The Diagenesis and Porosity of the Mixed Deposits of the Azagador Member (U. Miocene) in the Turre Area, Almeria, Spain

Håvard H. Enge

Thesis for
Candidatus Scientarium degree
in
Sedimentology/Petroleum Geology

Geological Institute
(Department of Earth Science)
University of Bergen

2002

The mind cannot possibly grasp the full meaning of the term of a hundred million years; it cannot add up and perceive the full effects of many slight variations, accumulated during an almost infinite number of generations.

Charles Darwin – The Origin of Species
(Chapter 14: Recapitulation and Conclusion)

ABSTRACT

Mixed siliciclastic and temperate calcarenitic deposits are one of sedimentology´s “grey areas”. Defined as rocks that contain an intimate mixture of siliciclastic and bioclastic allochem-material, such heterogenic systems have attracted little research interest, or have been (miss-)interpreted as either impure siliciclastic or carbonate systems. In addition, the temperate (cool-water) carbonates, sometimes associated with such systems, have only recently received increased attention. However, little or no literature on the diagenesis and reservoir characteristics of such mixed deposits has been published so far. The present study is therefore one of the first presented.

The investigated Azagador Member crops out along the relatively narrow transition between the Sorbas and the Vera basins in the province of Almería in south-eastern Spain. Huge channelized structures dominate the area and a study of the diagenesis in- and outside of these structures form the basis in this study. A carbonate approach with regards to burial and diagenesis has been justified and a discussion on rock and porosity classification in such systems has been included. A new classification scheme has been produced for the classification of mixed sediments. This is a simple triangular classification constituting the three end members of the Azagador Member: Siliciclastics, bioclastic allochems and mud.

Thin-sections were investigated and form the basis for quantitative studies of porosity and interpretations of the depositional environment. The investigated facies of the Azagador Member are interpreted to be of a purely marine origin. Lack of early lithification due to a high energy depositional area and other qualities of cool-water carbonates appear to be representative for mixed deposits as well. The lack of early cement strongly influences the compaction history, promoting mechanical compaction and thus pressure dissolution. The presence of quartz grains and/or relatively shallow burial may have delayed compaction.

Cements characteristic for deep burial, such as coarse mosaic calcspar, have been identified in the samples. The porosity is fabric- and non-fabric selective. Intra- and interparticle as well as some moldic and abundant vuggy porosity is frequently observed. Primary porosity was partially or completely occluded by compaction and burial cement and secondary porosity appears to have been created by dissolution of grains, in particular allochems. Both the reduction of, and the present amount of porosity, is randomly distributed in samples collected in- and outside the channelized structures.

The origin of secondary porosity in the Azagador Member is not obvious. Two processes are suggested: 1) Dissolution by acid fluids from dewatering of shaley deposits at depth in the Vera Basin, and/or 2) Meteoric waters that may have penetrated down to the buried rock and created a mixture of brines and meteoric water, undersaturated with respect to $CaCO_3$.

The lack of extensive chemical dissolution suggests burial to only a few hundred meters. The low porosity indicate that the Azagador Member has passed a diagenetic threshold limit that is perhaps diagnostic for cool water carbonates.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Michael R. Talbot at the University of Bergen (UiB) for supportive reviews and critical reading of my thesis. I would also like to emphasise the support from post doc. Tine Lærdal (UiB) for constructive discussions and for thoroughly and critically reading through the manuscript. Thanks to Johannes M. Rykkje and Geir Torkelsen at Norsk Hydro Research Centre for helping out with the sample preparations and also Arve Lønøy and Bjørn Reksten for reading selected sections of the manuscript. Camilla Thrana, fellow student, is thanked for being a constructive partner on sunny and not so sunny days when doing fieldwork in Spain and for discussions when writing the thesis. Also thanks to my friend Jon Vøllestad for a critical review of the manuscript. As the present work is collaboration between the UiB and Norsk Hydro I wish to thank Hydro and Tom Dreyer for financial support.

I would like to thank several of my fellow students; my days as a student would not have been the same without you. Finally I would like to thank friends and others for bearing with my geology point of view on everything and constantly reminding me of the other World out there.

Håvard H. Enge
Bergen, November 2002

CONTENTS

1. INTRODUCTION

1.1. The aim of the present study

The Azagador Member is a highly variable, but widely distributed body of predominantly mixed siliciclastic and temperate cool-water calcarenites. It crops out extensively in several of the Neogene basins along, and inland of, the Mediterranean coast of south-eastern Spain.

This thesis is based on fieldwork carried out in collaboration with Camilla Thrana, a fellow student at the University of Bergen (Thrana 2002), who studied the sedimentology of the study area. Ideally the two sub-projects should, in combination, enable a three dimensional reconstruction of the internal geometry and reservoir properties of the dominant facies of the Azagador Member.

The Azagador Member represents a potential analogue for stratigraphic hydrocarbon traps formed in high-energy settings at the margin of marine basins. The main emphasis of this thesis is an investigation of the diagenesis and reservoir characteristics of the Member. Hence special effort has been devoted to investigation of the porosity characteristics of the dominant facies. Huge channelized structures dominate the Azagador Member, and an understanding of the diagenesis in these structures has been central to the study. Furthermore, studies of mixed systems are at a relative immature stage. A discussion of rock and porosity classification in such systems has therefore been included.

Typically, when a possible hydrocarbon trap has been identified, studies are undertaken to develop a data base on porosity and permeability. This is done to determine the amount of oil in place (STOIIP) and the most efficient way to extract it. Starting prior to drilling, data are collected from surface outcrops and these are extended to adjacent fields. Field analogues, such as the Azagador Member, play an important role in enhanced understanding of reservoirs. An improved understanding of the depositional environment and the subsequent diagenesis in the analogue will hopefully lead to better understanding of the reservoir, improved models and ultimately improved oil recovery. Tobin (1997) lists a series of possible limitations to outcrop-based predictions of subsurface reservoir quality compared to those based on subsurface data alone. The same author also acknowledges the great value of outcrop analysis as long as the limitations are understood.

This project is a part of SYNTESA, a collaboration programme between the Geological Institute at the University of Bergen and Norsk Hydro Research Centre in Bergen.

1.2. Study Area

The study area is located in the province of Almería in Andalusia, the south-eastern region of Spain. The studied successions crop out approximately 70 kilometres northeast of the Mediterranean coastal city of Almería (fig.1.1).

Fieldwork was carried out on outcrops situated in the south western part of the Vera Basin and along the relatively narrow transition between the Sorbas basin in the west and the eastern Vera basin. Focus has been along the south western border of the Vera Basin, approximately 10km inland of the coast (fig.1.1).

To the north and south the area is surrounded by elevated Permo-Triassic metamorphic rocks and carbonates, together with older metamorphic basement rocks of the Sierra de los Filabres and Sierra Cabrera (Nijhuis 1964; Westra 1969). During the late Tertiary the two basins are believed to have formed a narrow intramontane seaway (Thrana 2002).

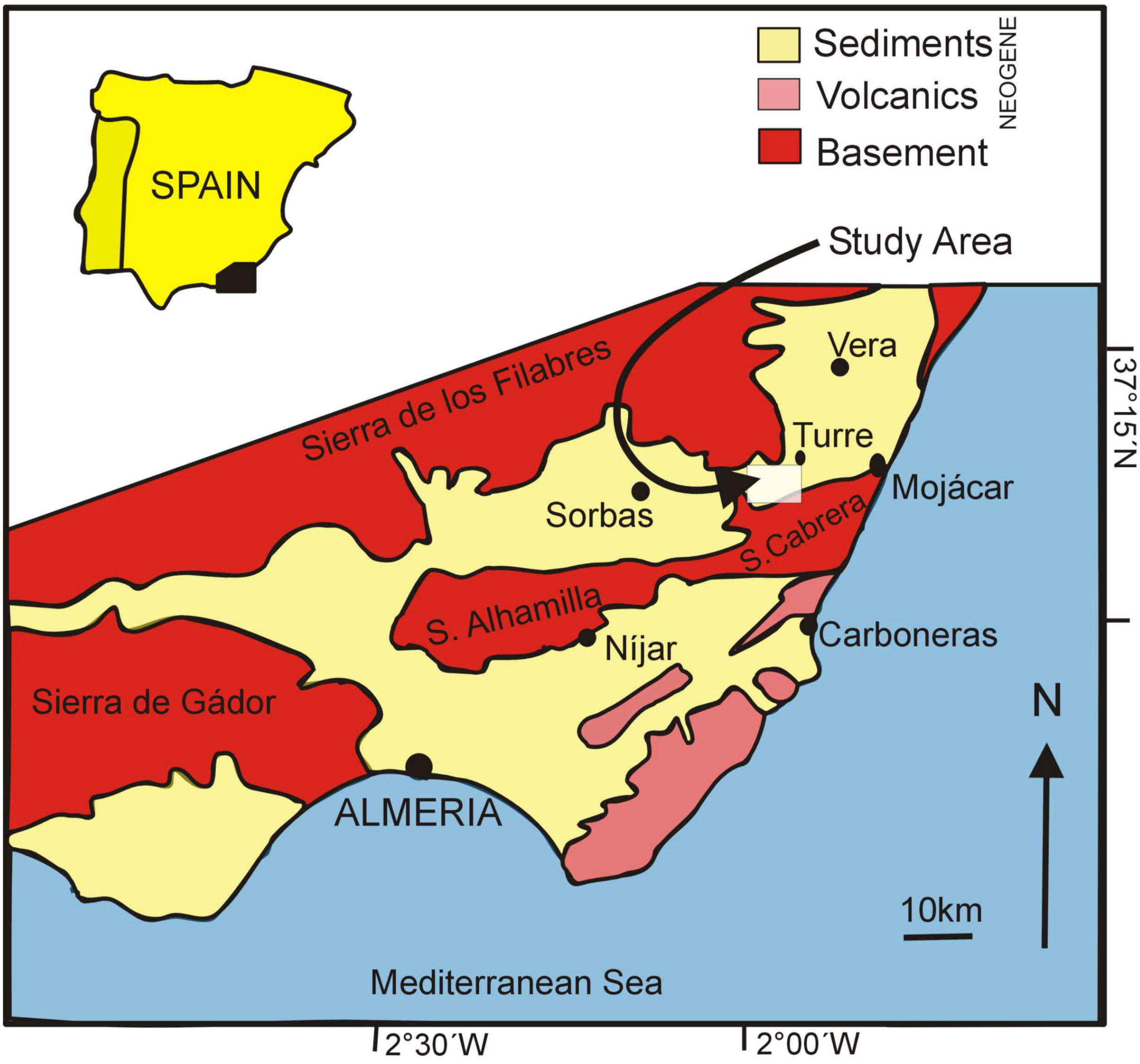

Fig.1.1. *Geological location of the study area. The Neogene rocks of the Azagador Member investigated in this study crop out in the Vera Basin. Focus has been along the south western border of the basin.*

Situated in and south of the Río de Aguas, the study area lies within a triangle between the town of Turre, the Barranco Azagador (-valley) south of the village of Alfaix, and the small village of El Cortijo Grande (fig.1.2).

Within this triangle, the topography comprises deeply incised river valleys and steep cliffs, and extensive flat areas, which are ideal for mapping. The outcrop area covers approximately 12 square kilometres. Apart from the numerous vertical cliff sections, the area is accessible by foot and to some extent by car.

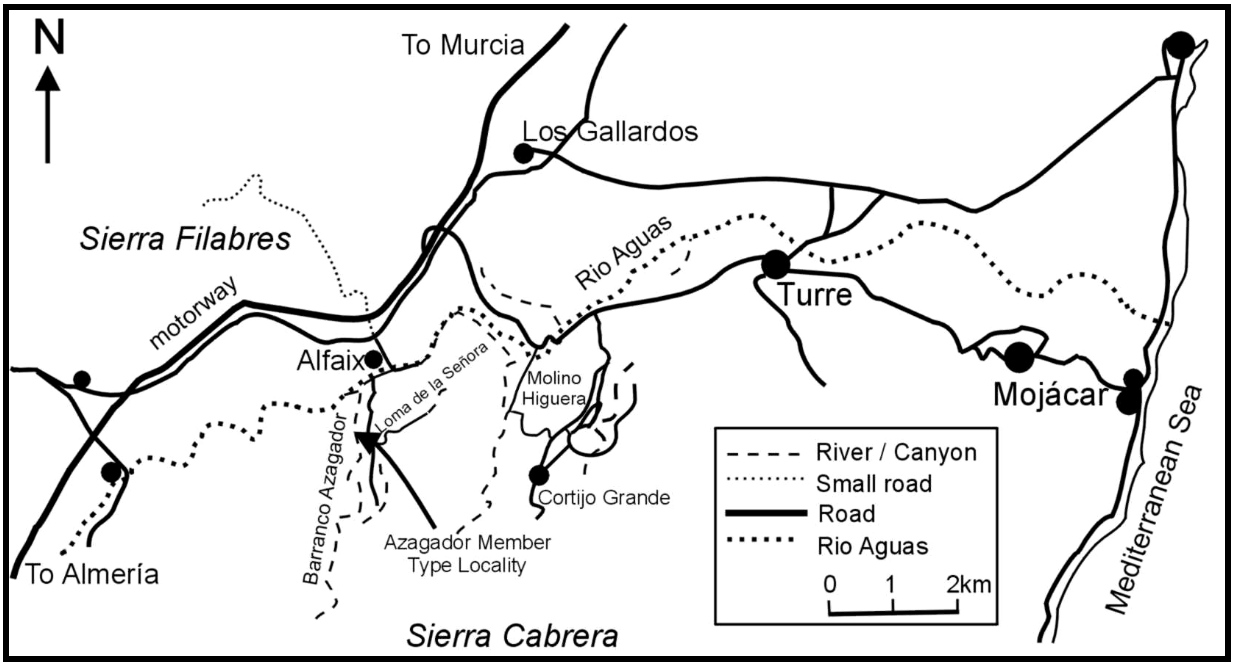

Fig.1.2. *Detailed geographical map of the study area, showing the main towns, roads and rivers*

To the north and northeast of the study area the Azagador Member is buried by younger deposits. The outcrop continues west of the Barranco Azagador-valley, while to the south the Azagador Member is truncated by a major southwest-northeast running fault south of El Cortijo Grande.

1.3. “Mixed siliciclastic-carbonate”-system

The term *mixed siliciclastic-carbonate system* has previously been defined in two different ways: 1) Siliciclastic and carbonate layers that interfinger on a millimetre to seismic scale (Lomando and Harris 1991), and 2) sediments that contain both siliciclastic and bioclastic material within the same sample. Hence, siliciclastics and carbonates (i.e. bioclastic allochems) do not interfinger, but are intimately mixed as parts of the same rock (fig.1.3). The latter is characteristic for the Azagador Member.

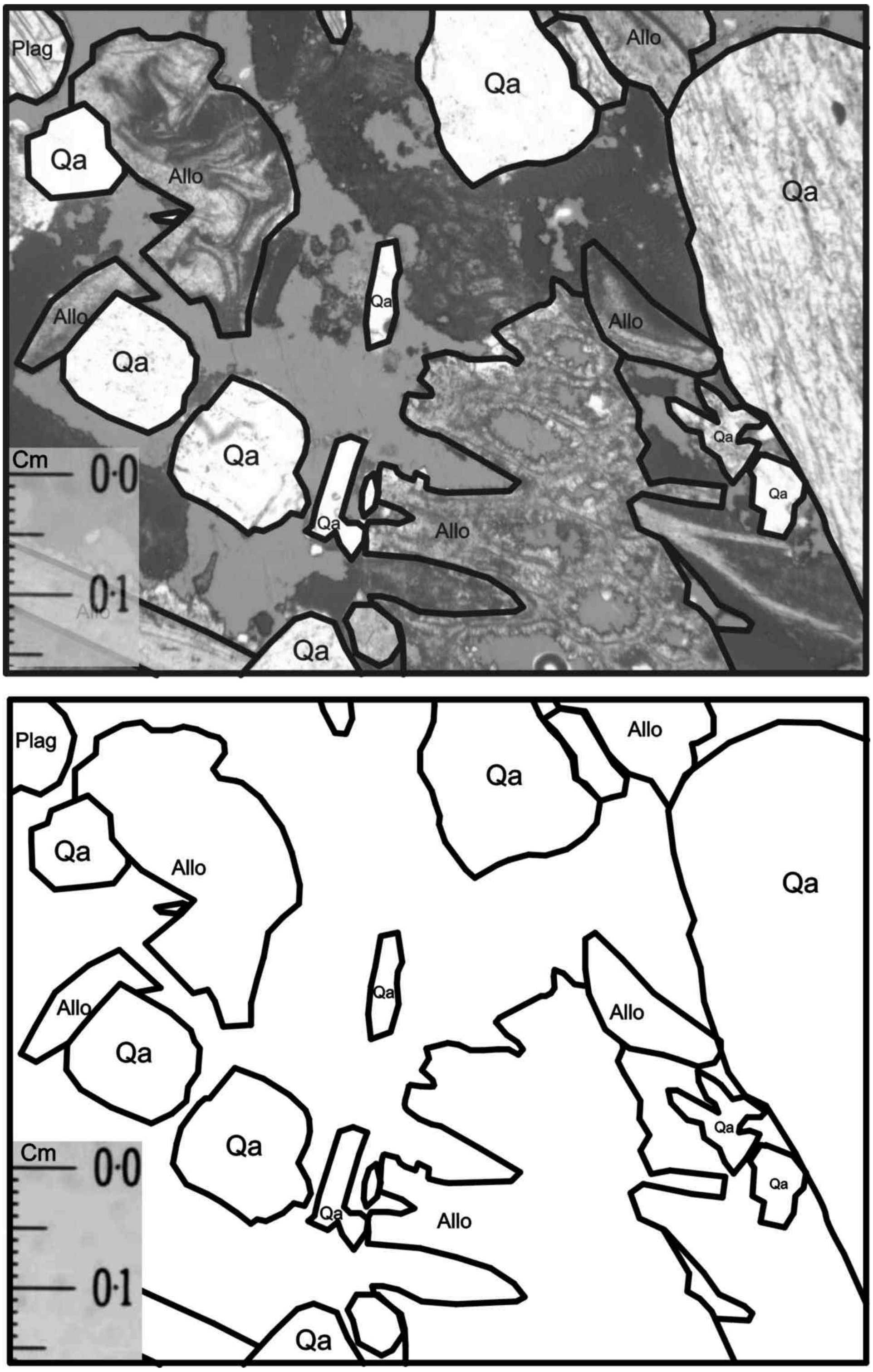

Fig.1.3. *Thin section from locality one (sample I02), illustrating the mixture of siliciclastics and allochems.* ***Qa****=Quartz****, Allo****=Allochems. Dark areas with dim outline are most probably alga, whereas grey areas are pores (pores are stained blue in the original colour picture). Ratio between quartz and allochems is approximately 1:2 and porosity is estimated to about 10 percent. Magnification x10.*

2. STRATIGRAPHY & REGIONAL GEOLOGY

2.1. Stratigraphy of the study area

Lower and Middle Miocene (Burdigalian to Serravallian) marine lime- and sandstones of the Alamo Formation are the oldest Neogene rocks present in the study area. These are overlain by alternating continental sandstones and conglomerates, and marine limestones and sandstones together with alluvial conglomerates of the Gomara and Umbria Formation (Table 2.1.) (Rondeel 1965; Braga et al. 2001). Unconformably overlying these rocks is the Lower Tortonian aged Chozas Formation, comprising shallow marine conglomerates at the base, followed by pelagic marls and turbidites.

These deposits are unconformably overlain by the investigated Azagador Member of the Turre Formation (Völk and Rondeel 1964) of late Tortonian to early Messinian age, which mainly comprises calcarenites. The Azagador Member was formally defined by Völk (Völk 1967) in the type locality of the Barranco del Azagador (see fig. 1.2 and 2.3). Interfingering with or overlying the Azagador Member is the younger Abad Member, also of the Turre Formation. The Abad Member is principally made up of deep marine deposits, varying from pelagic marls to sandy turbiditic facies. On top lies the reefal limestone of the Cantera Member, and the interbedded marls, turbidites, conglomerates and sandstones of the Cuevas Formation and the Espiritu Formation.

2.2. Regional geology and tectonic setting

The Neogene Vera and Sorbas basins are part of a system of interconnected, intramontane structural depressions within the Betic Cordillera (fig.2.1). Situated on the south-eastern Iberian Peninsula, the Cordillera form the westernmost part of the Alpine Mediterranean mountain chain. The Betic Cordillera is subdivided into an Internal Zone to the south, constituting the Alboran continental block and held as the Betic *sensu stricto*, and an External Zone

Table 2.1. *Stratigraphy of the Vera Basin and surrounding areas. The focus of this study is on the calcarenites of the Azagador Member. Based on Völk and Rondeel (1964), Rondeel (1965), Völk (1967), Weijermars et al. (1985), Braga et al. (2001) and Thrana (2002).*

Geocron. Units	**Stratigraphic Nomenclature**		**Facies & palaeo-environment**	**Tectonic consequences in the Vera Basin**
Pliocene	Espiritu FM		Deltaic facies, conglomerates, marls and sandstone interbeds	Uplift
	Cuevas FM		Pelagic marls and turbidites	Subsidence Transgressive facies
Messinian	Turre FM	Cantera MB	Reefal limestone	Uplift at basin margins Regression
		Abad Mb	Pelagic marls and turbidites	Subsidence Erosion of basin margins Possible tectonic influence
		Azagador Mb	Coarse grained bioclastic calcarenite. Platform or ramp facies	Uplift and erosion (partly submarine) Discordance
Tortonian	Chozas FM	Gatar Mb	Shallow marine conglomerates, pelagic marls and turbidites	
		Loma Colorada Mb		
Serravallian	Umbria FM	Mofar Mb	Alternating continental sandstones and conglomerates, and marine limestones and sandstones together with alluvial conglomerates	Several incidences of faulting, uplift, erosion and transgression
		Lomas Blancas Mb		
		Romano Mb		
Langhian	Gomara FM			
Burdigalian	Alamo FM	Lino Mb	Marine limestones and sandstones	
		La Huelga Mb		

to the north (Sanz de Galdeano and Rodríguez-Fernández 1996). The two zones are separated by a major ENE-WSW trending wrench fault corridor (the North Betic Wrench Fault equals the ´foreland´ area in fig. 2.1) (Montenat and D'estevou 1996). The Inner Betic Zone, also trending ENE-WSW, stretches from the Atlantic coast of Spain in the west, to the city of Valencia just north of Alicante on the Mediterranean coast (fig.2.1). Inland it is limited northwards by the foreland (the External Zone). The best known part of the Cordillera is probably the eternal-snow covered Sierra Nevada, rising to 3478 meters, located in the heartland of the Inner Betic Cordillera.

