Rivas, E., Salas, R., Sizun, J.-P., Vergés, J., Corbella, M., Stafford, S. L. & Alfonso, P., 2015. Fault-controlled and stratabound dolostones in the Late Aptian-earliest Albian Benassal Formation (Maestrat Basin, E Spain): Petrology and geochemistry constrains, Marine and Petroleum Geology, 65, 83 -102.

McDaniel & Associates, 2017. Genel Energy International - Competent Person's Report Taq Taq Field, p. 47.

Moore, C.H. 1989. Carbonate diagenesis and porosity. Developments in Sedimentology 46, Elsevier, p. 338.

Montgomery, S. L., Wood, J.R. & Harrison, W. B., 1998. Devonian Dundee Formation, Crystal Field, Michigan Basin: Recovery of Bypassed Oil Through Horizontal Drilling, AAPG Bulletin, 82, 8, 1445 – 1462.

Murray, R.C. & Lucia, F.J., 1967. Cause and Control of Dolomite Distribution by Rock Selectivity, Geological Society of American Bulletin, 78, 21-36.

Nelson, R., 2001. Geologic analysis of naturally fractured reservoirs, Gulf Professional Publising, p. 332.

Nielsen, J.K. and Pederson, M. 1998. Hydrothermal activity in the Upper Permian Ravnefjeld Formation of central East Greenland – a study of sulphide morphotypes. Geology of Greenland Survey Bulletin 180, 81–87.

Ogiesoba, O. C., 2010. Porosity prediction from seismic attributes of the Ordovician Trenton-Black River Groups, Rochester field, southern Ontario, AAPG Bulletin, 94, 11, 1673 – 1693.

Oliver, J., 1986. Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena, Geology, 14, 99 -102.

OIEC, 2017. The second phase of early production from Azar joint oilfield started. [Online] Available at: http://www.oiecgroup.com/SitePages/website/news.html?52

Packard, J. J., Al-Aasm, I., Samsom, I., Berger, Z. & Davies, J., 2001. A Devonian hydrothermal chert reservoir: the 225 bcf Parkland field, British Columbia, Canada, AAPG Bulletin, 85, 1, 51 – 84.

Patchen, D. G., Smith, T., Riley, R., Baranoski, M., Harris, D., Hickman, J., Bocan, J. & Hohn, M., 2005. Creating a Geologic Play Book for Trenton-Black River Appalachian Basin Exploration, report, April 1, 2005, p. 109.

Petroceltic, 2011. Capital Markets Day Introduction & Agenda. [Online] Available at: http://www.petroceltic.ie/~/media/Files/P/Petroceltic-V2/presentation/2011/capital-markets-day-27oct2011.pdf

Pierce, W. G. & Rich, E. I., 1962. Summary of Rock Salt Deposits in the United States as Possible Storage Sites for Radioactive Waste Materials, USGS Bulletin, 1148, p. 91.

Qing, H. & Mountjoy, E., 1989. Multistage dolomitization in Rainbow buildups, Middle Devonian Keg River Formation, Alberta, Canada. Journal of Sedimentary Petrology, 59, 1, 114 – 126.

Qing, H. & Mountjoy, E., 1994. Formation of Coarsely Crystalline, Hydrothermal Dolomite Reservoirs in the Presqu'ile Barrier, Western Canada Sedimentary Basin, AAPG Bulletin, 78, 1, 55 – 77.

Reimer, J. D., Hudema, T. & Vau, Ch., 2001. TSR-HTD Ten years later: an exploration update, with examples from western and eastern Canada, Canadian Society of Petroleum Geologist, Rock the Foundation convention, June 18 -22, 2001, abstract, p.4.

Reinson, G. E., Lee, P. J., Warters, W., Osadetz, K. G., Bell, L. L., Price, P. R., Trollope, F., Campbell, R.i & Barclay, J., 1993. Devonian gas resources of the westerns Canada Sedimentary Basin, Geological Survey of Canada Bulletin, 452, p. 157.

Rullkötter, J., Meyers, Ph. A., Schaefer, R. G. & Dunham, K. W., 1986. Oil generation in the Michigan Basin: A biological marker and carbon isotope approach, Advances in Organic Geochemistry, 10, 359 – 375.