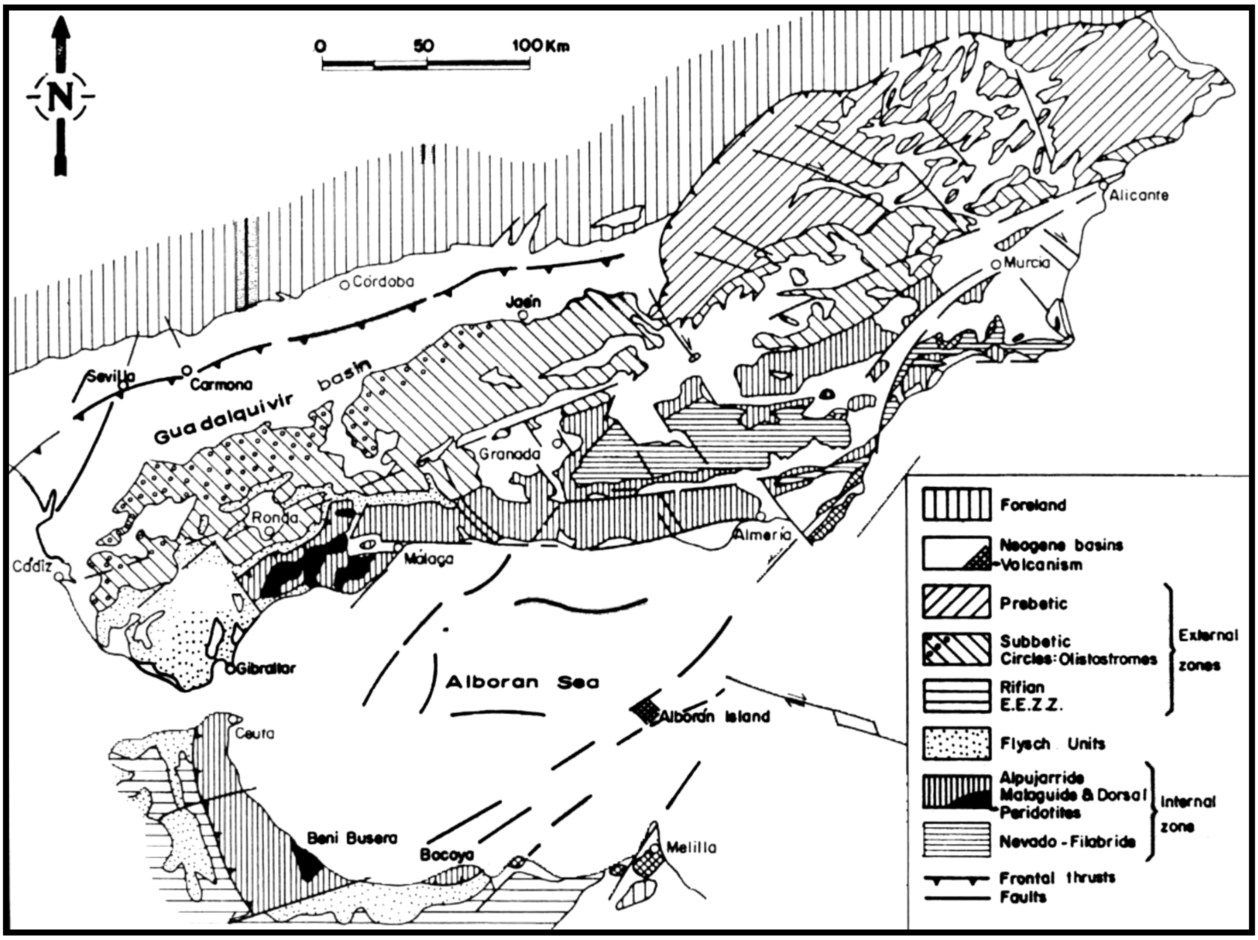

Fig.2.1. *General map of the Inner Zone of the Betic Cordillera. The Sorbas and Vera basins are situated just north-east of Almería. After Sanz de Galdeano and Rodríguez-Fernández* (1996)*.*

Collision between the African and the Euro-Asian tectonic plate started in the Mesozoic and lead to the formation of the Alpine orogen, including the Betic Cordillera. But it was not until Miocene times, approximately 23 million years ago, that the Betic orogen became a major structure. During the whole of the Miocene the dominating direction of the movement alternated between a northwest-southeast and a north-south compression of Iberia and Africa. The continuous collision resulted in a left-lateral movement along the older and major trans-Alboran corridor. For the last 10 million years only this movement has been estimated to as much as several tens of kilometres (Montenat et al. 1987). A segment of this northeast-southwest running transcurrent shear zone passes through the area between Almería and Alicante in south-eastern Spain (fig.2.2) This constitutes the eastern Inner Zone of the Betic Cordillera – an area where the shear movement was, and still is, controlling the geometry of the basins (Montenat et al. 1987).

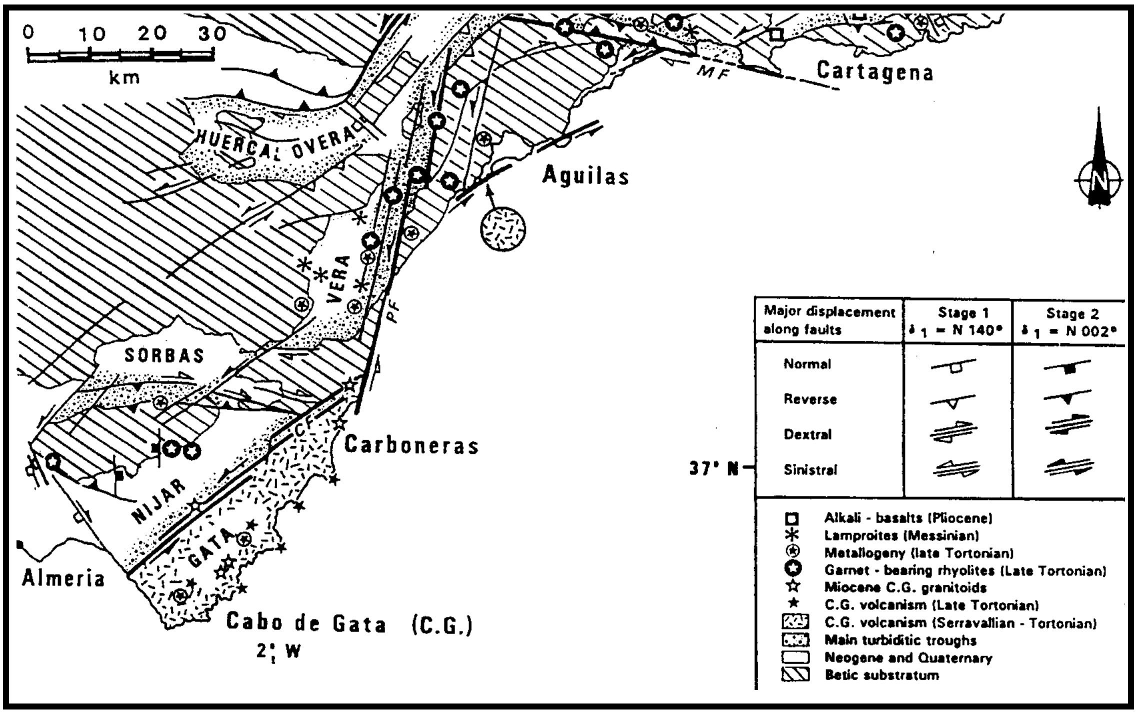

Fig.2.2. *Structural framework of a segment of the late Neogene basins of the eastern Inner Betic Zone. Note the prevailing NE-SW-trending branch of faults formed by the Carbonera (CF) and Palomares (PF) wrench faults, as opposite to the dextral Moreras Fault (MF) to the north. Modified from Sanz de Galdeano and Rodríguez-Fernández* (1996)*.*

The intramontane structural depressions, defining several sedimentary basins such as the Vera and Sorbas basins, are entirely or partly separated by mountain ranges (“sierras” in Spanish). Both the depressions and the sierras formed as a direct result of the strike-slip movement within the shear zone, or branches of this (Völk 1967; Montenat et al. 1987; Montenat and D'estevou 1996). The exposed allochthonous rocks are faulted and refolded as a result of the plate collision and the accompanying wrench tectonics. The Inner Betic Cordillera zone is classically categorized into three complexes overlying each other in the basement. In ascending order these complexes are:

1) *Nevado-Filábride* – metamorphic rocks, primarily mica schists and quartzites of Palaeozoic and older age, polyphase deformed
2) *Alpujarride* – phyllites and quartzites of Permo-Triassic age and carbonate rocks of Triassic age, polyphase deformed
3) *Malaguide* – mainly non-metamorphic rocks, mostly carbonate rock, sandstone, shale and conglomerate of Silurian to Oligocene age

Within the study area the Nevado-Filábrides and the Alpujarrides are exposed in the Sierra de los Filabres and the Sierra Cabrera ranges (Nijhuis 1964; Westra 1969; Weijermars et al. 1985) (see fig.1.1). The Malaguide complex is not present.

The allochthonous rocks constitute the basement to Neogene sediment, the first generation of which developed during the early and middle Miocene (Montenat and D'estevou 1996). Simultaneously the allochthonous massifs provided the source for much of the siliciclastic sediment in the associated basins throughout the Miocene (Weijermars et al. 1985). At that time, large areas of the shear zone were covered by the sea and sedimentary and tectonic processes occurred simultaneously. This gave rise to a range of synsedimentary structures (Montenat and D'estevou 1996). In the study area, the Sierra de los Filabres and the Sierra Cabrera have largely controlled the sedimentary patterns. In addition, the morphology of the strait located between the two mountain ridges (see fig.1.1) appears to have influenced, and possibly enhanced, marine currents (Thrana 2002).

Both the Sorbas and the Vera basins are categorized as compressional wrench-through syncline-shaped basins, defined by relatively thick sedimentary successions (>1000m) deposited within narrow areas (initial width of about five kilometres) along the major strike-slip faults (Montenat et al. 1987) (fig.2.2). The Sorbas Basin is oriented roughly east-west while the Vera Basin has a more northeast-southwest orientation. The transitional area between the two basins is bounded by the Sierra de los Filabres to the north and the Sierra Cabrera to the south (fig.2.2). The Vera basin verges on to the Mediterranean Sea further east.

A northeast-southwest-oriented sinistral strike-slip fault is associated with the transition between the Sorbas and the Vera basins. However, the investigated outcrops of the Azagador Member are not directly affected by this fault. There is a southern limitation of the outcrop areas south of El Cortijo Grande related to a northeast-southwest oriented fault, in addition to a similarly oriented fault cutting into El Cortijo Grande, south of locality five (fig.2.3). The latter has deformed the Azagador Member within a limited area close to the fault plane. As a result of tectonic influence, the Azagador Member dips at four degrees in a generally north eastern direction. In general, the Azagador Member is scarcely affected by tectonics. No further investigation was performed to map these faults as they are not considered relevant for the purpose of this thesis.

The Sierra de Filabres formed a topographic relief prior to the onset of the Neogene sedimentation (Martín and Braga 1996). The Sierra de los Alhamilla, which now forms the southern margin of the Sorbas basin, was only elevated towards the end of the Tortonian period, i.e. before the onset of the Messinian sedimentation (Weijermars et al. 1985). The combined effects of tectonic uplift and a sea-level fall towards the end of Tortonian resulted in the formation of an unconformity located at the top of the upper Tortonian siliciclastics in the Sorbas basin (Martín and Braga 1996), and most probably, also in the Vera Basin (Braga et al. 2001). The resulting angular unconformity separates the Chozas Formation from the overlying Azagador Member of the Turre Formation.

Braga et al. (2001) suggest that the Sierra Cabrera formed a progressively uplifted submarine swell that *affected* the local sedimentation. However, these authors suggest that a *major* topographic relief did not emerge until after the deposition of the Azagador Member. Whether or not it was a major high determines if the Azagador Member was deposited on an open platform or on a platform within a narrow strait. A credible interpretation of the palaeoenviroment and hence the understanding of the generation of the major (channelized) structures within the study area (fig.2.5-8) hinges on this distinction. This question is examined in more detail in the thesis of Thrana (2002).

2.3. Lithology and localities

The studied sedimentary sequences are all part of the Messinian-aged Azagador Member of the Turre Formation (Völk and Rondeel 1964), which also crops out in several other Neogene basins in the area (Braga et al. 2001). The Quaternary deposits of the study area occur mainly within the river bed of Rio de Aguas (fig.2.3). The pre-Azagador deposits are for the most part the Tortonian aged Chozas Formation.

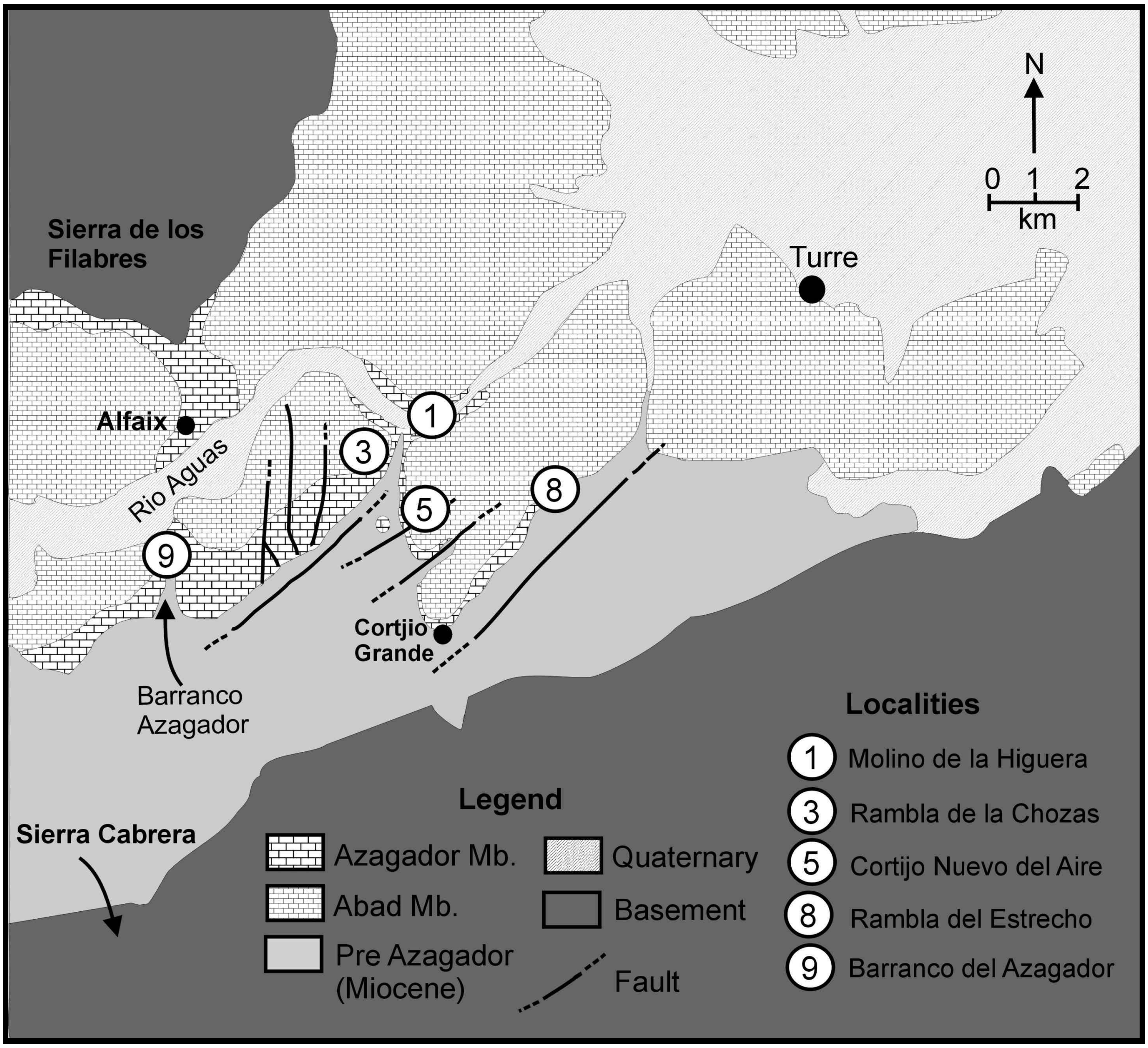

Fig.2.3. *Detailed geological map with numbered localities. Azagador calcarenites occur in several areas, especially along cliffs, whereas it is covered by the Abad Member in others, mainly table areas. Numbers in circles indicate field localities. Modified from Rondeel* (1965) *and Braga et al. (2001).*

A cross section through the area shows that it is dominated by Neogene deposits and that the Azagador Member comprises small, disconnected bodies (Braga et al. 2001)(fig.2.4). Although the basement does not outcrop in the study area, clasts of the surrounding nappes are present in the Azagador Member.

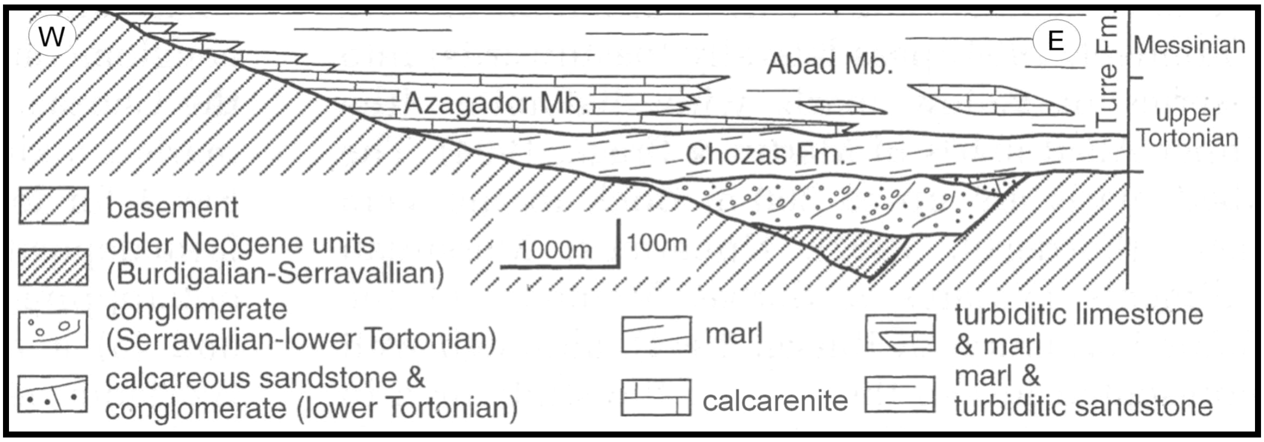

Fig.2.4. *Schematic W-E stratigraphic section through the study area. The Azagador Member occurs along the basin margin and, according to Braga et al. (2001), as small disconnected bodies. Burdigalian to Lower Tortonian sediments occur within half-grabens related to early rifting. Strike slip movement is considered to have controlled the Upper Tortonian to recent sedimentation, and the present day basin configuration. Modified from Braga et al. (2001).*

Five localities have been investigated in detail (fig.2.3). A majority of the investigated samples were taken from locality 1, 3, 5 and 9 (fig.2.5-8). See methodology-chapter for a more comprehensive presentation of the localities. These five localities are:

1) *Molino de la Higuera*
3) *Rambla de la Chozas*
5) *Cortijo Nuevo del Aire*
8) *Rambla del Estrecho*
9) *Barranco del Azagador*

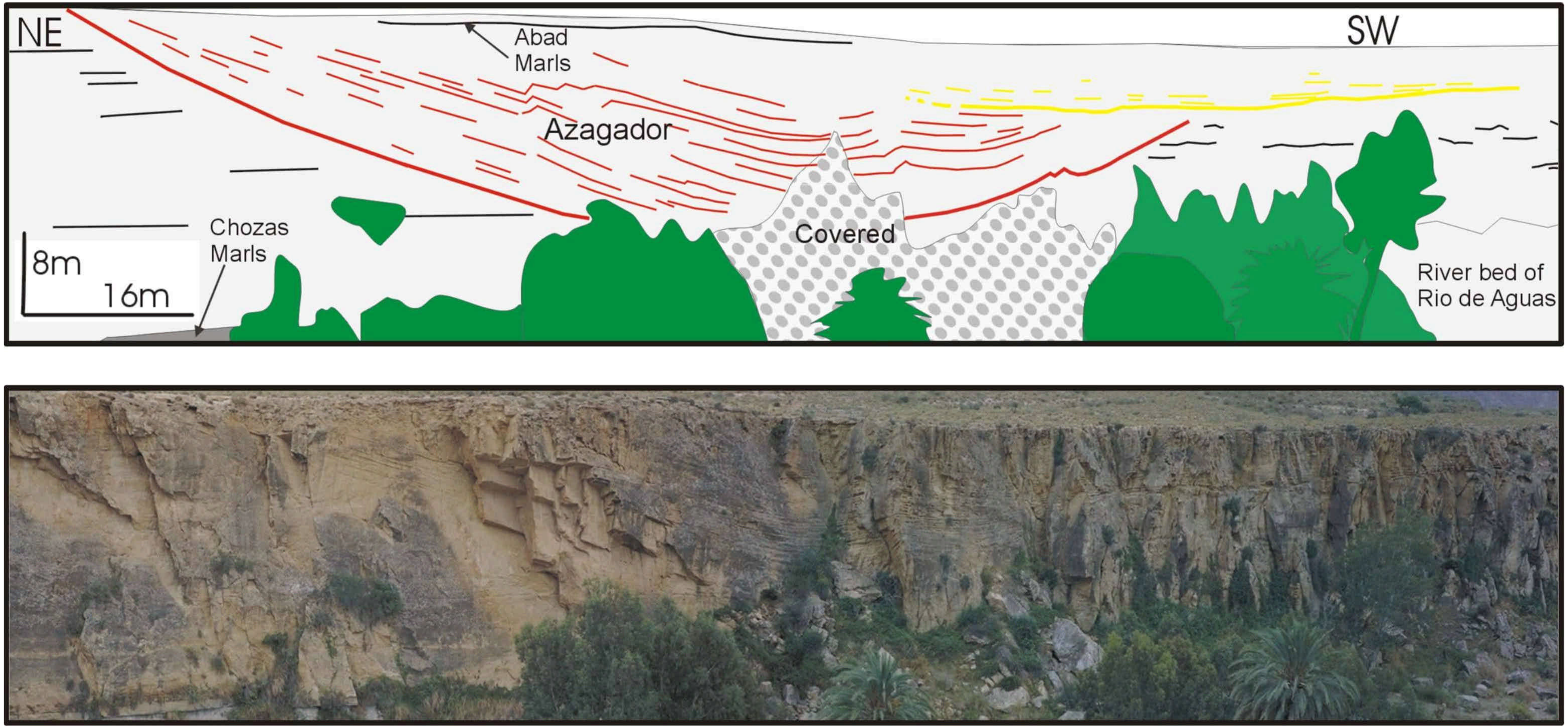

Fig.2.5. *Locality 1 – The NE-SW oriented cliff of Molino de la Higuera along the River Aguas. The figure shows the channel outlines (top) and a picture of the locality (bottom). Major channel structures appear to have eroded into platform or ramp sediments. This was later filled by calcarenite sediments at two, possible three different stages. Note also the marls of the Chozas Formation located below the Azagador Member, and the overlying Abad Member.*

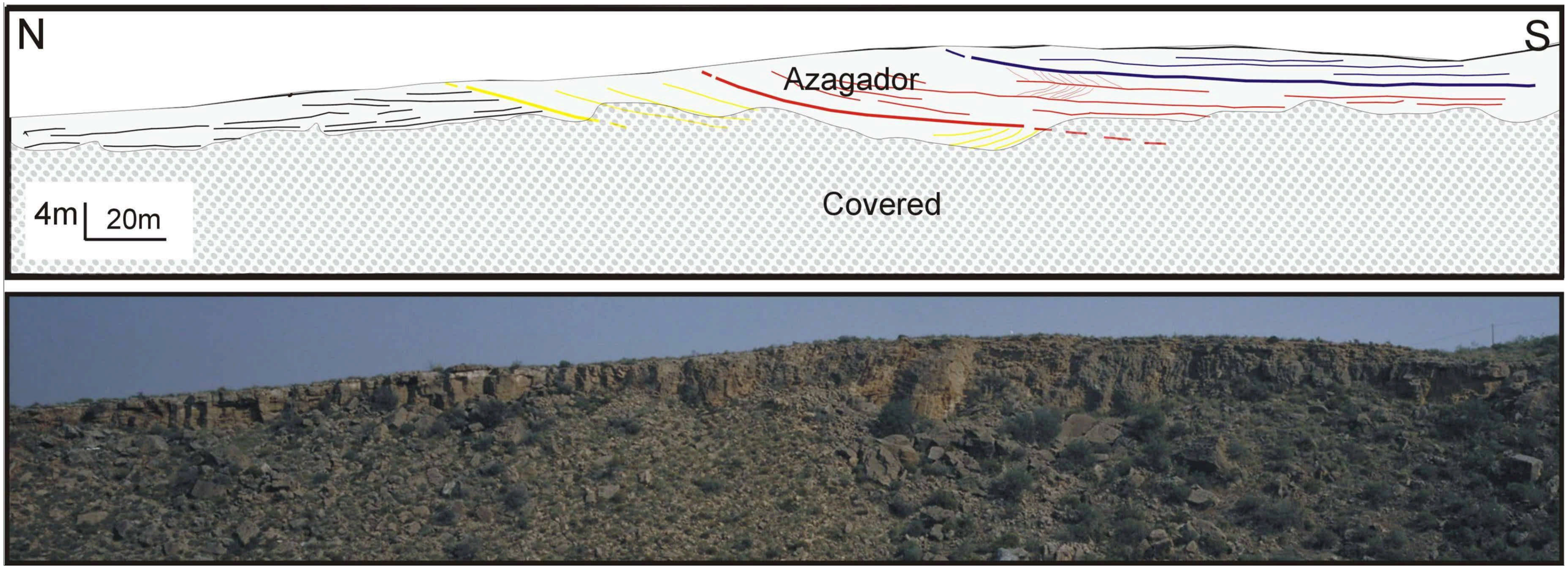

Fig.2.6. *Locality 5 – The N-S oriented outcrop of Cortijo Nuevo del Aire. The figure shows the channel outlines (top) and a picture of the locality (bottom). Several major channels appear to have eroded the platform or ramp sediments. These channels were later filled by calcarenite sediments at different stages.*

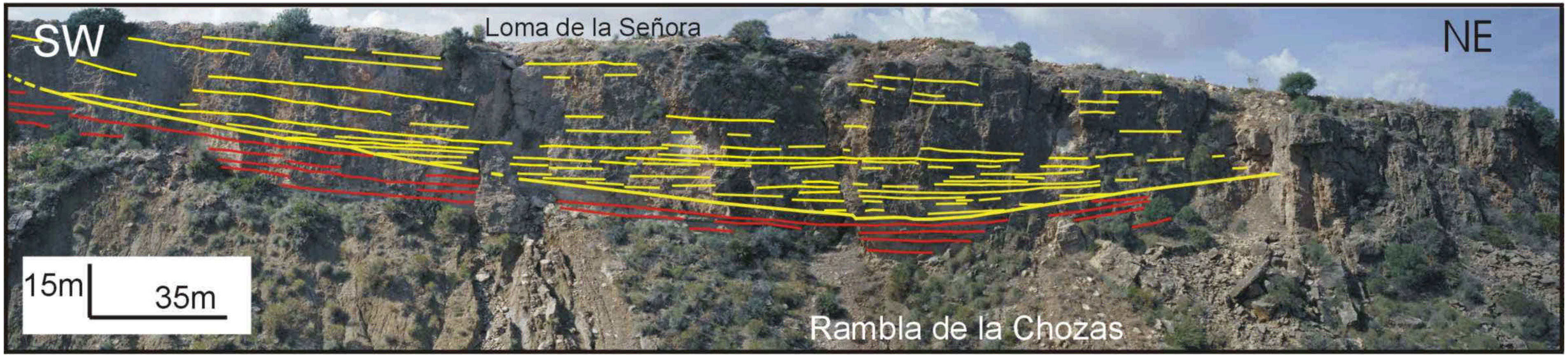

Fig.2.7. *Locality 3 – The NE-SW oriented outcrop of Rambla de la Chozas. The figure shows the interpreted channel outlines in colours on top of picture. One, possible two major channels appears to have eroded the platform or ramp sediments.*

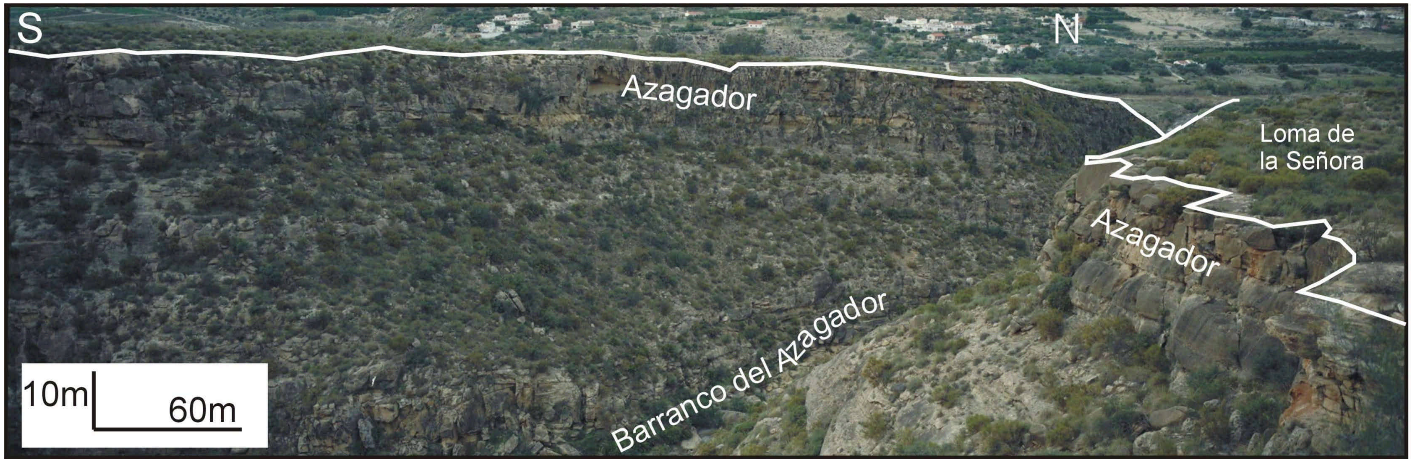

Fig.2.8. *Locality 9 – The N-S oriented outcrop of the Barranco del Azagador – the type locality for the Azagador Member. No major channel structures are recognized. The deposits are up to 60 meters thick.*

3. GEOLOGICAL BACKGROUND

3.1. Sequence stratigraphy of the Vera Basin

The relative sea level changes of the Vera Basin are thought to have been the same those as of the neighbouring Sorbas basin. The eustatic curves from Martín (1996)(fig.3.1) are therefore believed to be valid for the Azagador Member (Braga et al. 2001; Martín and Braga 2001). The Azagador Member is interpreted as deposits of a Low Stand Systems Tract (LST) of a third order cycle, which can be correlated to the TB3.3 cycle of Haq et al. (1987)(fig.3.1). At a higher frequency fourth order cycle the deposits of the lower Azagador/lower Abad are tentatively assigned to the Lowstand System Tract of a fourth order sequence.

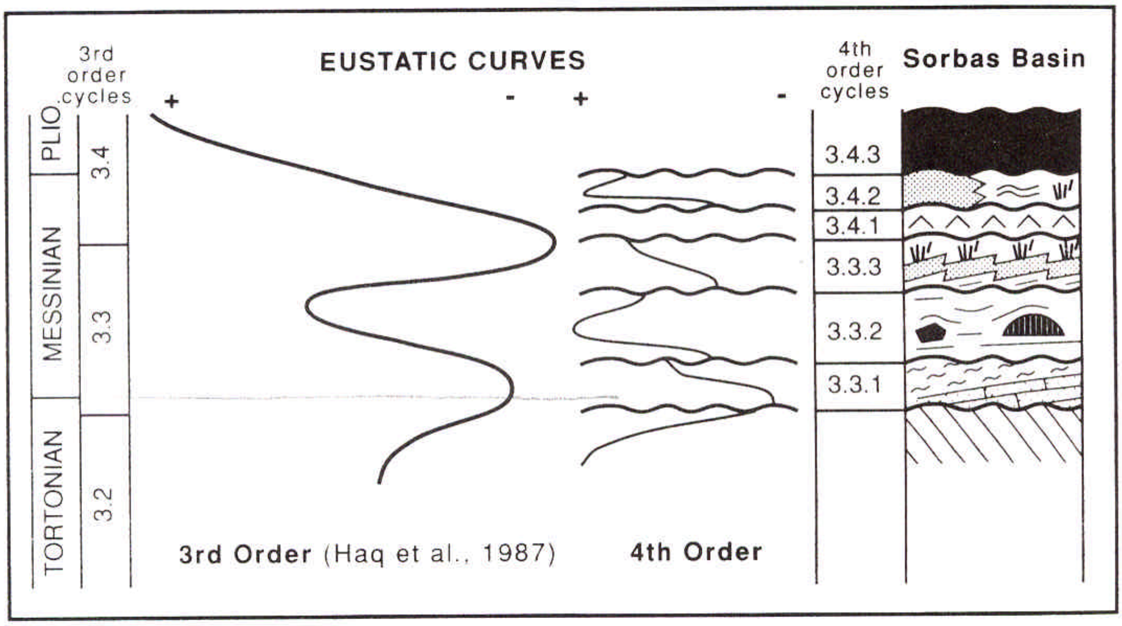

Fig.3.1. *3rd and 4th order sedimentary sequence stratigraphy cycles represented in the Messinian of the Sorbas basin and the neighbouring Vera basin, and the inferred eustatic curve. The temperate calcarenites of the Azagador Member belong to unit 3.3.1 in the 4th order cycle. After Martín (1996).*

The platform deposit facies of the Azagador Member are interpreted as part of the subsequent Transgressive Systems Tract (Braga et al. 2001), presumably deposited in a shallow sea (cycle 3.3.1 in fig.3.1). The bioclastic constituents of the Azagador member are of marine origin (fig.3.2). No highstand is believed to be present in the area.

The Azagador Member may thus have experienced early burial during sea level rise. This would have prevented both extensive subsurface weathering and early diagenesis. However, locally developed paleosols suggest local exposure of the Azagador Member prior to “final” burial.

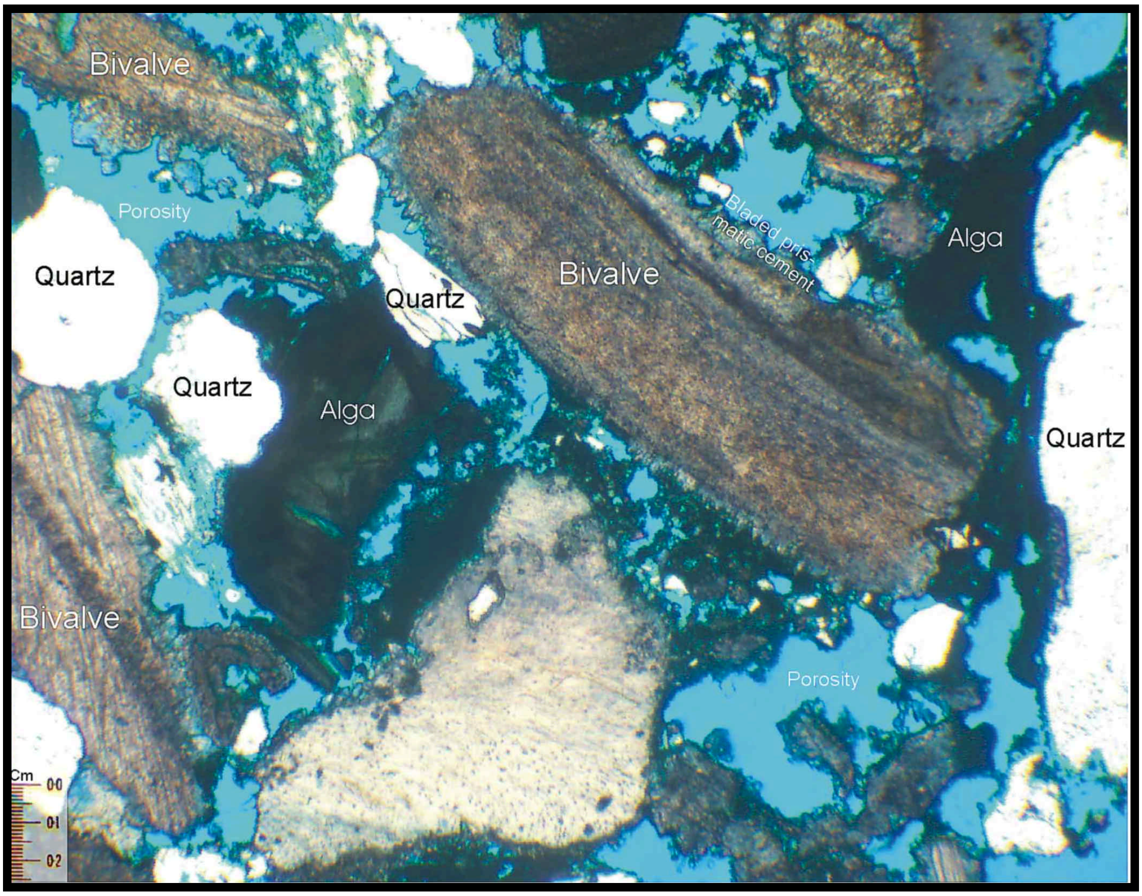

Fig.3.2. *Thin section from locality one (sample I127), belonging to facies three (F3), illustrating typical marine carbonate fossils such as bivalves and red calcareous algae in addition to bladed prismatic burial cement. Note lack of typical signs of meteoric phreatic and vadose influence such as meniscus or microstalactite cement. Porosity stained blue. Magnification x3,2.*

The origin of these local exposure surfaces is believed to be a result of palaeotopography on the sea floor, due to variable relief on the erosion surface cut into the underlying Tortonian sediments. This created highs and lows in the Azagador Member, thus controlling sediment thickness.

3.1.1. Uplift and weathering of the Azagador Member

There is little evidence of alteration of the Azagador Member due to recent weathering processes. For example, no typical weathering-textures, such as karst topography and intense cementation of originally porous rocks, nor extensive formation of secondary porosity in an originally tight rock, are observed. This is attributed to the present arid climate and alkaline groundwater. Samples were taken in order to avoid any possible weathered surfaces.

3.2. Facies & constituents of the Azagador Member

3.2.1. Facies of the Azagador Member

In all eleven different facies have been recognised within the Azagador Member exposed in the study area (Thrana 2002), but the 27 samples investigated in detail in this thesis come from only six of these (see chapter five)(table 3.1)

3.2.2. Constituents of the Azagador Member

The constituents of the Azagador Member are 1) siliciclastics, 2) rock fragments, 3) bioclastic allochems and 4) cement (table 3.2). The proportion and fabric of each grain-type varies.

Table 3.1. *The eleven different facies present within the Azagador Member. Modified from Thrana (2002).*

F1 *Granular sandstone in lag deposits* ▪ 1,5 meters vertical thickness, tabular geometry ▪ Massive amalgamated surfaces
F2 *Crossbedded pebbly calcarenite* ▪ Up to 30 meters vertical thickness, tabular geometry ▪ Parallel lamination, tabular crossbedding, trough crossbedding
F3 *Large-scale channelized structures with heterolitihic calcarenite* ▪ Maximum 25 meters vertical thickness, limited to channel structures ▪ Alternating massive to parallel laminated geometry ▪ "Hummocky" crossbedded and large-scale tabular crossbedding
F4 *Massive pebbly calcarenite* ▪ Up to 6 meters thick, tabular to lens shaped geometry ▪ Massive to normally graded
F5 *Massive, pebbly and granular to parallel-laminated, medium-grained calcarenite* ▪ Maximum 50cm vertical thickness, lens-shaped to tabular geometry ▪ Normally graded from massive to parallel laminated ▪ Water-escape structures, occasionally swaley cross-stratification (SCS) and smallscale tabular crossbedding
F6 *Trough crossbedded calcarenite* ▪ Four meters thick, tabular geometry ▪ Trough crossbedded, sometimes truncated by parallel lamination
F7 *Sandy marl* ▪ 1,4 meters thick ▪ Massive to weakly developed normal grading
F8 *Homogenous sandy calcarenite* ▪ One meter thick, tabular geometry ▪ Weak parallel lamination, tabular crossbedding
F9 *Laminated micrite* ▪ 25cm vertical thickness, laminated
F10 *Clast-supported conglomerate* ▪ Maximum six meters thick, low angle erosional surfaces, clast imbrication
F11 *Matrix supported bioclastic conglomerate to massive and parallel laminated medium grained sandstone* ▪ Maximum 2,4 meters thick, lens shaped to tabular geometry ▪ Inverse to normal grading and massive to parallel lamination

Table 3.2. *The common constituents and deformation features of the investigated samples.*

Siliciclastics	▪ Single and polycrystalline quartz by far the most abundant siliciclastics. Feldspar extremely rare ▪ All grainsizes represented, but the middle range dominates. Occasionally, pebble-sized grains average dia. ~5mm occur ▪ With a few exceptions, grains sub-rounded to very angular ▪ Pressure solution at several quartz-quartz contacts. A few of the polycrystalline grains partly disintegrated, but not necessarily at grain-grain contacts. Some also cracked ▪ No quartz overgrowth observed
Rock fragments (RF)	▪ Fragments of metamorphic crystalline rock occasionally observed ▪ In addition clasts of sands- and limestones ▪ Average size about 0,7 cm and normally sub rounded ▪ RF originated from the nearby bed rock
Bioclastic allochems	▪ Allochems vary in size from millimetres to tens of centimetres, but average less than one cm ▪ Concentrations of a particular species occasionally observed, e.g. echinoderms and red alga have a tendency to cluster ▪ Almost all of the grains partly to sometimes almost entirely dissolved and/or disintegrated, sometimes also cracked ▪ Quartz commonly penetrate the allochems, leaving the latter partly dissolved by pressure solution ▪ Other allochems, such as the fragile red alga, most probably partly disintegrated prior to lithification
Cement(s) & Matrix	▪ With the exception of rare micrite envelopes, all observed cements of two kinds; 1) bladed prismatic and/or 2) coarse mosaic calcspar ▪ Neomorphism, e.g. alteration of aragonite to calcite may have occurred, but no obvious example identified ▪ Cement occasionally completely to partly filling in pore space and cavities in allochems and cracks ▪ Cement appears to be more abundant around and close to allochems, rather than quartz and rock fragments, even when the grains only a few millimetres apart ▪ The matrix consists of varying amount of micritic mud

3.2.3. Sedimentology and fauna of allochems

The faunal assemblage of the Azagador Member is typical of a temperate climatic setting (Braga et al. 2001), represented by so called cool-water (platform) carbonates, also known as temperate carbonates. Such deposits accumulate in modern seawater that is generally colder than 20°C and/or under conditions of elevated nutrient supply. Increased nutrient supply is commonly related to transgressive phases (James 1997).

Oxygen isotopic studies carried out on planktonic foraminifera tests from the marls laterally equivalent to the Azagador Member, yield an average sea-surface palaeotemperature of 16°C ±2 for the associated carbonates (Martín and Braga 2001). Climate during the late Neogene is believed to have alternated between temperate and tropical condition. The periods prior to and after deposition of the Azagador Member are believed to have been tropical (Martín and Braga 1996).

The connection between past and present cool-water carbonates was first made by Lees and Buller (1972) and later by Lees (1975). They investigated modern carbonate sands and gravels from shelves (<100 meters deep) between 60°N and 60°S latitudes and compared these to ancient rocks. These carbonates are part of the *Heterozoan Association* (James 1997), originally termed *Foramol Association* by Lees and Buller (1972). The cool water carbonates of the Heterozoan Association are of particle types produced by coralline algae and benthic invertebrates. Modern sediments of this kind are found worldwide in platform environments, typically on unrimmed ramps and open-shelves, and their style is determined by the local input of terrigenous sediments (James 1997). The local terrigenous sediment input is a major control on the accumulation of carbonates in general. This is especially so for the relatively slowly accumulating cool-water carbonates (Chave 1967).

Presently, the connection between modern cool-water carbonate sediments and ancient rocks possessing the same components, is well established (Carannante et al. 1988; Nelson 1988; James 1997). Cool-water carbonates are dominated by a calcitic mineralogy. The main criteria for recognizing cool-water carbonates of the Heterozoan Association in the rock record is the presence of molluscs, foraminifera, bryozoans, echinoderms and commonly red alga. In addition, it is characterized by the absence of certain corals and/or green algae, typical of a “warm-water” association (the *Chlorozoan Association* of Lees and Buller) (Lees and Buller 1972). The Heterozoan Association and the Chlorozoan Association are both part of the larger *Photozoan Association* (James 1997). The bioclastic allochems of the Azagador Member belong to the Heterozoan Association, common all through the Cenozoic (table 3.3.). This is also confirmed by Braga et al. (2001).

Table 3.3. *The main bioclastic allochems of the investigated thin sections and samples, and the main features of each. All samples belong to the Heterozoan Association. Based on Adams et al. (1984), James and Choquette (1990), Adams and MacKenzie (1998) and Lønøy (2000).*

Calcareous red algae	▪ Cellular structure, usually 1-20cm in size ▪ Mostly shallow marine origin ▪ High-Mg calcite, neomorphism to low Mg-calcite
Echinoids (of the Echinoderms)	▪ Often broken down to microporous plates or spines of single calcite crystals ▪ Mostly shallow marine origin ▪ Often associated with calcite overgrowth ▪ If high magnesium calcite then neomorphism to low-Mg calcite during diagenesis
Foraminifers (benthonic)	▪ One-celled with one or several chambers, commonly less than 1mm in diameter ▪ Almost solely shallow marine origin ▪ Benthic foraminifera most common ▪ Primary mineralogy commonly low-Mg calcite
Molluscs	▪ Bivalves, oysters and gastropods usually 1-5 cm in size ▪ Most commonly shallow marine origin ▪ Only molluscs with low- or high-Mg calcite-shells have the wall-structure preserved

3.3. The siliciclastic/limestone approach

Whether the Azagador Member should be treated as a siliciclastics or carbonate unit depends on different factors, such as depositional processes and diagenesis. There are some similarities and many differences in the way that siliciclastics and carbonates are deposited and respond to physical and chemical conditions during burial and lithification. The generation and deposition of most carbonates, with certain exceptions such as for instance beaches and tidal flats, are controlled by biological activity. However, whilst siliciclastic sediments may be altered by biological activity after deposition, the actual sediment transport and the depositional processes are not controlled by it (but may be influenced by it) (Kupecz et al. 1997). Within mixed siliciclastic-carbonate systems the processes influencing the bioclastic allochems are not merely biological. Transportation is a key process that for instance controls the grain shape (see also Thrana (2002) for a more comprehensive discussion). Due to the absence of organic reef building organisms, allochems/sediments of the Heterozoan Association have a tendency to develop ramps. On ramps, depositional processes are often of a high energy type, influenced by waves, currents and tide waters.

Diagenetic porosity in sediments is in general strongly influenced by depositional and early diagenetic environments (Brown 1997). Choquette and Pray (1970) stress the relative importance of early diagenesis compared to burial diagenesis in shallow-water carbonates due to the chemical reactivity of carbonate sediments. This is also one of the reasons why pore systems in carbonates are much more complex than in siliciclastics (Moore 2001). The Azagador Member lacks typical diagenetic features diagnostic of a siliciclastic system (e.g. quartz overgrowth). On the contrary, the diagenetic features identified in the Azagador Member appear to have a strong connection to the carbonates present in the sediments (e.g. the type of dissolution, cement growth etc.).

Although mixed sediments are transported and deposited in a manner simular to siliciclastics, the aspects discussed here justify a carbonate approach with regards to burial and diagenesis of the Azagador Member. Hence, diagenesis and porosity in *carbonates* are of primary interest in the study of the Azagador Member.

3.4. Diagenetic environments and diagenesis

Sedimentary carbonate particles and cements at or near the seafloor are either calcitic or aragonitic, whereas in the burial realm dolomite may also be present. Calcite may be referred to simply as calcite or as low-Mg calcite (less than 2 mole percent Mg). If enriched in magnesium (Mg), it is commonly referred to as high-Mg calcite (between two and 18 mole percent Mg) (James and Choquette 1990). Cementation in carbonates takes place when pore fluids are supersaturated with respect to the cement phase and no kinetic factors inhibit precipitation. The actual fabric and mineralogy of cements mainly depend on the composition of pore-fluids (especially on the Mg/Ca ratio of the fluids and whether or not the pore fluids were marine, meteoric or subsurface brines), the carbonate supply rate and on the precipitation rate (James and Choquette 1990; Tucker and Wright 1990).

The principal carbonate diagenetic environments are (fig.3.3)

1) The meteoric diagenetic environment (vadose and phreatic)
2) The marine diagenetic environment / sea floor (vadose and phreatic)
3) The shallow to deep burial diagenetic environment

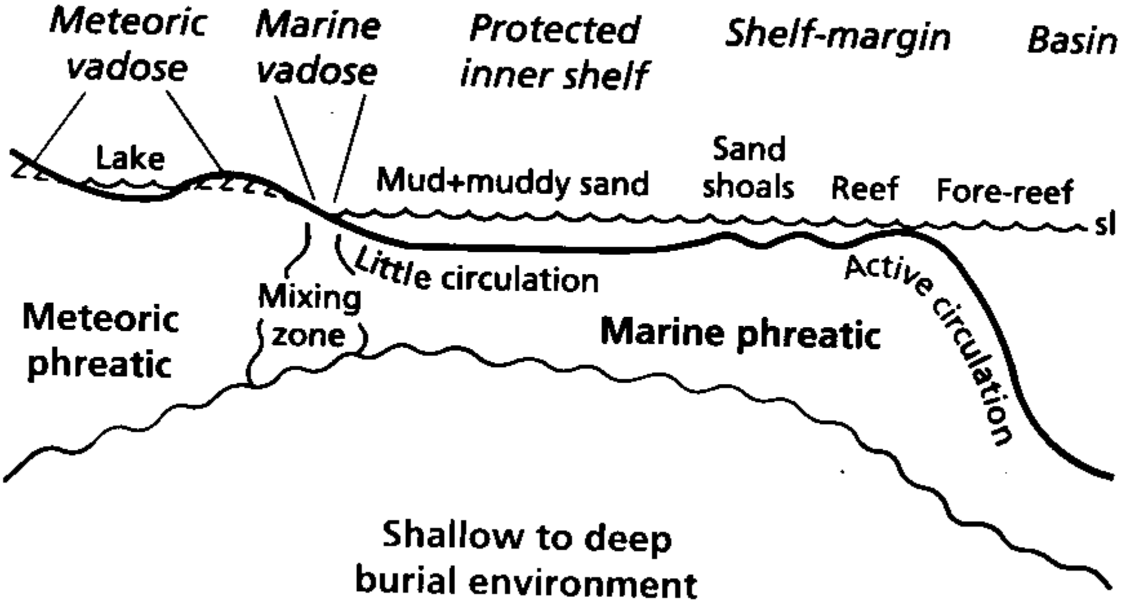

Fig.3.3. *The principal carbonate diagenetic environments on a rimmed shelf. After Tucker* (2001).