Rodríguez-Morillas, N., Playà, E., Travé, A. & Martín-Martín, J. D., 2013. Diagenetic processes in a partially dolomitized carbonate reservoir: Casablanca oil field, Mediterranean Sea, offshore Spain, Geologica Acta, 11, 2, 194 – 214.

Ronchi, P., Jadoul, F., Ceriani, A., Di Giulio, A., Scotti, P., Ortenzi, A. & Previde Massara, E., 2011. Multistage dolomitization and distribution of dolomitized bodies in Early Jurassic carbonates platforms (Southern Alps, Italy), Sedimentology, 58, 532 -565.

Ronchi, P., Masetti, D., Tassan, S. & Camocino, D., 2012. Hydrothermal dolomitization in platform and basin carbonate succession during thrusting: A hydrocarbon reservoir analogue (Mesozoic of Venetian Southern Alps, Italy), Marine and Petroleum Geology, 29, 68 -89.

Rosales, I. & Pérez-García, A., 2010. Porosity development, diagenesis and basin modelling of a Lower Cretaceous (Albian) carbonate platform from northern Spain. In: Van Buchem, F. S. P., Gerdes, K. D. & Esteban, M. (eds.), Mesozoic and Cenozoic Carbonate Systems of the Mediterranean and the Middle East: Stratigraphic and Diagenetic Reference Models. Geological Society, London, Special Publications, 329, 317–342.

Sagan, J.A. & Hart, B.S. 2006. Three dimensional seismic-based definition of fault-related porosity development: Trenton-Black River interval, Saybrook, Ohio. American Association of Petroleum Geologists Bulletin 90, 1763-1785.

Saller, A., 2013. Controls on hydrothermal dolomites and their reservoir properties, AAPG Distinguished lecture series 2012 – 2013, Search and Discovery Article #50838.

Saller, A., Lounsbury, K. & Birchard, M., 2001. Facies control on dolomitization and porosity in the Devonian Swan Hills Formation in the Rosevear area, west-central Alberta, Bulletin of Canadian Petroleum Geology, 49, 4, 458 – 471.

Saller, A., Schwab, J., Walden, S., Hagiwara, H., Robertson, S., Mizohata, S. & Nims, R., 2004. Three-Dimensional Seismic Imaging and Reservoir Modeling of an Upper Paleozoic ‘‘Reefal’’ Buildup, Reinecke Field, West Texas, United States, in Seismic imaging of carbonate reservoirs and systems: AAPG Memoir 81, 107 - 122.

Saller, A. & Dickson, J. A. D., 2011. Partial dolomitization of a Pennsylvanian limestone buildup by hydrothermal fluids and its effect on reservoir quality and performance, AAPG Bulletin, 95, 10, 1745 – 1762.

Sharp, I, P. Gillespie, D. Morsalnezhad, C. Taberner, R. Karpuz, J. Vergés, A. Horbury, N. Pickard, J. Garland and D. Hunt. 2010. Stratigraphic architecture and fracture-controlled dolomitization of the Cretaceous Khami and Bangestan groups: an outcrop case study, Zagros Mountains, Iran. From: Van Buchem, F. S. P., Gerdes, K. D. & Esteban, M. (eds.) Mesozoic and Cenozoic Carbonate Systems of the Mediterranean and the Middle East: Stratigraphic and Diagenetic Reference Models. Geological Society, London, Special Publications, 329, 343–396.

Slater, B. E. & Smith, L. B., 2012. Outcrop analog for Trenton-Black River hydrothermal dolomite reservoirs, Mohawk Valley, New York, AAPG Bulltin, 96, 7, 1369 – 1388.

Smith, L., 2006. Origin and reservoir characteristics of Upper Ordovician Trenton-Black River hydrothermal dolomite reservoirs in New York, AAPG, 90, 11, 1691 – 1718.

Smith, L., 2013. Subsurface corrosion of calcite dissolution and dolomite by fault-sourced hydrothermal fluids, AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013, Search and Discovery Article #50918.

Spitzer, R., 2013. Significant exploration success in northeastern British Colombia: A story of people resilience and learning from failure, AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013, Search and Discovery Article #110169.

Sun, Q., 1995. Dolomite reservoirs: porosity evolution and reservoir characteristics. AAPG Bulletin, 79, 186 – 204.

Swezey, C., Hatch, J. R., East, J. A., Hayba, D. O. & Repetski, E., 2015. Total Petroleum Systems of the Michigan Basin – Petroleum Geology and Geochemistry and Assessment of

Undiscovered Resources, chap. 2 of U.S. Geological Survey Michigan Basin Province Assessment Team, Geologic assessment of undiscovered oil and gas resources of the U.S. portion of the Michigan Basin: U.S. Geological Survey Digital Data Series DDS–69–T, p. 162.

Taylor, T. R. & Sibley, D. F., 1986. Petrographic and geochemical characteristics of dolomite types and the origin of ferroan dolomite in the Trenton Formation, Ordovician, Michigan Basin, U.S.A., Sedimentology, 33, 61 – 86.

Then, J., Wilson, M., E. J., Copp, I., Buschkuehle, M. & Carey, R., 2018. Depositional, diagenetic and mineralogical controls on porosity development in the Ungani Field, Canning Basin, AEGC 2018 (conference paper), p. 8.

Tinker, S. W., Caldwell, D. H., Zahm, L. C., Brinton, L., 2004. Integrated reservoir characterization of a carbonate ramp reservoir, South Dagger Draw field, New Mexico: Seismic data are only part of the Story, in Seismic imaging of carbonate reservoirs and systems, AAPG Memoir 81, 91 -105.

Van Noten, K. & Sintubin, M., 2010. Linear to non-linear relationship between vein spacing and layer thickness in centimetre- to decimetre-scale siliciclastic multilayers from the High Ardenne slate belt (Belgium, Germany), Journal of Structural Geology, 32, 377-391.

Van Sickel, B., 2017. Trenton-Black River hydrothermal reservoirs of the Michigan Basin, OPI conference and trade show, May 24 – 26, 2017, Presentation.

Voice, P. J. & Harrison, W. B., 2017. Depositional controls on reservoir quality in the Dundee-Rogers-City interval: Lithofacies and production characteristics, AAPG 2017 Eastern Section 46th Annual Meeting, Morgantown, West Virginia, September 24-27, 2017, Search and Discovery Article #51436.

Wallace, M. W., 1990. Origin of dolomitization on the Barbwire Terrace, Canning Basin, Western Australia, Sedimentology, 37, 105 – 122.

Warren, K. & Kempton, R., 1997. Evaporite sedimentology and the origin of evaporite-associated Missippi valley-type sulphides in the Cadjebut Mine Area, Lennard Shelf, Canning Basin, Western Australia, SEPM Special Publication, Basinwide diagenetic patterns: integrated petrologic geochemical, and hydrologic considerations, 57, 183 – 205.

Warren, J., 2000. Dolomite: occurrence, evolution and economically important associations, Earth-Science Reviews, 52, 1-81.

Westphal, H., Eberli, G.P., Smith, L.B., Grammer, M.G. & Kislak, J. 2004. Reservoir characterisation of the Mississippian Madison Formation, Wind River Basin, Wyoming. American Association of Petroleum Geologists Bulletin 88, 405-432.

Wierzbicki, R., Dravis, J.J., Al-Aasm, I. & Harland, N. 2006. Burial dolomitisation and dissolution of Upper Jurassic Abenaki platform carbonates, Deep Panuke reservoir, Nova Scotia, Canada. American Association of Petroleum Geologists Bulletin 90, 1843-1861.

Wood, J. R., Bornhorst, T. J., Chittick, S. D., Harrison, W. B., Quinlan & Taylor, E., 2001. Using recent advances in 2D siemic technology and surface geochemistry to economically redevelop a shallow shelf carbonate reservoir: Vernon field, Isabella County, MI. Fossil Energy Annual report, p. 25.

Wood, J.R. 1997. Recovery of Bypassed Oil in the Dundee Formation Using Horizontal Drains. Quarterly Technical Report, Michigan Technological University.