The burial diagenetic environment covers the interval between the lower limits of the shallow upper zone affected by surface processes (from tens to as much as hundreds of meter depth), down to the limit of metamorphic influence (fig.3.4). Choquette and James (1990) define the burial diagenesis as “any change or collection of changes that takes place below the zone of near-surface diagenesis and above the realm of low grade metamorphism” (Choquette and James 1990, p.75). It is unclear what distinguishes the *shallow* deep burial environment from the *deep* burial environment. It is clear that the shallow deep burial environment at maximum covers the first tens of meters of burial below the zone of near-surface diagenesis, but Choquette and James (1990) do not quantify this boundary any further. It is thus important to emphasise that the term “deep burial diagenesis” can be applied when burial is as little as tens of meters if the criteria(s) for burial diagenesis are fulfilled. The Azagador Member has been buried no deeper than 1000 meters (see chapters six and seven).

Both the chemical and morphological constituents of any environment are likely to be altered during diagenesis (James and Choquette 1990). With respect to porosity, the dominant trend in diagenesis is the long term reduction of porosity during burial, although porosity may also be created during burial diagenesis. Two processes act simultaneously to reduce the porosity: Cementation and compaction. Compaction may be defined as the sum of processes which result in a decrease of the volume of the rock, and include both mechanical and chemical processes. Examples of mechanical processes are dewatering, reorientation of grains and grain breakage (Scholle and Halley 1985). Chemical compaction includes pressure dissolution, fitted fabric, dissolution seams and stylolites (Buxton and Sibley 1981).

The depositional environment of the Azagador Member is interpreted to be a shallow marine origin (Völk and Rondeel 1964; Völk 1967; Martín and Braga 1994; Martín and Braga 1996; Braga et al. 2001) or at least dominantly marine origin (Thrana 2002).

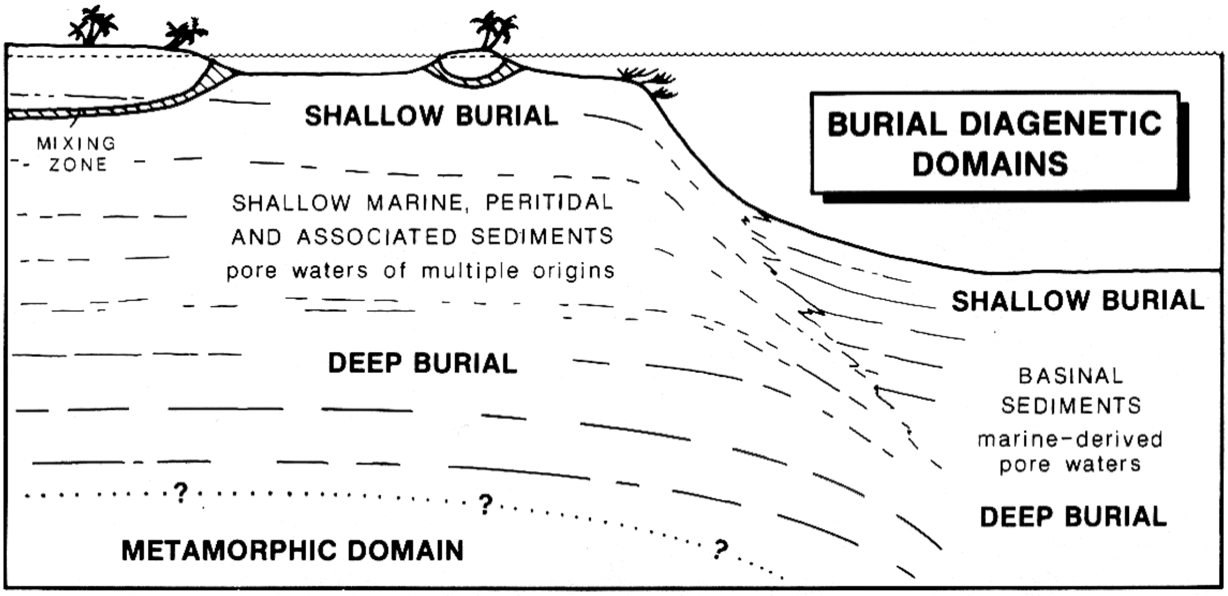

Fig.3.4. *Choquette and James (1990) distinguish between near surface, and the shallow and deep burial diagenetic domains with regards to diagenesis of limestones. The nature and depth of the boundary with the metamorphic realm are poorly known. The drawing is of a tropical system, but the same principal burial diagenesis domains are believed to be found cool water carbonates. After Choquette and James (1990)*

Petrographic and geochemical studies of the different cements in sedimentary rocks enable interpretations of depositional environment and also condition for cementation. However, similar types of cement can be precipitated in different diagenetic environments. For instance, drusy calcite spar, the major pore filling cement in limestones, may be precipitated in near-surface meteoric environments as well as in the deep burial realm. A combination of facies and environmental analysis, together with petrographic and geochemical studies, can help separate between the different diagenetic environments.

3.4.1. Shallow marine environment and cements

Meniscus cements formed in the vadose zone tend to be concentrated at grain contacts. In the phreatic zone where pores are saturated with water, cements precipitate as circumgranular crusts (equally distributed around grains) (James and Choquette 1990).

The most characteristic feature of the *sea floor* diagenetic environment is carbonate precipitation. Surface marine water generally precipitates fibrous-to-bladed cements of metastable aragonite phases, or high magnesium calcite (fig.3.5). Subsurface waters generally precipitate equate-to-complex polyhedral calcite cements (Tucker and Wright 1990).

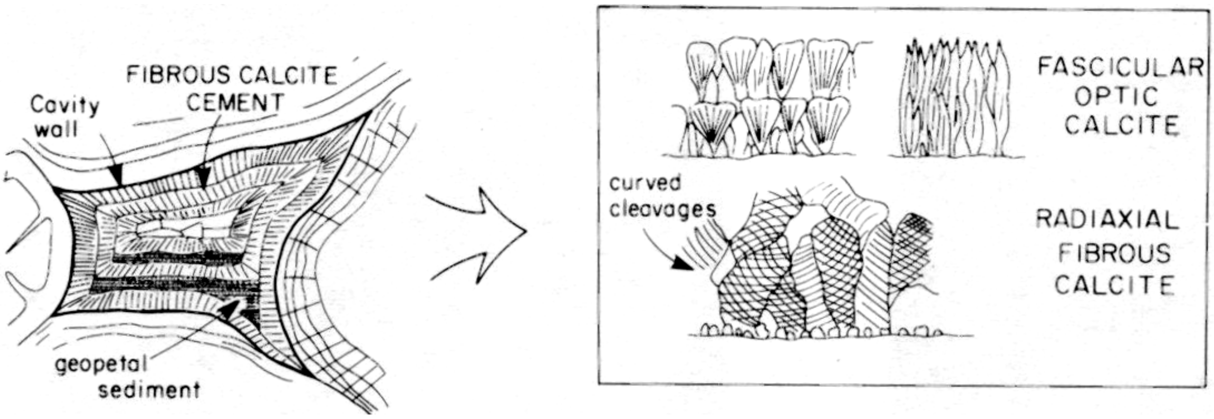

Fig.3.5. *Fabric and morphology of fibrous calcite, a kind of coarse shallow marine (sea-floor) cement. Modified from James and Choquette (1990).*

According to Tucker (2001), precipitation of cement is most common in high-energy areas, such as shallow subtidal environments, where seawater is forced through the sediments. In contrast, calmer conditions tend to result in precipitation of microbial micritization. Micrite envelopes are not necessarily formed in situ – the grain with the envelope may have experienced transportation. Precipitation of carbonate may cause lithification of loose carbonate sediments and form sea-floor limestones. Temperature is a major controlling factor in sea floor diagenesis, although recently, it has been confirmed that limited sea-floor diagenesis *can* take place in some cool-water carbonates (James and Choquette 1990).

3.4.2. Deep burial cements and diagenesis

Certain features are diagnostic for *deep burial* cements (Choquette and James 1990), and bladed prismatic and coarse mosaic calcspar (also referred to as sparite or calcite spar) are the most common carbonate cements in this setting (fig.3.6). Syntaxial overgrowth in optical continuity with a host grain or polikilotopic cements enveloping grains also occur.

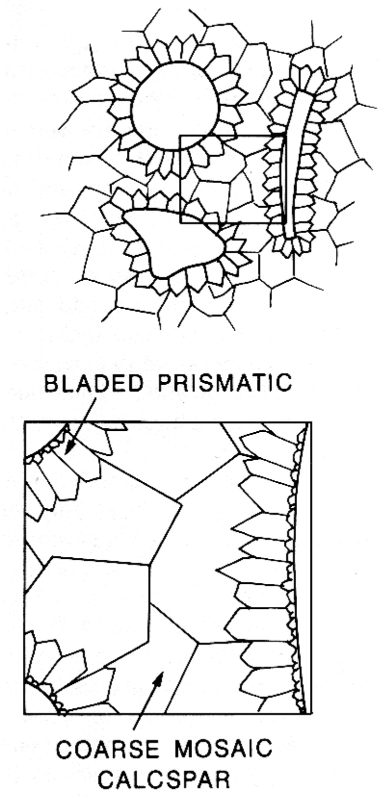

Fig.3.6. *Two types of burial-diagenetic calcite cements as they appear in plane light. Modified from Choquette and James (1990).*

Both a source of $CaCO_3$ and efficient fluid flow mechanisms are needed for complete lithification/cementation. In the marine realm the source of $CaCO_3$ is seawater. In the meteoric and burial environment the carbonate source is mostly sediment or rock dissolution (Choquette and James 1990; James and Choquette 1990). During deep burial metastable forms of $CaCO_3$ (aragonite and high-Mg calcite) are converted to low-Mg calcite. Several attempts have been made to relate crystal morphology of the cement to the chemical environment during precipitation (See Moore (2001) for a more detailed summary and discussion. According to Choquette and James (1990), the bulk of the cement occurring in deep-basinal sediments that have never been uplifted into the meteoric zone, must have originated during burial. In fact, much of the cement in ancient shallow marine limestones appears to be of burial diagenetic origin by replacement of for example aragonite (Talbot 1971; Moore 2001).

Another important porosity reducing process is mechanical compaction. In fact, most porosity loss during burial is due to mechanical compaction and pressure solution. Porosity loss due to pressure solution-related cementation is strictly limited (Heyari 2000). However, the reported results are from deep-burial areas, e.g. 1000s of meters. The onset of comprehensive compaction effects require a certain overburden, a condition that limits the influence of extensive mechanical compaction at shallower deep burial.

4. POROSITY

One of the main aims for investigating the petrophysical characteristics of the Azagador Member is to improve the understanding of the relationship between depositional conditions, burial history and porosity. There are significant differences between porosity in siliciclastic and carbonate sedimentary rocks. This will be discussed in more detail below. Carbonate porosity is of primary interest in the studies of the Azagador Member (see section 3.3).

4.1. Porosity per se

Porosity is a measure of the pore space in a rock (Tucker 2001). *Effective porosity* is the pores connected with other pores via pore throats (catenary or cul de sac pores) in a continuous network. This is of particular interest with regards to fluid flow. *Absolute porosity* includes isolated pores that have no connection to other pores (closed pores e.g. intragranular pores), or pores that are linked within a closed network. The following equations define the two types of porosity (Tucker 2001):

$$\text{Absolute porosity, } P_t = ((\text{bulk volume-solid volume})/\text{bulk volume})X100$$

$$\text{Effective porosity, } P_e = (\text{interconnected pore volume/bulk volume})X100$$

Porosity discussion in this thesis relates to the effective porosity.

4.1.1. Primary porosity

At the time of deposition, both-mud free siliciclastics and carbonate sediments have an initial or primary porosity, mainly interparticle. This is reduced by burial and diagenesis. Modern siliciclastic sediments can have an initial porosity of maximum 48% if minimum packing has occurred. Commonly, initial porosity is in the range of

25-40% (Choquette and Pray 1970). The wide variability of particle shape in carbonates gives a higher initial porosity, often in the range of 40-70% (Choquette and Pray 1970), but it may be a high as 80% in deep marine oozes (Enos and Sawatsky 1981). The biggest differences between siliciclastic and carbonate porosity is the common presence of intraparticle porosity in carbonates (Moore 2001). Carbonate rocks show a high diversity of grains and structures, both due to the wealth of different fossil organisms and to a wide variety of diagenetic processes. Mixed siliciclastic-carbonates are expected to fall somewhere between these ranges. However, quantitative figures have not been previously published.

4.1.2. Secondary porosity

Secondary porosity is the porosity developed as a result of diagenesis (e.g. dissolution or partial dissolution of grains), or other effects (e.g. fracture porosity) following deposition. Moreover, chemical reactivity in carbonates also results in the development of secondary porosity due to pervasive diagenetic processes (Moore 2001). Secondary porosity plays an important role in limestones, and is generally of two types (Moore 2001):

1) Porosity generated by dissolution, and
2) Porosity modification as a result of dolomitization

In general, carbonates are more easily dissolved than siliciclastics. Intraparticle porosity in carbonates may originate from dissolution of tissue in living chambers of various organisms or the ultrastructure of tests and skeletons of organisms. The amount of intraparticle porosity in the Azagador Member is significant and is probably a part of the effective porosity. Fenestral and moldic porosity (see section on the classification of porosity) occur to some extent. However, they are not counted as effective porosity and therefore left out the porosity discussion. As no dolomitization was observed in the Azagador Member, only porosity by dissolution will be discussed further.

4.1.3. Pore preservation, generation and occlusion during diagenesis

Carbonate sediments undergoing progressive burial will be subject to increased temperatures and pressure, leading to a variety of modifications. Moreover, the pore fluid undergoes a slow compositional evolution because of interaction with the surroundings (fig.4.1). During burial, porosity is generally reduced by compaction, both physical and chemical, and by cementation (James and Choquette 1990). Compaction is the major process affecting porosity. Grain size, shape and the degree of compaction changes due to tighter packing and increased density, whereas cement is chemically precipitated.

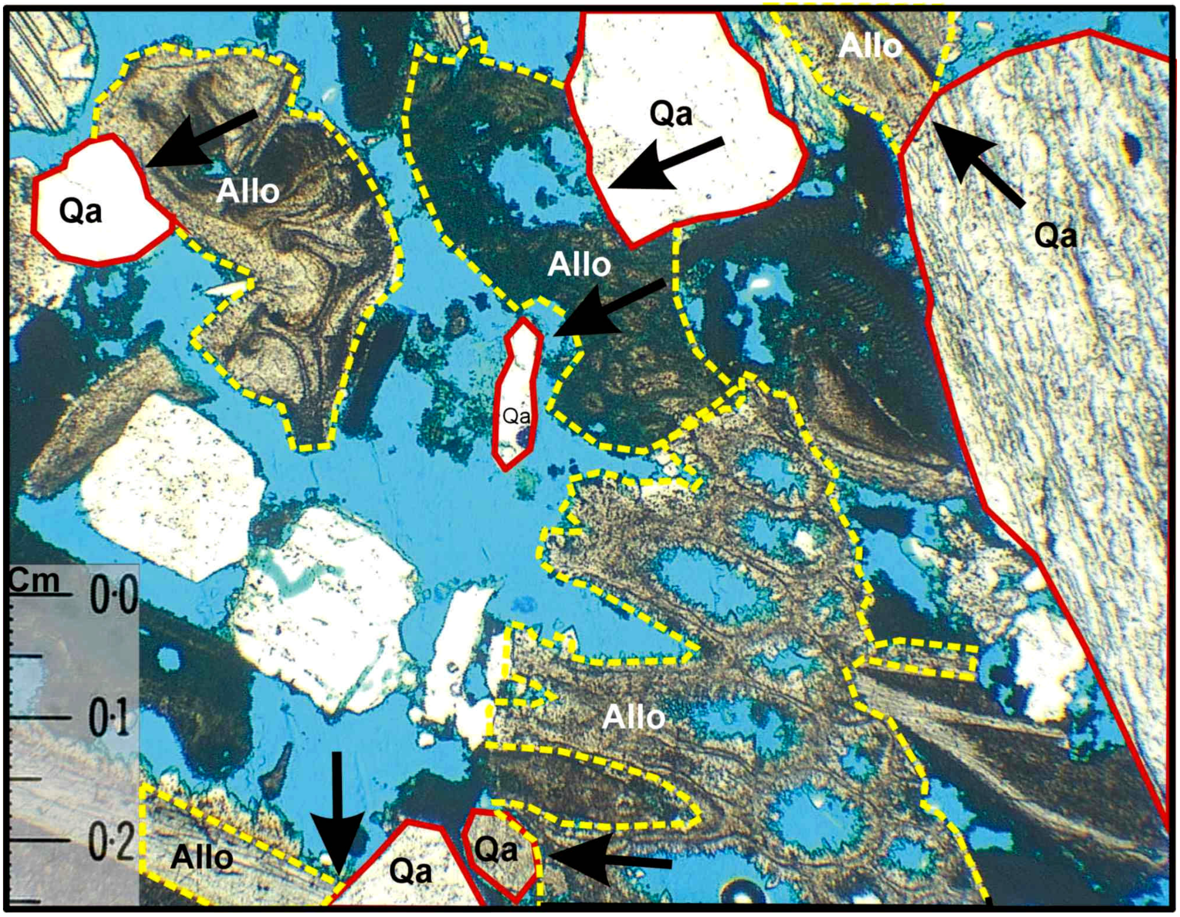

Fig.4.1. *Thin section from locality one (sample I02), belonging to facies four(F4), illustrating diagenetic effects.* ***Qa=****siliciclastics,* ***Allo****=allochems, pores coloured blue. Ratio between quartz and allochems is approximately 1:2 and porosity is about 10 percent. Arrows point to boundaries between siliciclastics (red continuous outline) and allochems (yellow dotted outline) grains, where the former has dissolved the latter by pressure solution. Note also the distinct bladed prismatic cement (carbonate crystals) precipitated on and within cavities of the allochems in the lower right hand quadrant. Magnification x3,2.*

In spite of the pore occlusion, the presence of hydrocarbon reservoir in both carbonates and clastic sedimentary rocks relies open the fact that at least some porosity is preserved. In addition to partial preservation of primary porosity (mostly in siliciclastics), secondary porosity may be produced during diagenesis. Most ancient carbonate rocks show very little preserved porosity whilst carbonate rocks in hydrocarbon reservoirs typically show 5-15 percent (Choquette and Pray 1970; Choquette and James 1990; Adams and MacKenzie 1998) (fig.4.2). The sort of porosity depends on the diagenetic history of the sediment.

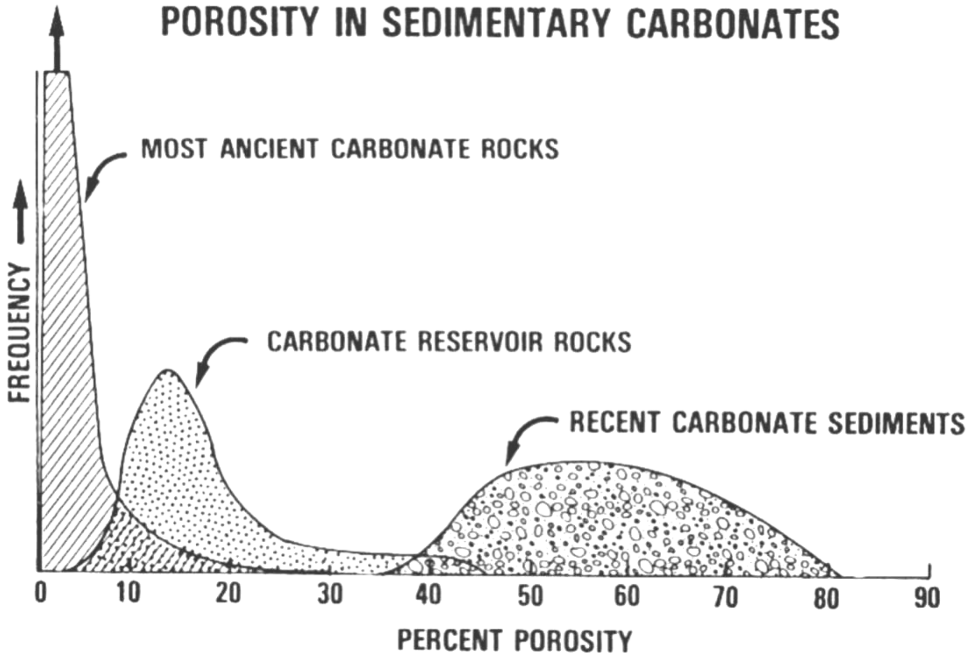

Fig.4.2. *The distribution of porosity in sedimentary carbonates. After Pray (1966)*

Subsurface fluids are believed to be supersaturated with respect to most carbonate phases (Moore 2001). This is a result of long term extensive rock-water interaction, and makes the evolution of subsurface porosity difficult to explain. The author suggests several possible explanations for secondary pore space:

- High pressure
- Temperatures
- Hydrocarbon maturation
- Thermal degradation
- Post-orogenic-meteoric recharge

These features and processes can result in aggressive (carbonic acid) subsurface fluids capable of developing secondary porosity in both carbonates and siliciclastics. These processes might influence the rock at any stage during burial.

4.2. Classification of porosity

When classifying porosity in carbonate rocks, it may be important to relate rock fabric to petrophysical properties. Archie (1952) made the first attempt to estimate porosity in such a manner. But his effort to distinguish between invisible, so called matrix porosity, and visible pore space was problematic (using a 10 power microscope). According to Lucia (1995), the main problem is that Archie's method does not distinguish between visible interparticle pore space and other types of pore space (e.g. moldic pores). Contrary to the widely used classification of Choquette and Pray (1970) (Table 4.1), Archie's description cannot be defined in depositional or diagenetic terms.

Table 4.1. *Schematic presentation of Choquette and Pray's classification of carbonate porosity. Modified from Choquette and Pray (1970). See text and fig.4.3. for explanation.*

Fabric-selective	Interparticle	Intraparticle	Intercrystalline	Moldic
	Fenestral	Shelter	Growth framework	–
Non-fabric selective	Fracture	Channel	Vug	Cavern
Fabric-selective or not	Breccia	Boring	Burrow	Shrinkage

Choquette and Pray (1970) use a genetic and not a petrophysical division of carbonate porosity (fig.4.3 and 4.5). In their classification, both the solid deposits and the diagenetic constituents of a sediment or rock are defined as its fabric. If the type of porosity is controlled by the depositional or post-depositional fabric of the rock, they term it *fabric-selective*. Porosity that cuts across the rock fabric is termed *non-fabric selective*. In some cases it might be *fabric-selective or not*. Out of the 15 different main classes of carbonate porosity (Choquette and Pray 1970), seven of them are fabric selective.

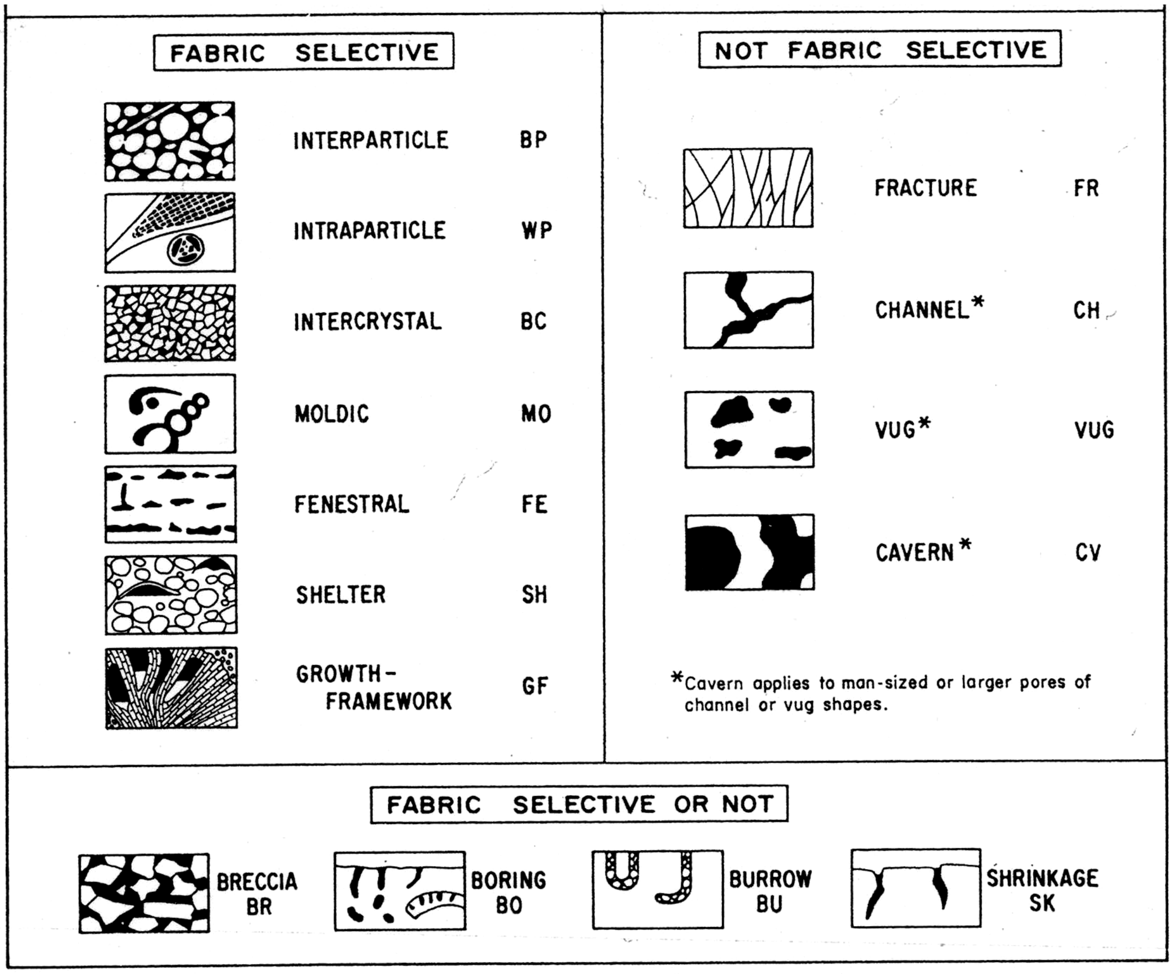

Fig.4.3. *Classification of carbonate porosity. In modifications of the scheme, the phrase "particles" are often substituted with "granular" and "growth framework" with simply "framework". After Choquette and Pray (1970).*

Lucia (1995) argues that classifying both moldic and intraparticle pore types as fabric selective (Choquette and Pray 1970), is somehow deceptive. In his classification, Lucia demonstrates that moldic and intraparticle pore types "have a different effect on petrophysical properties than do interparticle and intercrystalline pores and thus should be grouped separately" (Lucia 1995 p.1277). Porosity is divided into pore space between grains or crystals, termed interparticle porosity, and all other types of pore space, termed vuggy porosity (Lucia 1983; Lucia 1995; Lucia 1999) (fig.4.4)

PORE TYPES

NTERGRAIN INTERCRYSTAL	MOLDIC INTRAFOSSIL SHELTER	CAVERNOUS FRACTURE SOLUTION-ENLARGED FRACT.

ARCHIE (1952)

MATRIX	
VISIBLE (from no visible pore space to larger than cutting size)	

LUCIA (1983)

INTERPARTICLE	VUGGY	
	SEPARATE	TOUCHING

CHOQUETTE and PRAY (1970)

FABRIC SELECTIVE	NON-FABRIC SELECTIVE

Fig.4.4. *Comparison of different porosity-classification schemes. After Lucia (1995).*

This is a rather new approach, where emphasis is placed more on rock fabric and petrophysical characteristics, and may be important when generating reservoir models. On the other hand, the more geologically-based classification of Choquette and Pray is commonly used in geological exploration models.

As the calcarenites of the Azagador Member are not pure carbonate rocks, they do not readily fit into Lucia’s strict scheme. Some vuggy porosity as defined by Lucia (e.g. moldic porosity), is present in the Azagador member, but this is neither of primary interest nor common in the investigated facies. Furthermore, Lucia’s porosity classification is difficult to use in geological exploration models where diagenetic history and porosity evolution is critical (Wilson 2002).

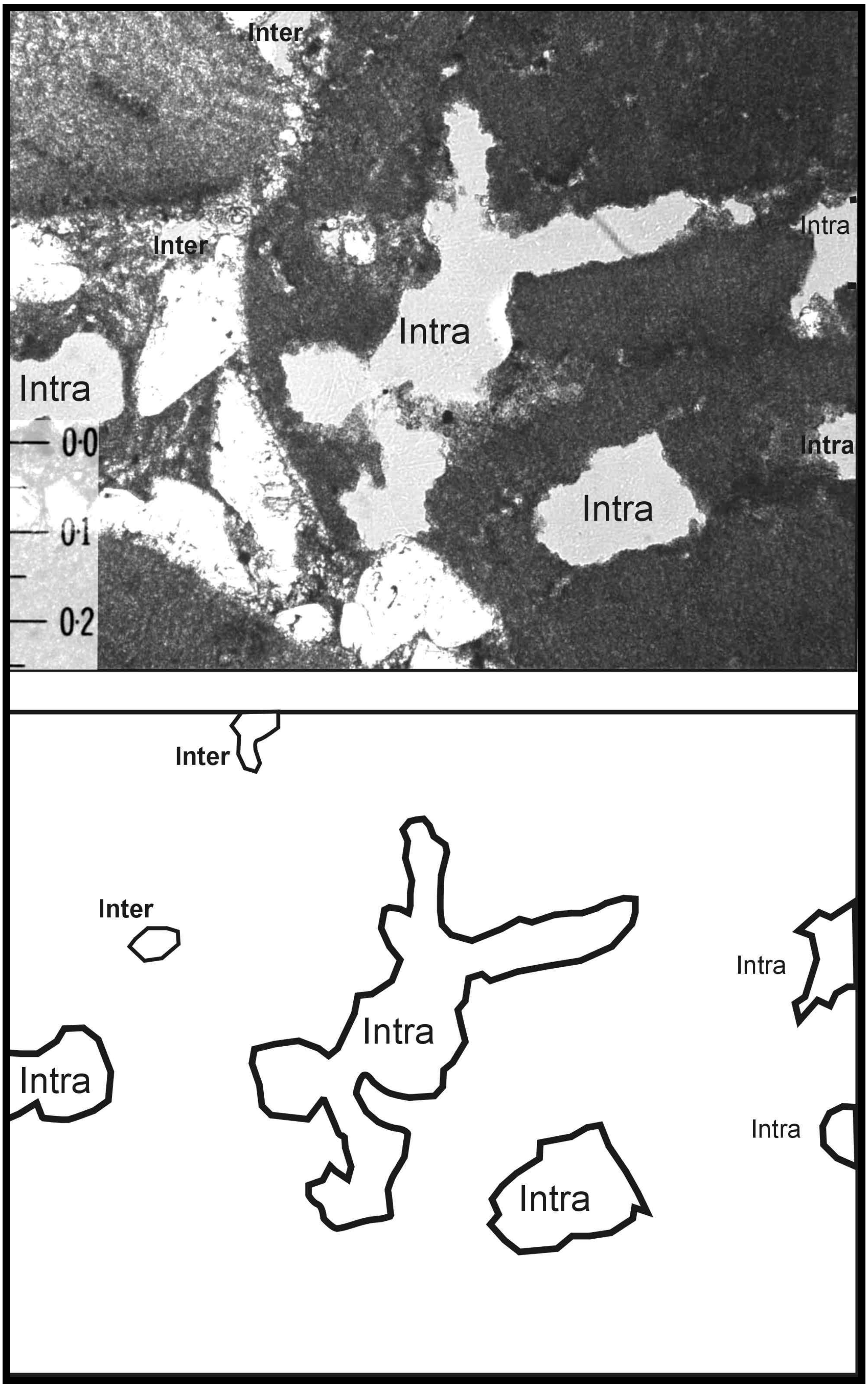

Fig.4.5. *Thin section from locality nine (sample IX50), belonging to facies two(F2). Example of intraparticle porosity (within the bigger contour lines marked* ***Intra****) and intraparticle porosity (within the two small contour lines in the upper left hand quadrant marked* ***Inter****). Classification after Choquette and Pray (1970). Magnification x10.*

In this thesis the emphasis has been on the diagenetic history and porosity evolution of the Azagador Member. Therefore, the genetically oriented classification scheme of porosity in carbonate sediments proposed by Choquette and Pray (1970) (fig.4.3) is used here. The relationships between particle size, porosity and permeability presented by Lucia (1995) is discussed below (section 4.3). Prefixes introduced by Choquette and Pray (1970) as an attempt to describe certain aspects of porosity are not in common usage and will not be discussed in this thesis.

4.3. Permeability

Permeability is based on the effective porosity, the shape and size of the pores and pore interconnections (throats), and on the properties of the fluid itself (Choquette and Pray 1970; Lucia 1995).

Permeability is a characteristic of a material that determines how easily a fluid (or gas) can pass through it. The Darcy is the standard unit of permeability, but the millidarcy (1 md=10^{-3} darcys) is also in common usage. A rock with a permeability of 0,1 millidarcy is considered to be tight, while a rock with 10md or more of vertical permeability is considered to have moderate to high permeability.

In his classification of carbonates, Lucia (1983) ties together porosity and permeability in one model. A premise for this model is that pore-size distribution controls permeability and that pore-size distribution is related to rock fabric. This forms the basis for Lucia’s division of non-vuggy carbonate porosity into three classes (fig.4.4). These classes are established with the aid of the relationship between average particle size and mercury displacement pressure (Lucia 1995) (fig.4.6).

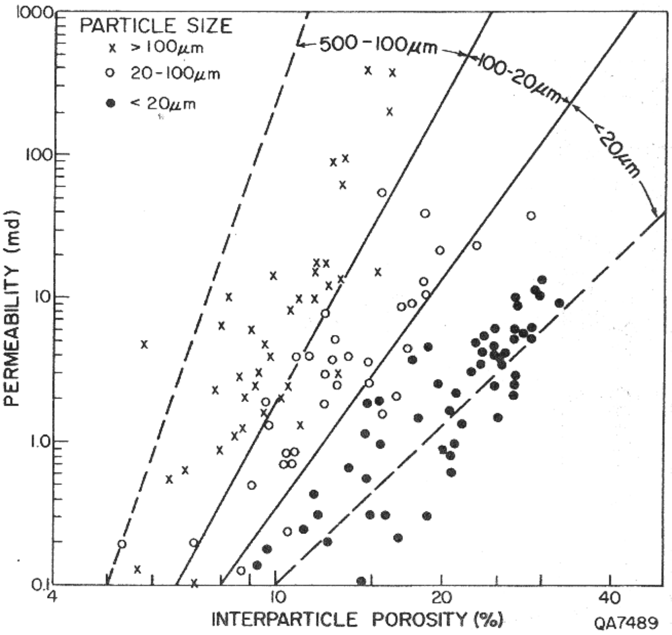

Fig.4.6. *Lucia (1995) focuses on the relationship between porosity and permeability, both determined, among others, by particle size. Basis for Lucia's classification system of non-vuggy carbonate rocks is the porosity-air permeability relationship. After Lucia (1995).*

Contrary to siliciclastics, the permeability-porosity interrelation in carbonates is greatly varied and commonly independent of particle size and sorting (Choquette and Pray 1970). The problem with verifying such a relationship in the Azagador Member also supports the arguments for choosing the classification of Choquette and Pray (1970) relative to the one of Lucia (1995). A possible way of investigating the permeability in the Member would have been with the aid of minipermeameter-methods. The rather tight rocks of the Azagador Member as well as the inaccessible cliff walls of the outcrop made such an approach both uncertain and risky and it was not carried out. Furthermore, the available data from the Azagador Member data are not appropriate for further permeability analysis (see section 5.2.3)

5. METHODS & DATABASE

5.1. Mapping and data collection

Fieldwork was carried out during four weeks in early autumn of 2000, and additional ten days during the spring of 2001. Field investigations focused on two main tasks:

1. Identification and mapping of the sedimentary structures and facies within the Azagador Member
2. Collecting samples, primarily from the channelized structures of the Azagador Member

In this thesis the focal point has been task number two, whereas Thrana (2002) focused on task number one. Approximately 50 vertical sections distributed between ten localities were logged. Five of these localities are discussed in this thesis, three of which are discussed in depth (see fig.2.5-6 and 2.8). Visual chart estimations were used both in the fieldwork and when investigating thin sections, in an attempt to determine the relative abundance of siliciclastic and allochem components. Furthermore, a lens was used to measure grain size in sampled and logged sections. Where possible, rock samples were collected at different vertical levels in the logged section. Several sections on high, vertical to overhanging cliffs were not accessible and thus impossible to satisfactorily sample and log. During the two fieldwork seasons some 130 samples were collected. Thin-sections of limited quality for preliminary qualitative studies were made from all of them. In addition, 27 quality thin-sections (i.e. sections with stained pores, standardized thickness and carefully prepared to avoid air inclusions, and with half of each thin-section impregnated to colour the carbonates) from the five localities were made for quantitative studies. Panorama view photos were taken of several of selected outcrops for further studies and illustrations.

5.1.1. Investigated localities

A majority of the samples were taken from within the preferred channel structures. For reference purposes, samples were also taken from outside the channels. Therefore, several localities are left out from this thesis. This also explains the odd numbering of the localities; 1, 3, 5, 8 and 9 (fig.5.1) – the missing numbers refer to the localities that are left out (See Thrana (2002) for details about localities).

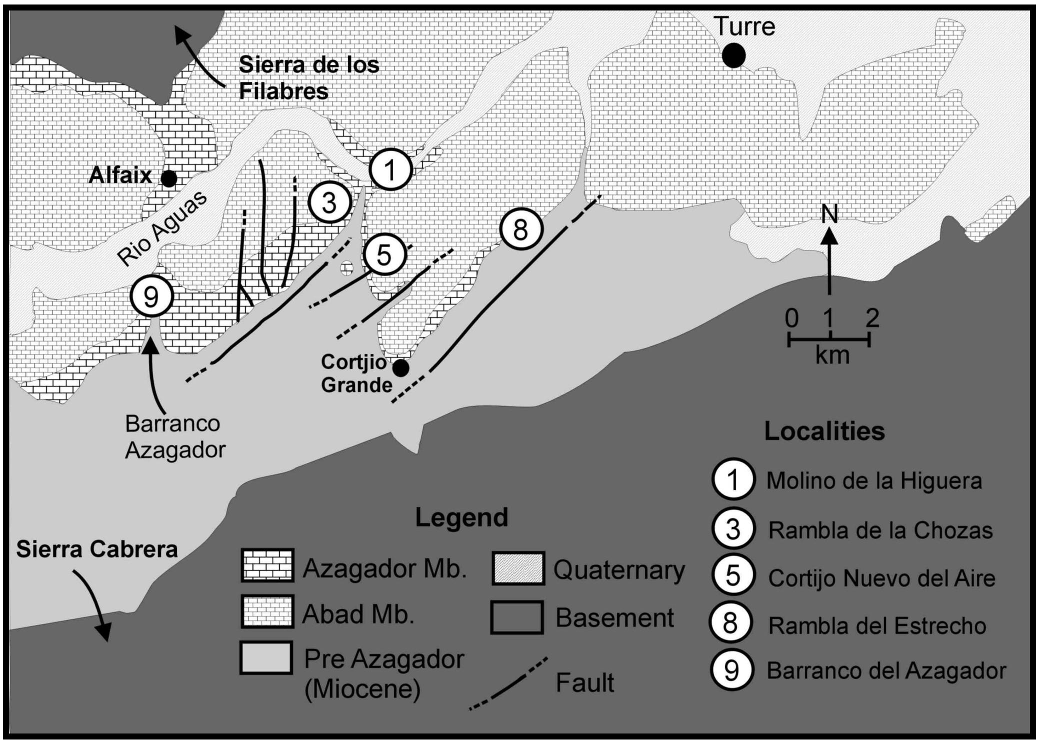

Fig.5.1. *Detailed geological map with numbered localities. Modified from Rondeel* (1965) *and Braga et al. (2001).*

The locality numbers correspond to the ones used in the introduction to localities in section 2.3. and throughout in the text. The five localities are:

1) Molino de la Higuera – The southern most outcrop next to the Molino de la Higuera along the Rio Aguas. Major channel structures up to 25-meter deep and several tens of meters wide appear to have eroded into platform or ramp sediments. These were later filled by calcarenite sediments at two, possibly three different stages, giving rise to an impression of partly stacked and nested channels.

3) *Rambla de la Chozas* – just west of the intersection with the Rio Aguas at the eastern end of Loma de la Señora. The outcrop seems to be dominated by one, possibly two channel structures.

5) *Cortijo Nuevo del Aire* – western side of cliff wall between Molino de la Higuera and El Cortijo Grande. Nuevo del Aire seems to be made up from several major channels that appear to have eroded the platform or ramp sediments. A presumably smaller channel intersection with a steep levee on meter scale is found in the lower level of the locality.

8) *Rambla del Estrecho* – immediately north east of El Cortijo Grande, along the river of Ramble del Estrecho. One, perhaps two channels a few tens of meters wide can be identified in the outcrop.

9) *Barranco del Azagador* – west of Loma de la Señora and type locality for the Azagador Member (Völk 1967). Varies between 0 and 60 meter in thickness from north to south. It is possible, but not likely, that this outcrop is entirely or partly made up from channels at ten-meter scale. However, this has been impossible to map due to vegetation, steepness of the cliffs and the general location within deeply incised valley with no possibility of access to major to parts of the outcrop.

5.2. Laboratory methods

Limited budget permitted the preparation of only 27 quality thin sections. Samples studied in this way were selected on the basis of an examination of the about 130 thin sections of limited quality made for preliminary qualitative studies. The 27 thin sections, assumed to be representative for the purpose of this thesis, were studied in detail, using both qualitative and quantitative methods. These sections make up the database (appendix) and provide the basic information when discussing diagenesis and porosity with respect to the different facies associations.

5.2.1. Scanning Electron Microscope (SEM) and Cathodoluminescence microscopy (CL)

Scanning Electron Microscope (SEM) is used when investigating features down to 0,1 µm in size at a magnification up to x100.000. For example, SEM is suitable for image analysis, allowing the identification of modification of primary porosity in carbonates. The output SEM-picture is a so-called grey-scale “reflective mode” image (BSE - backscattered), that may be interpreted by computer software to give a quantitative output of variation in the grey-scale (Trewin 1988). SEM is thus appropriate to determine present porosity. Furthermore, primary porosity can be estimated on the basis of present cement and porosity (primary porosity=cement volume + present porosity), also from a reflective mode image. Using a computer and appropriate software, variations in grey-scale representing the different features (e.g. pores) may be registered and quantified. The grey-scale is set automatically, but can be manually adjusted. The equipment is tuned so that the intensity of the grey in e.g. pores is reflected in the lowest frequency-peak (fig.5.2). Because of the huge magnification, to get the most reliable number it is convenient to use the average measurement from four pictures covering different areas in the same sample.

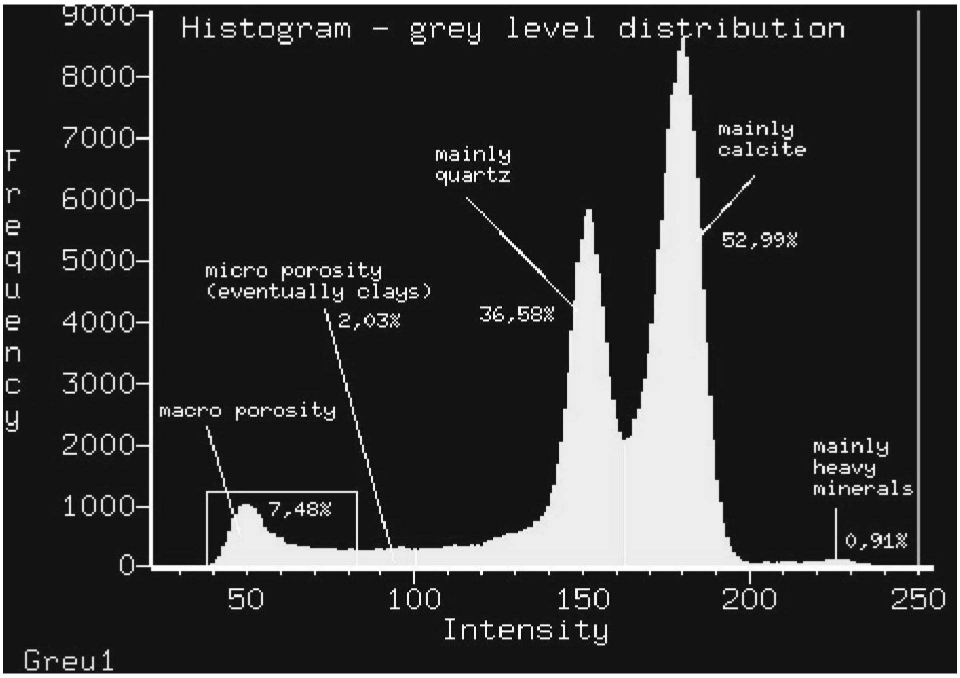

Fig.5.2. *Histogram from a SEM picture (sample V20), illustrating how a certain frequency of the intensities of grey corresponds to pores. The computer will give the figure of the area covered by this peak, corresponding to the amount of porosity.*

When subjected to a beam of electrons (i.e. energy) from a cathode in a vacuum tube, a mineral will emit light (called luminescence) as a result of electron excitation (Miller 1988). The method for investigating this effect is called cathodoluminescence microscopy (CL). The visible spectrum of emitted light from CL can reveal details of post-depositional changes like cement growth and mineral overgrowths with a higher resolution than is possible with an ordinary optical microscope inspection. In particular, CL can reveal successive stages or zones of calcite cements, reflecting change in pore water chemistry through time. This allows a detailed interpretation of cement history and present porosity. In addition, it is appropriate for visualization of distribution of optically closely related minerals (e.g. calcite and dolomite minerals) (Miller 1988). It can be difficult to distinguish between grains and cement if the samples lack early cementation and generations of cement.

5.2.2. Point counting

Using a petrographic microscope, the 27 samples were point counted to determine the quantity of the following ten different features (appendix)

- Quartz
- Calcareous red algae
- Echinoids
- Foraminifers
- Molluscs
- Other allochems
- Micritic matrix
- Carbonate cements
- Unknown
- Pores

To reduce the numerical data to a manageable level, the amount of the different allochems were combined to form one assembly. Cement, matrix, pores and unknown form another assembly (table 5.1).

A majority of the investigated samples were collected from the channel structures. Occasionally, the channel-complexes appear to be composed of several different facies (Thrana 2002). Thin section studies showed that the similarities between several of the facies within the channels far exceed the differences. Therefore these facies have been combined to one facies *association* (table 5.1). Three different

Table 5.1. *Distribution of quartz, allochems and "others" (i.e. cement, matrix, pores and unknown) in the investigated samples. The porosity of facies association F3 is compared with the porosity of facies F2, F4 and F5, the latter three organized into one facies association. The other samples (F6, F5 and F10) are for reference purpose. See text for explanation. Facies classification modified from Thrana (2002). Numbers in percent.*

Facies association	Facies	Sample Number	Quartz	Allochems	Cement+ Matrix+ Pores+ Unknown
Facies F3 (in-channels)	F3	I2	24.8	55.4	19.8
	F3	I127	26.4	57	16.6
	F3	I128	42.8	31.4	25.8
	F3	I130	47.4	26.4	26.2
	F3	I120	40.6	36.8	22.6
	F3	III133	18.6	56.4	25
	F3	III143	16.6	47.2	36.2
	F3	V17	38.2	33	28.8
	F3	V18	40.4	18.6	41
	F3	V19	36.6	23.4	40
	F3	V22	61.8	15	23.2
	F3	V21	32.6	27.2	40.2
	F3	VIII149	30.4	45.2	24.4
Comparison facies F2, F4 and F5 (outside-channels)	F2	I12	43.4	39.2	17.4
	F2	V114	12.6	62	25.4
	F2	V23	46.6	25	28.4
	F2	V135	41.8	25.4	32.8
	F2	V116	24	49.4	26.6
	F5	IX52	30.6	47.8	21.6
	F4	IX51	60.4	15.6	24
	F4	IX50	3.6	64.6	31.8
	F4	IX54	51.2	28.2	20.6
Reference samples	F6	V140	18.6	34.6	46.8
	F6	I119	23.8	28.2	48
	F5	V20	48.4	24.4	27.2
	F10	V138	69	10.2	20.8

facies (F2, F4 and F5) from nearby the channels were chosen to allow comparison of porosities within and outside the channel complexes. A few of the facies from outcrops with no dominant structures or far away from such structures were investigated only briefly for reference purposes (samples from facies F5, F6 and F9) (table 5.1).