Wood, J. R., 2003. Mapping large-scale faults in the Michigan Basin using tops data, AAPG Annual convention, Salt Lake city, Utah, May 11 – 14, 2003.

Wood, J.R. and Quinlan, W. 2003. Using Recent Advances in 2D Seismic Technology and Surface Geochemistry to Economically Redevelop a Shallow Shelf Carbonate Reservoir: Vernon Field, Isabella County, MI. Michigan Technological University, Houghton.

Wood, R. J. & Harrison, W., 2002. Advanced characterization of fractured reservoirs in carbonate rocks: the Michigan Basin. Michigan Technological University. Final Report T DE-AC26-98BC15100, p. 62.

Wood, R. J. & Seneshen, D., 2006. Geochemical investigations in the Michigan Basin: Vernon field and Springdale Township, AAPG Annual convention, Houston, Texas, April 9 -12, 2006, Search and Discovery Article #20036.

Worden, R.H., Smalley, P.C. & Oxtoby, N.H. 1995. Gas souring by thermochemical sulphate reduction at 140°C. Bulletin of the American Association of Petroleum Geologists, 79, 854-863.

Worden, R.H., Smalley, P.C. & Oxtoby, N.H. 1997. Gas souring by thermochemical sulphate reduction at 140°C - reply to discussion American Association of Petroleum Geologists Bulletin, 81, 816-817.

Worden, R.H., Smalley, P.C. & Oxtoby, N.H. 1998. Gas souring by thermochemical sulphate reduction at 140°C - reply to discussion American Association of Petroleum Geologists Bulletin, 82, 1874-1875.

Yang, L., 2015. A petrophysical evaluation of the Trenton_Black River Formation of the Michigan Basin, Michigan Tech, Dissertations, Master's Theses and Master's Reports, p. 51.

Xiao, Y., Jones, G. D., Whitaker, F. F., Al-Helal, A. B., Stafford, S., Gomez-Rivas, E. & Guidry, S., 2013. Fundamental approaches to dolomitization and carbonate diagenesis in different hydrogeological systems and the impact on reservoir quality distribution, International Petroleum Technology Conference held in Beijing, China, 26–28 March 2013, IPTC 16579.

Zhan, Y. & Mory, A. J., 2013. Structural interpretation of the Northern Canning Basin, Western Australia, Western Australian Basins Symposium (conference paper), 18 – 21 August 2013, p. 18.

Zenger, D. H., Dunham, J. B. & Ethington, R. I. (eds.), 1980. Concepts and models of dolomitization, SEPM Special Publication, Tulsa, 28, p. 320.

10. APPENDIX – FIELD DETAILS

Albion – Scipio and Stoney Point fields

	Albion	Scipio	Stoney Point
Average depth to pay zone	1219 m		
Pay thickness	15 - 18 m		
Gross reservoir thickness	180 m		
Initial hydrocarbon column	46 - 61 m	64 m	64 m
Cumulative production 1987	124 MMBO		3.6 MMBO
Cumulative production 2006	250 MMBOE		10 MMBO
Initial production rate discovery well	200 BOPD	140 BOPD	

The heterogeneous distribution of reservoir properties made the estimation of original oil/gas in place complicated and the STOOIP of 290 MMBO and GIIP of 276 BCF for the Albion-Scipio trend and Stoney Point field need to be regarded with caution. (Scipio field STOOIP 170 MMBO + Albion field 120 MMBO STOOIP; Grammer, 2007).

Wells producing from fracture-related dolomite are typically treated with 250 to 8000 gallons of HCl. Wells penetrating limestone may receive fracture and acid-fracture jobs to promote communication with the dolomite reservoir. Periodic hot-oil treatments are needed in some producing wells (Hurley & Budros, 1990).

Ladyfern field

Ladyfern	**Discovery well**	**A97H**
initial gas column	100	MMCFGPD
initial reservoir pressure	4400	psi
initial production rate	100	MMCFGPD
cumulative production (2001)	12	BCF
gas composition: H_2S	5	ppm
gas composition: CO_2	4	%

Reinecke field

	Reinecke	**Reference**
Cumulative production (2004)	83 MMBO	Saller et al 2006