In the following, it is the distinction between the two *facies associations*, representing *in*- and *outside* the channel complexes, that have been compared and discussed with respect to constituents and porosity of the Azagador Member.

5.2.3. Comparison of methods

Both point counting and SEM-analysis provide a quantitative estimate of existing porosity. However, the validity of the SEM-results may be questioned due to a possible confusion of the grey dye toning.

Assuming that cement grows in open pores and replace pore space in the ratio of one to one, porosity reduction can be quantified. Point counting of cement thus provides a number on loss of porosity after deposition and initiation of cement growth. Again, this is difficult to do with SEM-analysis because of the grey-scale interpretation-aspect. This may be further complicated if the samples lack the distinctive early cementation and the late cement is a syntaxial overgrowth in optical continuity with a host grain. This may cause difficulties in the identification of differences between grains and cement with SEM-analysis.

Consequently, point counting is the preferred method for comparison purposes. By adding the amount of cement to the amount of current porosity a measure of primary porosity is established. This allows comparison between the amount of present and primary porosity. Such a comparison may reveal differences in porosity reduction between the facies associations and between the different rock categories. In spite of the uncertainty in the SEM-analysis, its results may be used to test the validity of the porosity numbers revealed by point counting. This has been done in this thesis (appendix), and the results from point counting was confirmed by the SEM-analysis.

None of the described methods reveal information on the assumed loss of permeability. Two dimensional examination of porosity is qualitatively different from dynamic techniques such as minipermeameter investigations of permeability, and does not reveal sufficient information for a detailed interpretation of permeability (see section 4.3.). Initially, the use of a minipermeameter-instrument was planned. But, investigations made it clear that the outcome of such a procedure would be rather limited, due to the available time, the inaccessibility of the outcrops and tightness of the rocks. Consequently, the permeability was not measured and will not be discussed any further.

6. RESULTS & INTERPRETATIONS

In this chapter, the results from the investigations of the Azagador Member will be presented, discussed and interpreted. The chapter will commence with investigation of rock classification and continue with cements and porosity. These results will then be evaluated relative to the distribution of porosity between the two main facies-associations. Finally, the porosity reduction will be investigated. An assortment of the 27 investigated samples will be used to illustrate the main discoveries. The facies division is based upon the work by Thrana (2002).

Cathodoluminescence microscopy (CL) was used in this study in an attempt to aid the interpretation of porosity. However, after a series of trials it became obvious that it was virtually impossible to use CL to separate between cement generation(s) and grains. One explanation for this is, as will be discussed later, is the lack of an early cement generation and more than one generation of later cement. The fact that the Azagador Member is not a pure limestone might also have influenced the poor outcome of the method. Hence, point counting and SEM-analysis were preferred methods and CL was not used any further.

6.1. Rock Classification

In the classification of the samples from the Azagador Member, it is of fundamental importance to take into consideration the mixed siliciclastic-carbonate framework of the rocks (see section 1.3). Not much literature has been released on this subject. This is due to the rather immature stage of the level of understanding of mixed rocks.

Neither the most common classification scheme developed for siliciclastics (e.g. Folk (1954) or McBride (1963)), nor the ones developed for limestones (e.g. Folk (1959) or

Dunham (1962)), are adequate for classifying the Azagador Member. These schemes treat such deposits as a geological oddity one way or another. Either not as a part of the classification at all, or as falling in between the two categories (pure sand- and limestones). They are never taking in to consideration the whole aspect of these rocks, which may include calcarenites, quartz and muds.

Another widely used classification scheme for sandstones is the one of Pettijohn et al. (1987) concerned mainly with mineralogy. The calcarenites are included as calclithite, sorted under rock fragments. Nevertheless, only sand-sized grains are encompassed, which leaves out any type of admixed mud, making also this scheme somehow unsatisfactory. Several other sandstone classification schemes were evaluated as well, but not considered adequate for classifying the Azagador Member.

Zuffa (1980) suggested a more suitable classification system for what he entitles hybrid arenites. He recognises four principal grain types, two of them being the non-carbonates (i.e. the typical sandstone components) and the carbonates. For instance, Zuffa distinguishes between intrabasinal and extrabasinal carbonate grains. This distinction is difficult to make in mixed systems and not even necessarily desirable. Secondly, variations in texture are generally ignored.

A perhaps more suitable classification scheme is that developed by Mount (1985) who proposes a first-order descriptive textural and compositional classification of mixed siliciclastic and carbonate sediments (fig.6.1)

In Mount’s classification, four principal end members are identified:

1) Siliciclastic sand (sand-sized quartz, feldspar etc.) – sandstones
2) Mud (silt and/or clay, <0.0625mm in diameter) – mud rock
3) Allochems (carbonate grains, e.g. ooids, bioclasts and intraclasts >20 µm)
4) Carbonate mud or micrite (<20 µm in size)

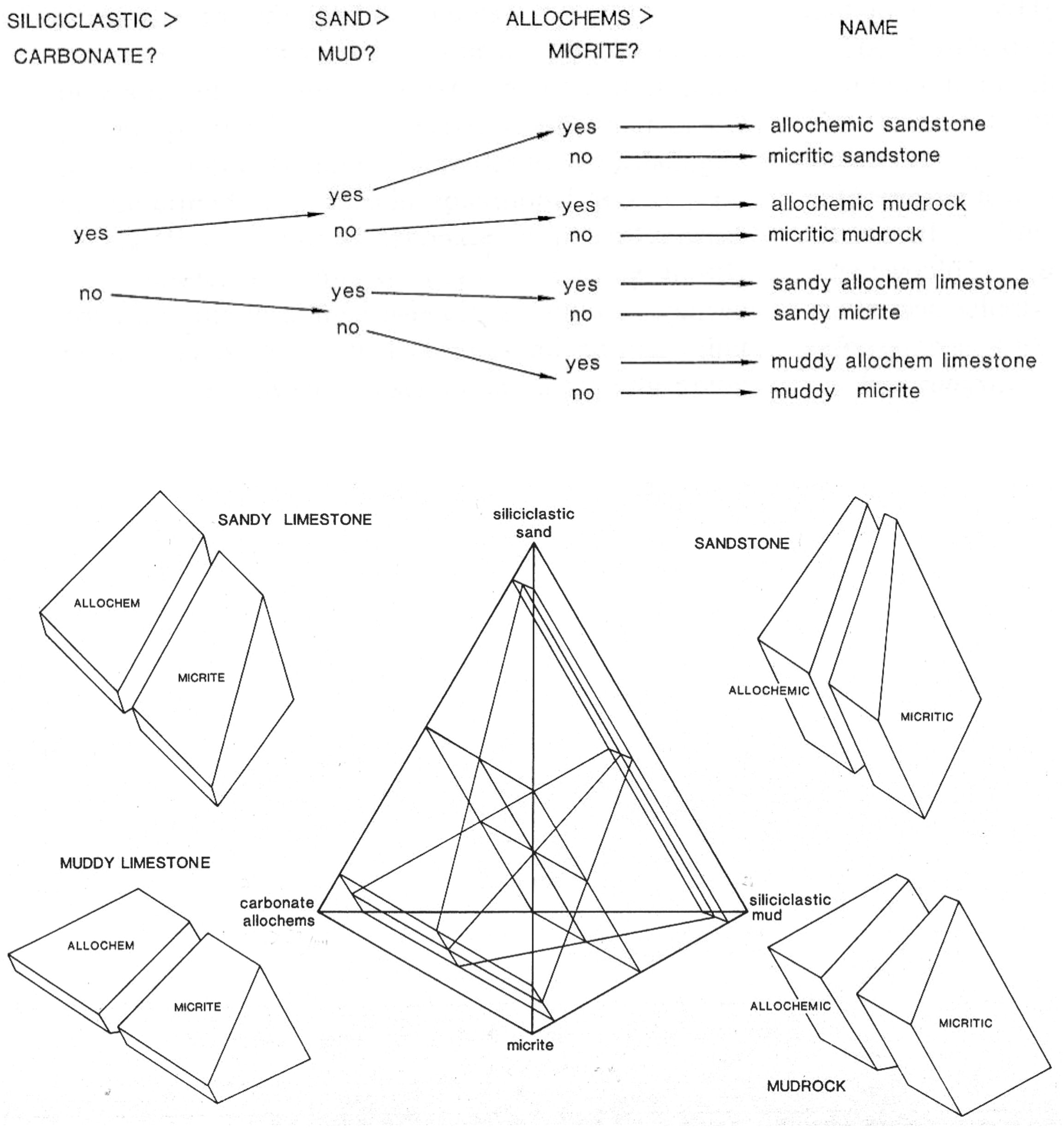

***Fig.6.1**. Naming procedure and classification scheme for mixed siliciclastic and carbonate sediments. Modified from Mount (1985).*

The four end components define a tetrahedra. The rocks are named after both the dominant grain type and the most abundant antithetic grain. Besides constituting a rather complicated tetrahedra, one drawback with these classes is the problem of distinguishing between siliciclastic mud and carbonate (lime) mud. This can be especially difficult if using only an optical microscope. Analysing a number of samples using Scanning Electron Microscope (SEM) to separate between these muds is time consuming and has not been considered to be within the scope of this thesis.

A new classification scheme has been produced for the classification of mixed sediments. This is a simple tripartite classification constituting the three end members of the Azagador Member: Siliciclastics (quartz); allochems (bioclastic); and mud (lime matrix) (fig.6.2). This simple triangular scheme is believed to be sufficient for the classification in this thesis, where the primary focus is on the porosity of the Azagador Member.

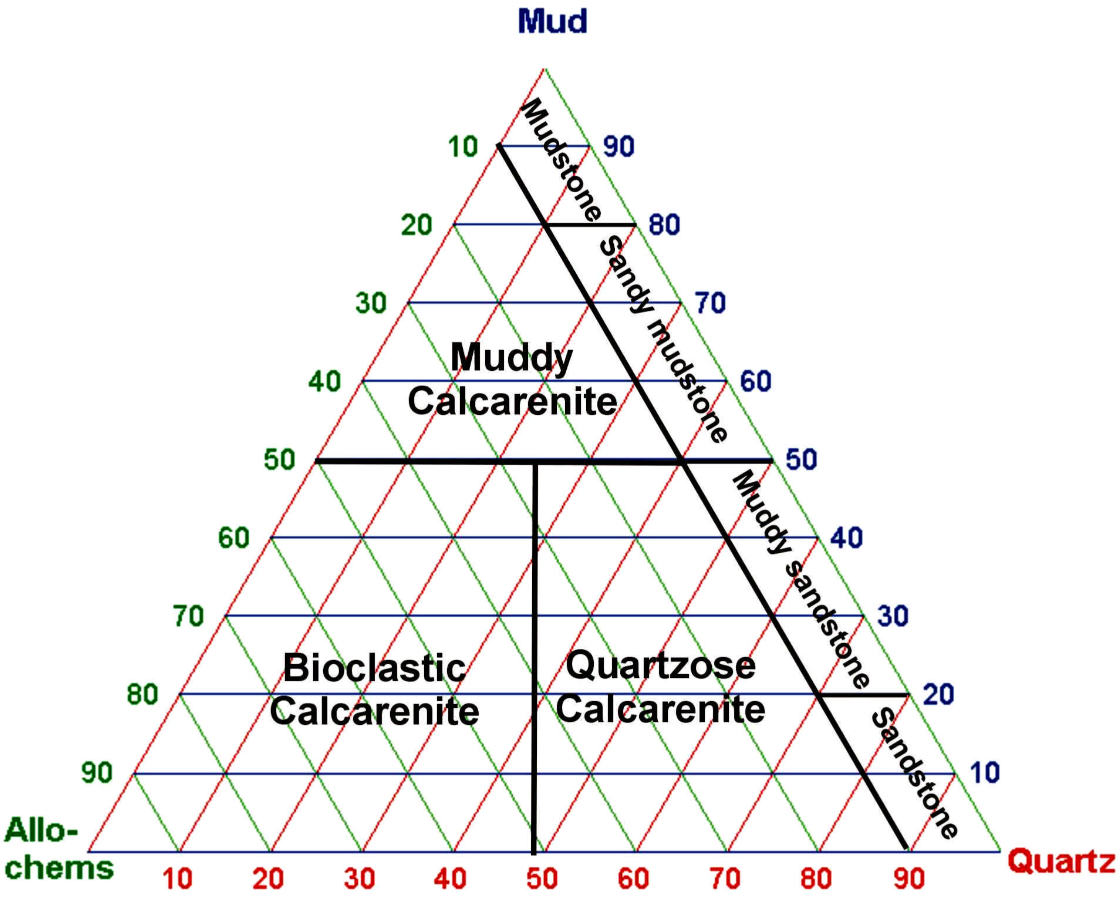

Fig.6.2. Simple triangle-classification scheme constituting the three end members of the Azagador Member: Siliciclastic (quartz); allochems (bioclastics); and mud (lime-matrix). The black lines separate the corresponding rock types. Units in percent.

This classification also allows a relatively easy naming of the calcarenite rocks. Calcite-rich sandstone and sand-rich limestone would have been adequate names. However, “calcarenite” – originally meaning limestones with limeclasts of sand size – is a reasonable name for the investigated rocks of the Azagador Member because it better reflects the rock constitutes. However, rocks with less than 10 percent allochems are not considered to be calcarenites, but straight siliciclastic deposits (fig.

6.2). Such a rock is classified as Mudstone if there is more than 80 percent mud and as Sandy mudstone if there is between 80 and 50 percent mud. When there is between 50 and 80 percent quartz it is classified as Muddy sandstone, and if there is between 80 and 100 percent quartz it is classified as Sandstone. With regards to the calcarenites, i.e. rocks with more than 10 percent allochems, a rock with more than 50 percent sand-sized bioclastic allochem-clasts and less than 50 percent mud is named Bioclastic Calcarenite. When there is more than 50 percent sand-sized quartz and less than 50 percent mud it is classified as Quartzose Calcarenite. When the rock contains more than 50 percent (lime) mud it is classified as Muddy Calcarenite.

An improvement to the classification scheme to make it more sophisticated would be to include other siliciclastics in addition to quartz. For example, one (!) feldspar-grain and several possible residues are observed in samples from the Azagador Member. However, with a small number of both samples and feldspar-grains, it was decided to leave this out in an attempt to keep the classification scheme simple, but still adequate for the scope of this study.

6.2. Diagenetic environments and diagenesis

6.2.1. Shallow marine environment textures

The investigated facies of the Azagador Member is interpreted to be of a purely marine origin (see section 3.4). Surface marine water generally precipitates fibrous-to-bladed cements of metastable phases of aragonite or high magnesian calcite, while subsurface marine water precipitates equate-to-complex polyhedral calcite cements. No cement characteristic for the marine or shallow marine burial is identified in the investigated samples. A small number of the allochems in the Azagador Member have a relatively dark micrite envelope around the grains (fig.6.3). Micrite envelopes are indicators of marine environment.

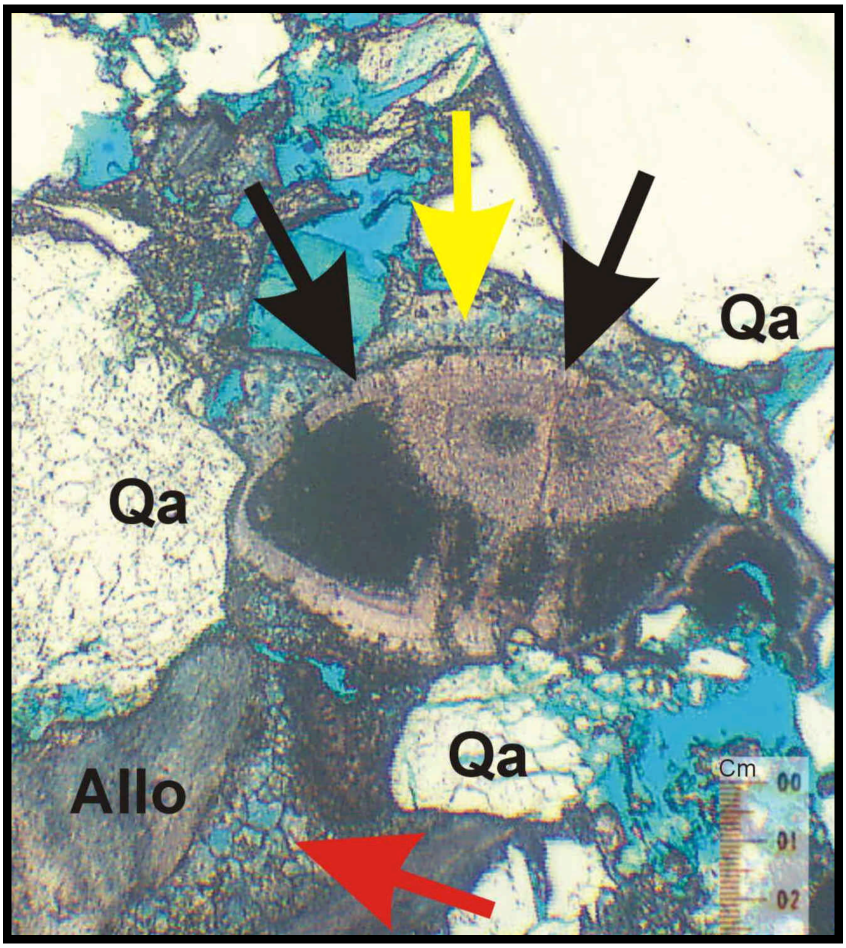

Fig.6.3. *Thin section from locality nine (sample IX54), belonging to facies two (F2). Dark micrite envelope (black arrow) covers the exterior of an allochems (foraminifera). The envelope gradually changes into a more bladed prismatic cement (yellow arrow), of deep burial origin. Notice also coarse mosaic calcspar (red arrow), of a burial diagenetic origin. Porosity stained blue.* ***Qa****=Quartz,* ***Allo=****allochems. Magnification x3,2.*

Micritization usually takes place in shallow (<50 meters) quiet water primarily due to the activities of endolithic algae, fungi and bacteria. This process is known to weaken grains considerably (Tucker and Wright 1990). Dissolution of the grain itself may thus be expected, but this is not observed here in spite of the fact that the Azagador Member was deposited in a generally high-energy environment. A possible explanation is that the foraminifera are not necessarily in situ, and this may explain why micrite envelopes are rare as well.

The high-energy conditions in the depositional area might have prevented both micritization and precipitation of sea-floor cements. Cement precipitation may also have been restricted by low temperatures, which might not just reduce or prevent precipitation, but possibly also dissolve certain constitutions. This is supported by studies by James and Choquette (1990), who argue that the bulk of high latitude carbonates are calcitic with only rare aragonite. Lack of sufficient dissolvable aragonite and high-Mg calcite prevents extensive sea floor cementation. Cool-water carbonates are dominated by a calcitic mineralogy. This is also reflected in the allochems of the Azagador Member which lack any signs of an aragonitic mineralogy. In general, neither non-skeletal grains nor marine cements commonly occur in cool-water carbonates. Due to the low carbonate saturation of sea water in non-tropical settings, early lithification of the sea floor occurs only sporadically. According to James and Choquette (1990), cool-water carbonate sediments of the Heterozoan Assemblage may be subject to some sea-floor diagenesis in shallow water, but it appears to be limited to precipitation within intraparticle pores. Generally this happens under conditions of sediment starvation (James and Bone 1991). Therefore, cool-water carbonates are dominated by deep burial cements (James 1997).

Lack of signs of early lithification of the Azagador Member made the sediments easily prone to resuspension and reworking. This is an important observation and greatly influences interpretation of the depositional processes of the Member (Braga et al. 2001; Thrana 2002).

6.2.2. Identification of deep burial diagenesis

There are several features observed in thin sections that indicate that the Azagador Member has experienced deep burial diagenesis. Bladed prismatic and coarse mosaic calcspar-cements occur in pores, cracks and in the cavities of allochems (fig.6.4). Although these cements are characteristic of deep-burial diagenesis, they can under certain circumstances also be precipitated from meteoric waters (Choquette and James 1990; Tucker and Wright 1990; Lønøy 2000). A rather shallow burial (less than 1000 meters, as mentioned in chapter three and discussed in chapter seven) does not necessarily prevent an introduction of fresh (meteoric) water to the system. A mixture of diverse subsurface fluids (e.g. brines and meteoric water) may then be partly or wholly responsible for the cements precipitated in the deep burial realm, but this is difficult to verify with the available data.

The cements are equally distributed around grains, which point to precipitation in the phreatic zone where all pores are filled with water. Moreover, the lack of typical exposure dissolution features (both on macro- and micro scale) and the marine origin of the Azagador Member favours a deep burial diagenesis-interpretation. The bladed cement is commonly observed around or nearby the allochems, whereas calcspar is more likely to fill in pores. It seems that both sorts of cements are widespread near the allochems but not siliciclastics, suggesting that one source for the $CaCO_3$ for cement precipitation was dissolution of bioclasts. The bladed cement could have represented recrystallized marine cement. However, as mentioned earlier, this is not likely due to the high energy and the cool-water depositional environment, and neither is there any direct evidence of a metastable precursor.

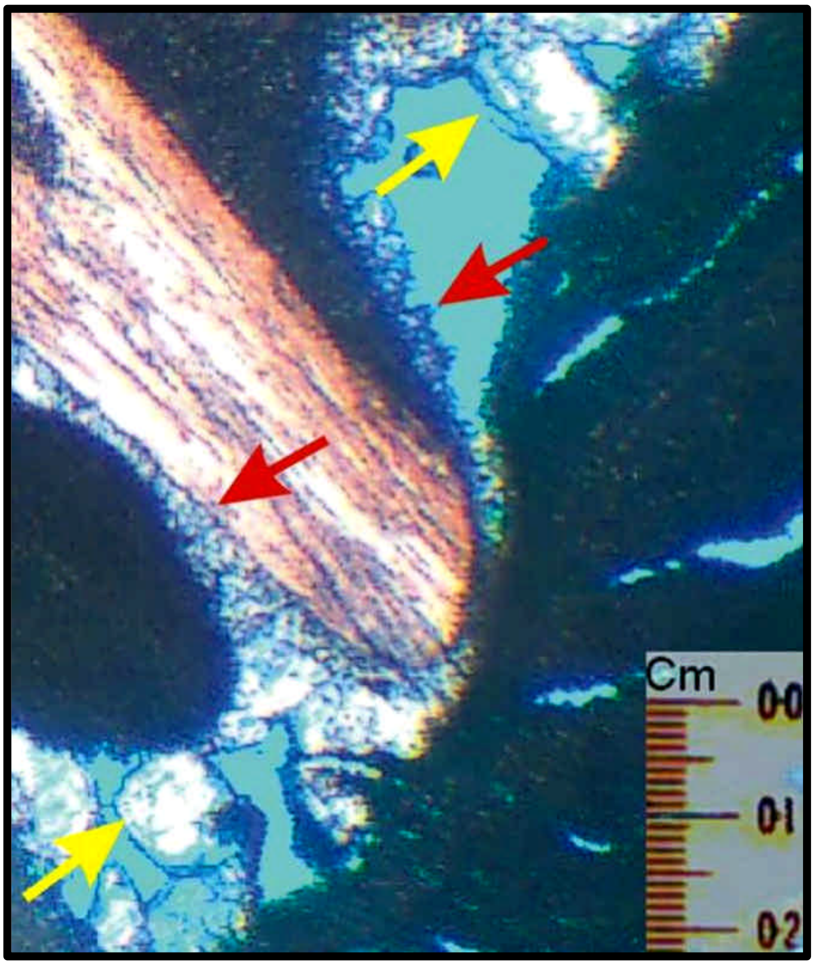

Fig.6.4. *Thin section from locality nine (sample IX50), belonging to facies two (F2). Red arrows point to bladed prismatic cement. Yellow arrows point to coarse mosaics cement. Magnification x10.*

Another sign of deep burial diagenesis is siliciclastics (e.g. quartz) that have dissolved allochems by pressure solution at grain-to-grain contacts (fig.6.5 and 6.6). This indicates that the allochem grains was a source for $CaCO_3$ to the pore water. The pore water itself can also have been saturated with $CaCO_3$, which is common in meteoric waters. Allochems that have dissolved other allochems by pressure solution in grain to grain contacts are also observed (fig.6.6). Furthermore, some of the allochems have been partly or entirely dissolved, leaving behind oversized pores (fig.6.6), which to a certain degree were subsequently partially filled with cement. In quite a few oversized pores, no cement is observed, indicating that dissolution and cementation took place simultaneously. Occasionally, both allochems and quartz grains have been partly dissolved. Allochems in the Azagador Member are more easily dissolved than siliciclastics, whereas polycrystalline quartz grains have disintegrated more extensively than monocrystalline grains.

Yet another sign of deep burial diagenesis is broken grains. Some quartz grains are intersected by one or several cracks, whereas allochems often are both broken into several pieces and slightly dislocated (fig.6.6), indicating compaction. Some of the allochems have not only disintegrated in this way, they also show evidence of tectonic stress after breakage (fig.6.6). Whereas the allochems in these occasions may be covered by bladed prismatic calcspar, the fracture surfaces of the pieces have no cement. Therefore, the fracturing must have occurred after burial and cementation. Consequently, it is not a result of compaction. The dislocations observed are never more than a few millimetres across and are never observed in quartz.

This fracturing may be related to uplift of the Sierra Cabrera, which occurred simultaneously with and following the deposition of the Azagador Member. If the tectonic elevation of the Sierra Cabrera resulted in thrusting in the area, it could have affected the Azagador Member. An increase in regional compression can have affected the pressure solution process, increasing the dissolution.

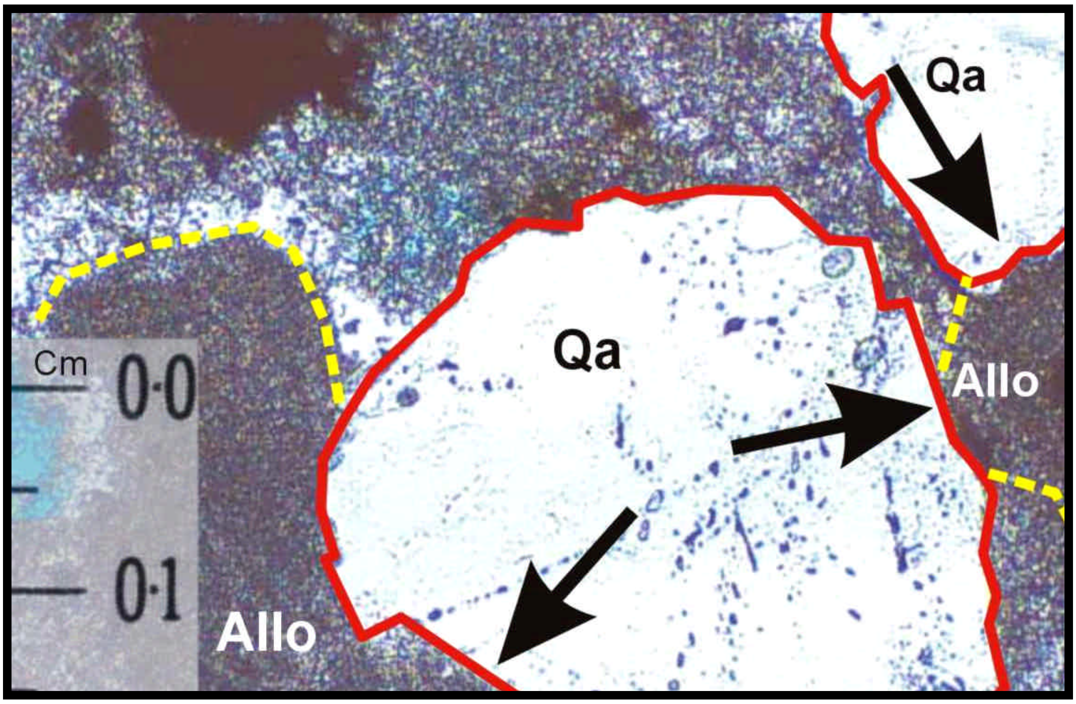

Fig.6.5. *Thin section from locality five(sample V114), belonging to facies two (F2). Arrows point to boundaries between siliciclastics (red continuous outline) and allochems (yellow dotted outline), where the former have dissolved the latter by pressure solution. Pores stained blue.* ***Qa****=Quartz,* ***Allo****=allochems. Magnification x10.*

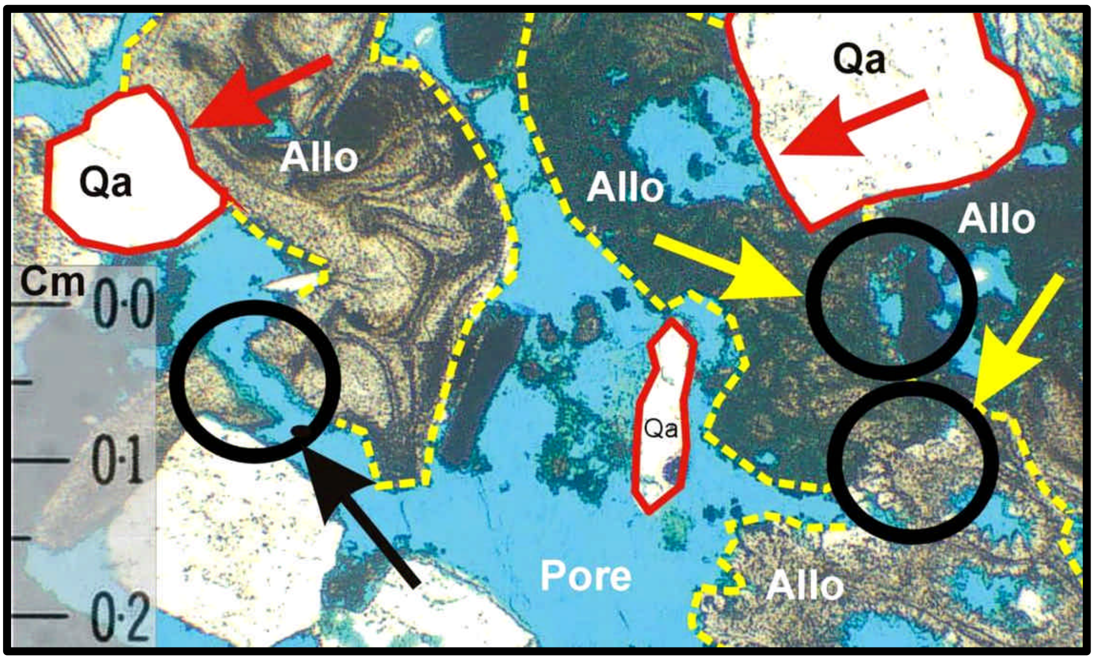

Fig.6.6. *Thin section from locality one (sample I02), belonging to facies four (F4). Red arrows point to grain boundaries where siliciclastics have dissolved allochems by pressure solution. Yellow arrows point to allochem-allochem contacts with either partly dissolution of both (upper circle) or of one (lower circle). The pore (stained blue) is oversized with residues of alga. Black arrow point to a circle with a broken allochem. Note that there is no cement on the broken surface, suggesting that breakage happened after cementation.* ***Qa****=Quartz,* ***Allo****=allochems. Magnification x3,2.*

Dolomitization has not been identified at all. The rather young age of the Azagador Member might be partially responsible for this, as it appears that dolomites increase in abundance back in time (Tucker and Wright 1990). This may be due to a change in the composition of seawater, a different climate or that simply through being older; the limestones have had more time for extensive dolomitization. An important consequence of dolomitization is an increase in porosity, due to the more compact crystal structure relative to calcite (Choquette and James 1990). Another typical phenomenon for extensive overburden is stylolites or dissolution seams, none of which are observed in the Azagador Member.

Despite the observed features suggesting deep burial diagenesis, it is often difficult to quantify exactly *how* deep the sediments were buried. On the other hand, the *relative* age of cements and degree of compaction can be determined. However, the *actual* time of, or *depth* of, burial under which, for instance, a cement-coated grain is broken, cannot be determined (Tucker and Wright 1990). It is rarely possible to decide exactly how much overburden is needed to accomplish the observed failure. One method is to estimate, if known, the maximum thickness of rocks that may have overlain the unit under study, which can give an indication on the minimum depth of burial. Trace elements, fluid inclusion data and/or stable-isotope geochemistry may also aid interpretations of burial depth, temperature and timing of porosity-related diagenetic events. Yet another method to determine depth of burial is to investigate chemical compaction features (see chapter seven).

6.3. Distribution of porosity

The Azagador Member is believed to have had a high initial porosity (see Chapter four). Nevertheless, most of what is thought to have been primary porosity has been occluded by cementation and compaction. The pore spaces identified in the investigated samples of the Azagador Member are both fabric- and non-fabric selective. With regards to the fabric selective porosity, moldic, intra- and interparticle porosity is commonly observed (see fig.6.6-8), whereas intercrystal porosity is also

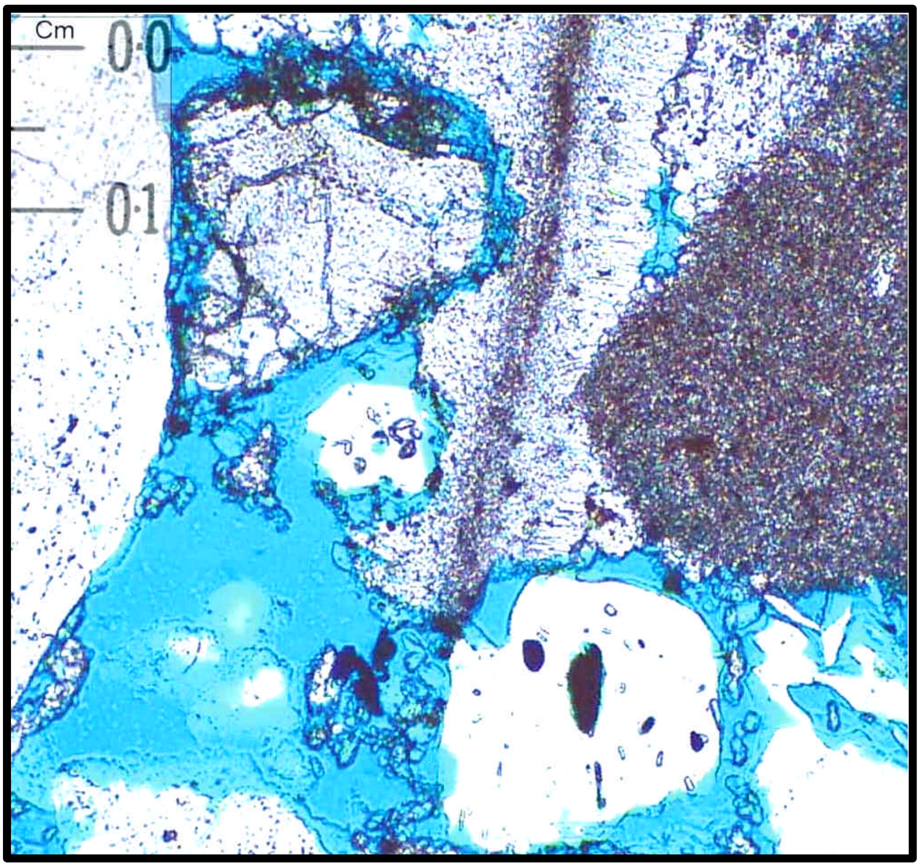

Fig.6.7. *Thin section from locality five (sample V17), belonging to facies three (F3). An oversized (vuggy) pore (blue colour) created from dissolution of one or several grains is seen in the lower left hand corner. Note also pressure solution of allochem from two sides (middle upper picture). Magnification x10.*

present in a few samples. Intraparticle porosity is restricted to allochems. The same applies to the observed moldic porosity. With the exception of rare fracture pores, the non-fabric selective pores are classified as vuggy porosity (fig.6.7).

Rarely, polycrystalline quartz, and in a few cases probably also feldspar, have been dissolved. In carbonates, intraparticle porosity is usually regarded as primary. In the Azagador Member it is frequently a result of dissolution of bioclastic grains (moldic or vuggy porosity). The ultimate porosity distribution seems to be have been developed in relation to and controlled by pre-existing interparticle porosity. Furthermore, initial porosity may also be a source for intraparticle porosity, but this porosity is limited during deposition of the sediments and later by crushed and disintegrated allochems filling in the pore space between the siliciclastic grains. This effect is probably amplified by burial and compaction, leaving dissolution of grains to be the main source for intraparticle porosity.

Pores are often oversized if they are the result of dissolution of one or several associated grains (fig.6.7). Dissolution of grains creates an impression of almost floating particles (in two dimensional thin section). Sometimes dissolution of grains has resulted in the creation of a pore with the shape of the dissolved grain, resulting in moldic porosity. Remnants of allochems in or around the pore may in such cases suggest that it is allochems that are most commonly dissolved. Sparry calcite cement (or micrite envelopes) surrounding the pore indicates dissolution after cementation (fig.6.8). This phenomenon seems to be especially common with very small bioclasts. If more than one grain is partly or wholly dissolved, the porosity is classified as vuggy (fig.6.7).

Evolution of subsurface porosity can be difficult to explain because subsurface fluids in carbonates are often believed to be supersaturated with respect to most carbonate phases (Moore 2001). One source of aggressive fluid acids (i.e. carbonic acid, largely controlled by the amount of CO_2 and H_2S in the pore water) capable of creating secondary porosity is dewatering of shale. Nevertheless, there is almost no shale in the Azagador Member. Furthermore, neither the underlying marl of the Chozas Formation nor the overlying Abad Member is capable of producing acid water – it is not likely that marl would produce aggressive fluids. Moreover, the Chozas Formation had been deformed and thus in all probability significantly dewatered prior to accumulation of the Azagador Member, making it even less likely that this Formation acted as the source for acid fluids. However, the neighbouring basin (the Sorbas Basin) to the west, contains abundant shale and mudstone deposits. Acid fluids forced out of these sediments during burial may have migrated into the calcarenites of the Azagador Member and acted as a dissolution agent. This explanation assumes lateral movement of the fluids quite a distance at a rather shallow depth in a compressional tectonic regime exposed to fracturing and other tectonic initiated changes. A more likely source then is acid fluids derived from an updip migration from (presumably) more shaley deposits at depth in the Vera Basin. This may have happen as a flushing event or gradually during burial (or even during uplift to present position).

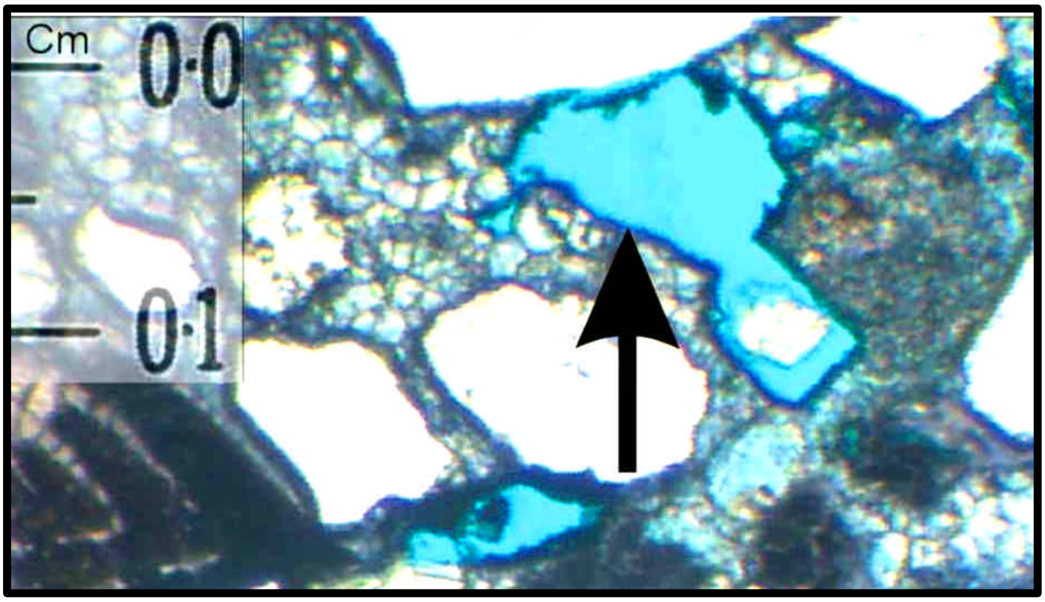

Fig.6.8. *Thin section from locality one (sample I130), belonging to facies three (F3). Dissolution of grain has led to an oversized moldic pore (blue colour) with the shape of the grain (arrow). Sparry calcite cement surrounding the pore indicates dissolution after cementation. There are remnants of the dissolved allochem(s), probably an alga(e), along the margin of the pore. This may also be a micrite envelope. Magnification x10.*

Another possible influence on the pore water may be hydrothermal events. Although no such events have been reported to have affected the Azagador Member, nor was any evidence for hydrothermal activity observed during the present study, numerous events have been identified in the Vera Basin throughout the Neogene (Penela and Barragán 1995). Moreover, the rather shallow burial of the Azagador Member makes it possible that meteoric waters may have penetrated down to the buried rocks at some stage. It is likely that an introduction of meteoric water at depth would take place gradually and/or in stages. A mixture of diverse subsurface fluids (e.g. brines and meteoric water) may then at some point have led to an undersaturation of the pore fluid water with respect to $CaCO_3$. This could lead to creation of secondary porosity (Morse et al. 1997). Finally, it is not possible to completely exclude that secondary porosity might originate from a (recent) unroofing of the Azagador Member. Dewatering of deeper buried shaley deposits and/or introduction of meteoric water seems like the most probable explanation for secondary porosity in the Azagador Member.

The overall impression of the Azagador Member is that the porosity evolution took place in more or less distinct stages. However, it is likely that more than one process occurred at the same time, especially the ones described in 2) and 3) below. When summarized, the evolution of the principal porosity types is assumed to have taken place in the following succession:

> 1) The primary porosity is believed to have consisted of mainly fabric selective interparticle pores, in allochems occasionally also intraparticle and rare intercrystal pores.
>
> 2) The creation of secondary porosity was initiated by partly or wholly dissolution of grains, especially allochems. This led to an increase in the fabric selective *intraparticle* porosity (in allochems) and sometimes creation of *moldic* pores (by dissolution of allochems), both pore types often later partly filled with burial cements. Rare fractures cutting across grains and filled with cement indicate that fracturing probably took place at this stage.
>
> 3) Some of the widespread secondary porosity appears to postdate compaction and pressure solution. By progressive dissolution moldic pores may have evolved into the more widespread *vuggy* pores (oversized pores), created by dissolution of more than just one grain (and most probably also cements – which again may have increased the interparticle porosity). Again, it was mainly the allochems and not the quartz grains that were being dissolved.

6.4. Sediment composition and porosity – relation to facies associations

None of the rocks from the Azagador Member are classified as Muddy Calcarenite. In fact, the samples from two facies associations are distributed rather evenly between the Bioclastic and Quartzose Calcarenite rock types (table 6.1 and fig.6.9). The lack of mud is the obvious trend in the diagram. The samples are otherwise apparently randomly distributed between the two end members quartz and allochems. Equally, the amount of mud in the samples is randomly distributed between the two end members. None of the samples have more than 50 percent of mud. This is not changed if the reference samples are taken into consideration (table 6.1). These samples are not systematically different from the two facies associations. None of them have more than 50 percent mud and they do not reveal any new information.

Table 6.1. *Rock classification and classification of facies association and reference samples. 100 percent means 100 percent of allochems, quartz and mud all together, not counting out cement and porosity. Figures in percent.*

Facies association	Sample Number	Quartz	Allochems	Mud	Classification
Facies ass. F3 (in-channels)	I2	30.92	69.08	0.00	Bioclastic Calcarenite
	I127	31.58	68.18	0.24	Bioclastic Calcarenite
	I128	57.53	42.20	0.27	Quartzose Calcarenite
	I130	63.71	35.48	0.81	Quartzose Calcarenite
	I120	47.65	43.19	9.15	Quartzose Calcarenite
	III133	23.31	70.68	6.02	Bioclastic Calcarenite
	III143	20.00	56.87	23.13	Bioclastic Calcarenite
	V17	50.13	43.31	6.56	Quartzose Calcarenite
	V18	51.14	23.54	25.32	Quartzose Calcarenite
	V19	45.30	28.96	25.74	Quartzose Calcarenite
	V22	72.88	17.69	9.43	Quartzose Calcarenite
	V21	36.55	30.49	32.96	Quartzose Calcarenite
	VIII149	37.35	55.53	7.13	Bioclastic Calcarenite
Facies ass. F2 (Comparison facies F2, F4 and F5 (outside-channels))	I12	51.91	46.89	1.20	Quartzose Calcarenite
	V114	15.11	74.34	10.55	Bioclastic Calcarenite
	V23	61.15	32.81	6.04	Quartzose Calcarenite
	V135	46.65	28.35	25.00	Quartzose Calcarenite
	V116	31.83	65.52	2.65	Bioclastic Calcarenite
	IX52	37.23	58.15	4.62	Bioclastic Calcarenite
	IX51	70.40	18.18	11.42	Quartzose Calcarenite
	IX50	4.85	87.06	8.09	Bioclastic Calcarenite
	IX54	61.69	33.98	4.34	Quartzose Calcarenite
Reference samples	*V140*	22.85	42.51	34.64	Bioclastic Calcarenite
	I119	26.15	30.99	42.86	Bioclastic Calcarenite
	V20	60.65	30.58	8.77	Quartzose Calcarenite
	V138	70.84	10.47	18.69	Quartzose Calcarenite

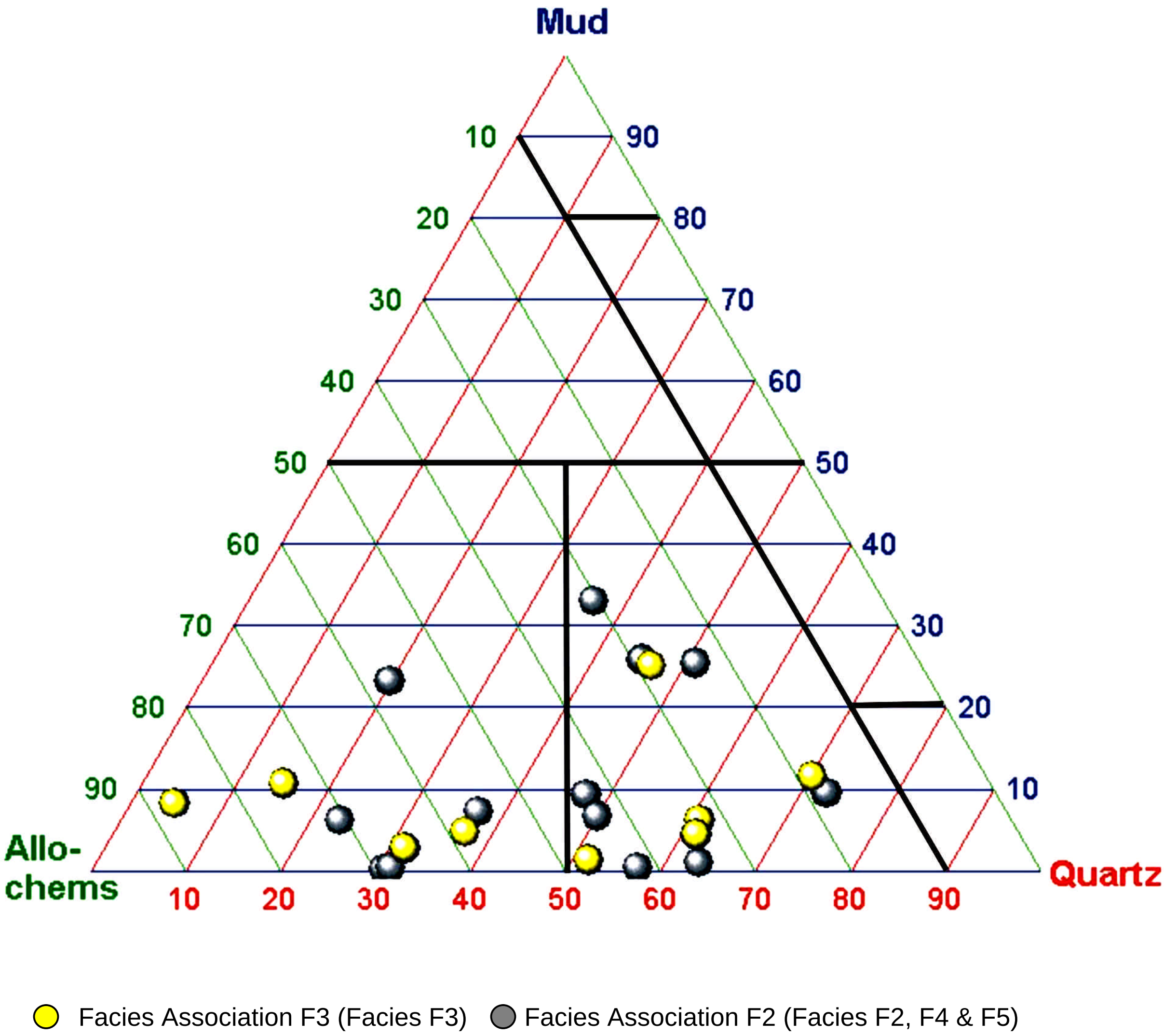

Fig.6.9. *Samples plotted in the classification diagram. Samples from the two facies associations are either Bioclastic Calcarenite or Quartzose Calcarenite. Note that all samples have less than 50 percent mud. All numbers in percent.*

In other words, the same sort of rock is identified both inside and outside of the channels, and does *not* appear to be related to facies association (or simply just facies). The different facies within facies association F2 do not show any apparent trend (see table 6.1). The relative amounts of quartz and allochems within the samples also appear to be randomly distributed in- and outside the channels.

The general absence of lime mud can be related to the high-energy depositional environment of the Azagador Member. The presence of mud can also reflect varying levels of energy. Field investigations show that facies association F3 (inside channel), generally has a higher amount of mud than association F2 (outside channel), but this is not obvious from the investigated samples. The infilling of the channels took place in stages, reflected in the presence of several stacked channels. If the channels were created and filled in episodes, muddy intervals probably represent periods with lower energy levels, for example when a channel was about to be abandoned.

With regards to porosity distribution, none of the samples have more than 20 percent porosity and a few are close to zero. Both samples with a high bioclastic allochem and quartz content show a random distribution of porosity. This is consistent with the distribution of the samples between the two rock types. It would be remarkable if there was a considerable difference in porosity but not in rock type (and allochem-distribution) within or outside the channels.

6.5. Porosity reduction

The porosity reduction in the two facies associations has been examined. To avoid confusion, it was decided to compare only results from point counting. These results have been confirmed by SEM analysis, both with regards to porosity and other features (table 6.2 and fig.6.10). 24 out of the 27 samples show a difference between the point counting result and the SEM results of less than four percent. All samples show a difference of less than nine percent (appendix).

Table 6.2. *Example of result from point counting and SEM analysis (average of four pictures) and the difference between them. See appendix for complete list. All numbers in percent.*

Sample	Present porosity point counting	Present porosity from average SEM porosity	Difference
V18	5.4	4.69	*0.72*

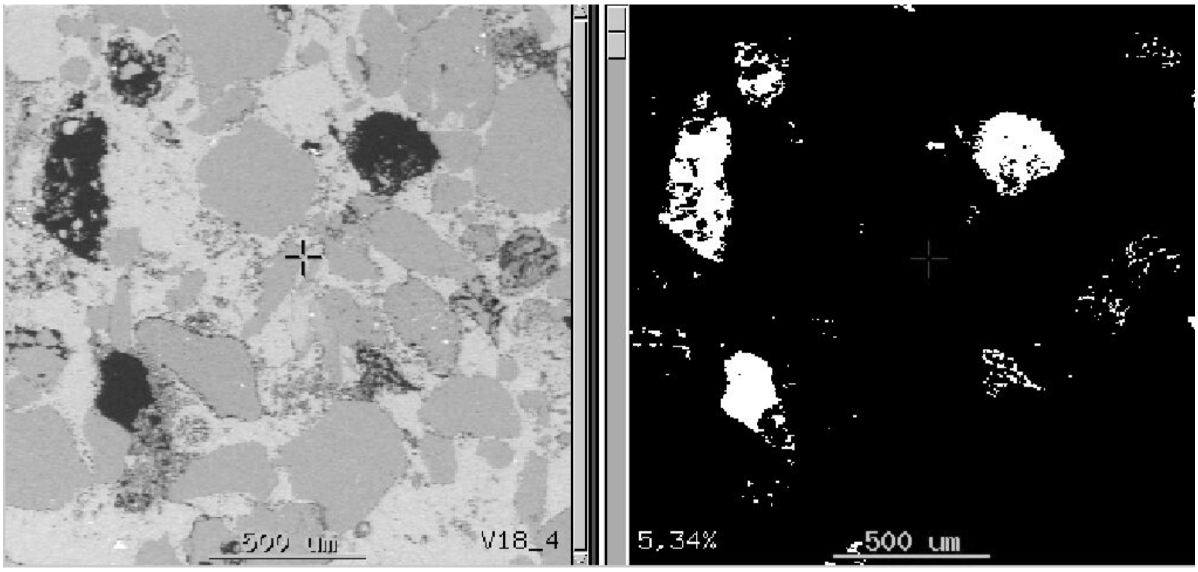

Fig.6.10. *SEM-picture of sample V18. The right hand picture is an inverted version of the grey scale picture on the left hand side. The white areas on the inverted pictures are the porosity, estimated to 5,34 percent.*

The amount of primary porosity may be estimated (amount of existing cement (in pores) plus existing porosity). A drawback with this method is that recent porosity may originate from secondary porosity and not just primary porosity. Furthermore, it does not consider the effects of compaction. Compaction reduces the porosity, both primary porosity and eventually also secondary porosity. On the contrary, compaction may also promote pressure solution leading to precipitation of cement. Nevertheless, the method may give rise to an educated guess on initial porosity. By comparing the estimated primary porosity with the present porosity, porosity reduction during burial diagenesis can be estimated (table 6.3).

Estimated initial (primary) porosity varies between 10,4 and 25,8 percent. Existing porosity varies between one and 12,6 percent. The reduction differs between the two facies associations. The average porosity reduction is 11,3 percent for F3 and 10,3 percent for F2,F4 & F5 (fig.6.11).

This randomly distribution is also clearly illustrated by a graphical representation of all the samples from the two associations (fig.6.12). The amount of reduction varies greatly, from 4,8 to 21,6 percent.

Table 6.3. *Porosity reduction in the two facies associations. Initial porosity is deducted from present amount of pores and cement, and reduction in porosity calculated from comparison.*

Facies association	Sample Number	Initial porosity	Present porosity	Reduction
Facies ass. F3 (in-channels)	I2	18.40	10.8	7.60
	I127	16.40	11.8	4.60
	I128	25.60	15	10.60
	I130	25.60	5.8	19.80
	I120	14.80	3.4	11.40
	III133	20.20	6.8	13.40
	III143	17.00	1	16.00
	V17	23.00	12.4	10.60
	V18	19.20	5.4	13.80
	V19	17.80	5.4	12.40
	V22	14.60	6.6	8.00
	V21	10.40	3.4	7.00
	VIII149	18.60	7.4	11.20
Facies ass. F2 (Comparison facies F2, F4 and F5 (outside-channels))	I12	15.00	9.4	5.60
	V114	16.40	3.4	13.00
	V23	21.80	6.8	15.00
	V135	10.40	3.2	7.20
	V116	24.20	2.6	21.60
	IX52	17.40	12.6	4.80
	IX51	14.00	5.6	8.40
	IX50	25.80	15	10.80
	IX54	16.80	10.2	6.60

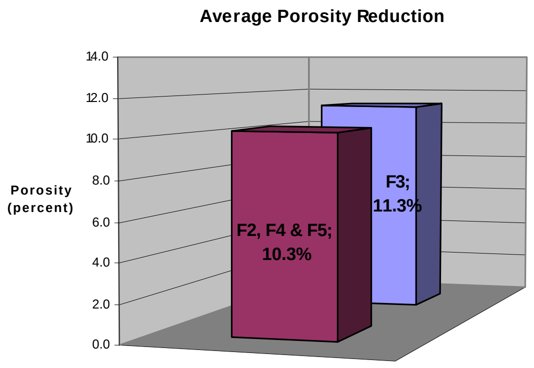

Fig.6.11. *Average porosity reduction in porosity in the two facies associations.*

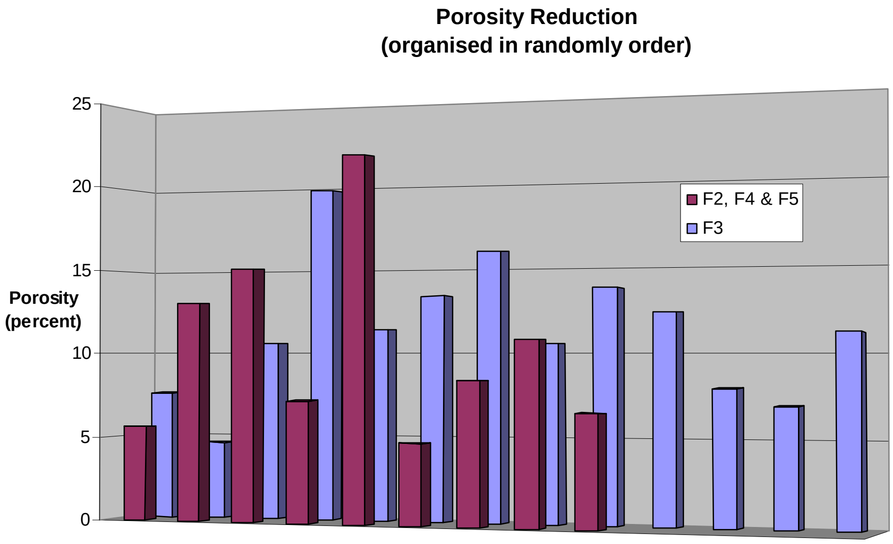

__Fig.6.12.__ Distribution of porosity between the two facies associations

With the samples arranged after decreasing amount of porosity, it is also obvious that there is not much difference between the two facies associations (fig. 6.13). Facies association F3 seems to have experienced the least reduction, but this effect is created by a higher number of samples.

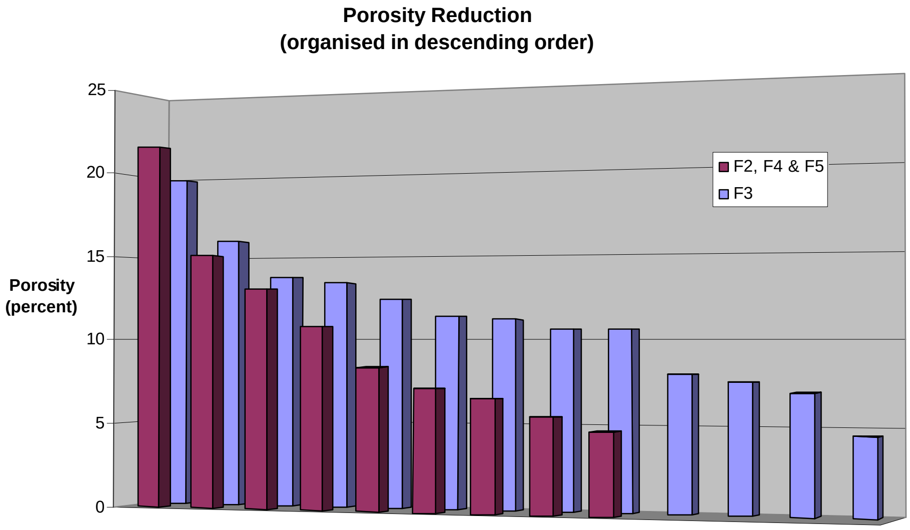

__Fig.6.13.__ Distribution of porosity between the two facies associations arranged after descending porosity.

In conclusion, both the porosity reduction and variation in porosity reduction is just as randomly distributed in the two facies as the ratio between quartz and allochems. This was expected. Fabric analysis and investigations performed by Thrana (2002) suggest that the difference between the samples from within and outside the channels is limited. The channel fill was reworked from the surrounding deposits, e.g. the outside-channel area, and accumulated in the channel(s) (Thrana 2002). Braga et al. (2001) also interpreted the channel fill to be of the same origin as the surrounding platform deposits.

7. DISCUSSION

7.1. Calcarenites

There is no such thing as a “standard” evolution of a sedimentary system during burial diagenesis. This is due to the highly variable petrographic composition and different burial and uplift history of various systems. Regardless of whether it is a siliciclastic- or carbonate-dominated system, variations occur (Choquette and Pray 1970; Burley et al. 1985; Tucker and Wright 1990; Morad et al. 2000). However, some patterns are more likely than others. With regards to carbonates, a gradual reduction of porosity during diagenesis and burial is generally the case (Bathurst 1980; Choquette and James 1990). A simple exponential function often fits a porosity-depth curve of carbonates down to 1000s of meters (Schmoker and Halley 1982; Schmoker et al. 1985; Tucker and Wright 1990). To a certain degree the evolution of porosity is controlled by facies, and more so in carbonates than siliciclastics (Choquette and James 1990). On the other hand, porosity can also be totally occluded in siliciclastics and preserved or created in carbonates. The degree to which porosity is occluded (or created) also depends on possible exposure of carbonates prior to burial, and degree of burial diagenesis – after final burial closely related to depth.

What about the calcarenites in the mixed siliciclastic-carbonate system (e.g. redistributed quartz and cool-water-bioclastic allochems) of the Azagador Member? Does the Member relate to an “ordinary” carbonate system, or did it respond differently to diagenesis? Two major processes convert loose carbonate sediments to lithified limestones (and hence reduce the porosity): Cementation and compaction (Choquette and James 1990). The effect of both these processes together with depth of burial and depositional environment will be discussed with respect to the Azagador Member.

7.1.1. Cementation and dissolution

Early sea floor cementation of cool water carbonates is not common and occurs only sporadically (James 1997; Pedley and Grasso 2002). In the Azagador Member virtually no early cement is observed. Moreover, the Azagador Member was deposited in a high-energy system (Thrana 2002). Significant and frequent reworking of the sediments is highly likely to occur in such a system. Additionally, bioclastic allochems are moved more easily than quartz grains (and feldspar grains) of similar size on the sea floor. This is due to a lower specific gravity than quartz grains of similar size, and the commonly platy morphology of many bioclastic fragments. Pure calcite is denser than quartz, but bioclasts generally contain microcavities generated by the decay of interstitial organics (Pedley and Grasso 2002). The unstable conditions limit sea floor cementation and deposits are likely to be kept free of mud by the actions of waves etc. (Martindale and Boreen 1997) (see chapter six). The presence of quartz in the Azagador Member may furthermore have limited cementation by reducing the relative amount of $CaCO_3$ available in the system. Quartz may also have acted as a crushing-agent of bioclastic allochems, and thus added to the unrest of the system. The absence of early cement is crucial to the burial history of temperate carbonates.

Bladed prismatic and coarse mosaics calcspar-cements, indicative of deep-burial diagenesis (Choquette and James 1990), occur in pores, cracks and allochem cavities in the Azagador Member. This lack of early cementation and extensive burial cement is typical of temperate carbonates (James 1997). Furthermore, as discussed earlier, the pore water in the Azagador Member is supposed to be of marine origin. However, a possible influence from meteorically-derived fluids would not necessarily have changed the cementation history. Nicolaides and Wallace (1997) have reported on cool-water carbonates in the late Oligocene-Miocene Clifton Formation in Australia. The calcarenitic deposits (predominantly skeletal carbonate grains) of the Clifton Formation form a possible analogue to the diagenesis of the Azagador Member. A present burial depth of the Clifton Formation ranging from 160 to 670 meters below present surface allows a comparison with the Azagador Member of diagenetic burial effects at different levels (fig.7.1). Besides the fact that the calcarenitic deposits of the Clifton Formation lack siliciclastics, the different tectonic conditions are important difference between the Azagador Member and the Clifton Formation to be aware of when comparing them. The former is situated in a compressional regime whereas the latter is situated on a stable craton. This makes the Azagador Member more prone to be affected by changing tectonic conditions, such as effects caused by the rise of the Sierra Cabrera. The main phase of uplift of the Sierra Cabrera postdates the accumulation of the Azagador Member. Hence, the Azagador was more likely to be influenced by changes in for example the ground water regime due to e.g. introduction of meteoric water to the system. In spite of these differences, a comparison might give valuable insight to the burial history of the Azagador Member.

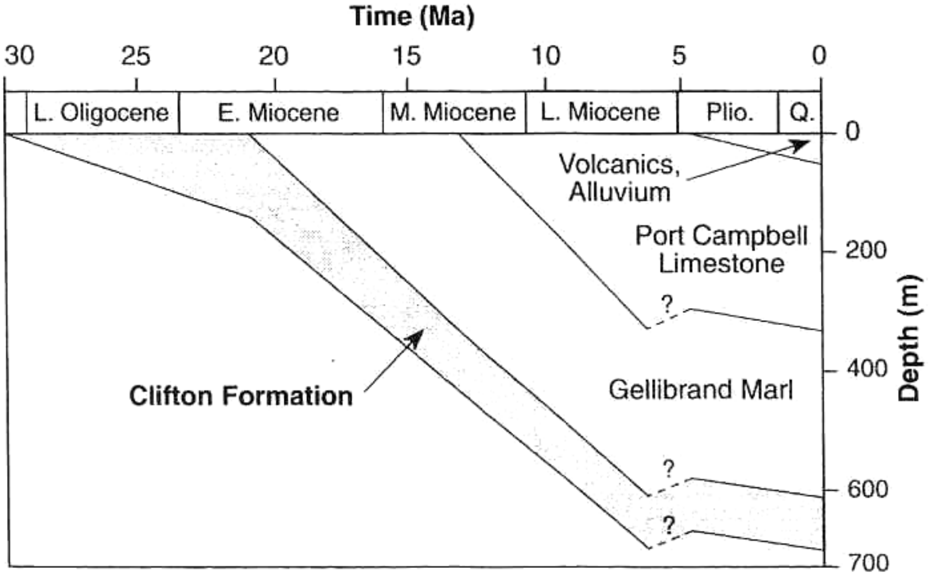

Fig. 7.1. *Burial history diagram of the Clifton Formation. A possible uplift of no more than 100 meters is indicated. Present burial depths range from 160 to 670 meters. After Nicolaides and Wallace* (1997).

The Clifton formation was deposited in a marine environment. The carbonates in the formation behaved like a typical temperate carbonate system with regards to cementation, and sea floor cement was limited to rare intraparticle calcite cement (Nicolaides and Wallace 1997). However, blocky calcite cement is believed to have formed in the burial environment from meteorically-derived fluids.

The authors argue that meteoric pore water probably promotes pressure dissolution because of its relatively low saturation level with respect to calcium carbonate. When grains are buried, intensified strain increases the solubility of calcium carbonate at grain contacts and may lead to pressure dissolution (Bathurst 1991). Away from the grain contact, strain is reduced and dissolved ions can be precipitated as cement at the grain surfaces. The Azagador Member shows a large amount of pressure solution, but not as comprehensive as the Clifton Formation. This is to be expected as the formation water in the Azagador Member is supposed to be of marine origin. Marine water has a higher saturation level with respect to calcium carbonate than fresh water (Tucker and Wright 1990; Nicolaides and Wallace 1997), and hence the rate of dissolution is slowed down. Both the Azagador Member and the Clifton Formation show regular grain to grain contact pressure dissolution.

Nicolaides and Wallace (1997) argue that lack of early cement strongly influences the compaction history, promoting the mechanical compaction leading to pressure solution. Early cementation, which is common in tropical aragonite carbonates, would almost certainly have delayed compaction significantly. Different authors have come up with a wide variety of depth estimates for the onset of different pressure solution features in pure carbonates. Numbers range from maximum 1500 meters in Devonian carbonates (Buxton and Sibley 1981) to as shallow as tens to hundreds of meters of burial in Mississippian grainstones (Meyers and Hill 1983). These divergent reports clearly indicate that it is impossible to generalise burial history and depths required for chemical compaction to initiate. The extent of pressure solution in the Azagador Member was probably also influenced by lack of early cementation. Another explanation supporting the explanation with the marine formation water-threshold effect is the presence of quartz. Quartz grains have a higher competence than bioclasts and might have acted similar to early cement and thus have delayed mechanical compaction and hence pressure solution. On the other hand, Moore (2001) reports from studies where presence of quartz has actually enhanced chemical compaction. However, these results are from fine grained carbonates where stylolites have a tendency to develop. The Azagador Member is neither fine grained nor has it developed stylolites. On the contrary, some of the relatively coarse bioclasts are capable of resisting mechanical failure as well. Experiments show that bioclasts can do this to a degree, so that the actual loss of porosity due to their failure may be less than 10 percent (at pressure equivalent to ~2500 meters burial) (Fruth Jr. et al. 1966).

Reorientation and distortion of grains are common mechanical compaction features (Meyers 1980; Tucker and Wright 1990) and do occur in the Azagador Member. Nevertheless, the relative importance of mechanical compaction is difficult to evaluate. Grain distortion, which includes mechanical grain breakage and plastic grain deformation, are common features in the bioclastic allochems of the Azagador. However, limited breakage of grains is far more common than total collapse. Hardly any of the bioclasts appears to have been complete prior to burial. The clasts were probably broken at the sea floor. The lack of total collapse may also be a result of supporting quartz grains, which may delay compaction. The most likely explanation may be relatively shallow burial, and hence less overburden than is required for extensive mechanical compaction features to develop.

7.1.2. Depth of burial

The absence of extensive chemical dissolution in the Azagador Member implies a rather shallow burial. Contrary to the Clifton Formation, the Azagador Member does not show any signs of fitted fabric (also called solution seam), dissolution seams or (micro) stylolites. Meyers (1980) orders the different compaction features and comments on the fact that mechanical compaction initiates prior to chemical compaction, and that pressure solution initiates prior to the development of (micro) stylolites. Microstylolites (only observable under the microscope) and stylolites (observable in hand specimens) usually develop after cementation and cut across grains, matrix and cement (Buxton and Sibley 1981). However, Bathurst (1987) and Tada and Siever (1989, and references therein) report that as little as 30-40 meters of overburden is required to produce interparticle pressure dissolution in carbonates. However, studies on the relationship between burial depth and the depth of formation pressure dissolution fabrics in carbonates are sparse. A hierarchic pattern of chemical dissolution features is observed by Nicolaides and Wallace (1997) in skeletal grainstone of the Clifton Formation. Pressure solution at grain contacts, similar to the ones described in the Azagador Member, are identified in a skeletal grainstone at all levels from 160 to 670 meters depth. Fitted fabric and microstylolites are observed at approximately 550 meters and greater in the Clifton Formation.

Apart from the pressure dissolution, none of the described features are observed at bioclast-bioclast contacts in the Azagador Member. The fragile anatomy of some of the bioclasts, e.g. red algae, may have contributed to the absence of fitted fabric by relieving some of the strain by adjustments or breakage. The more competent bioclasts may have dissolved the not so competent ones by ordinary pressure solution before fitted fabrics could develop. If the fitted fabric and microstylolites in the Clifton Formation are limited to a depth greater than 550 meters, this suggest that this is minimum depth for such features to develop. Initially, the absence of such dissolution features in the Azagador Member would then imply burial of the Member to a shallower depth than 550 meters. However, if the abundant quartz provided a partial framework that delayed compaction, it might also have delayed the onset of the different stages of pressure solution. On the contrary, if quartz held back compaction, this would give less cement (less available $CaCO_3$ from dissolution) to hold back compaction. Furthermore, less cement suggests that the rate of which quartz would dissolve bioclastic allochems by pressure solution would be higher than expected. Hence, it is reasonable to suggest that quartz neither prevented nor promoted compaction significantly. It is thus doubtful that quartz could delay the chemical dissolution and the onset of the different stages of pressure solution for very long (i.e. to a deeper burial).

A complicating factor when considering depth of burial is the observed secondary porosity. As discussed in chapter six, this could be due to introduction of aggressive fluid acids (carbonic acid) into the system. However, it is not possible to preclude other dissolution effects or even uplift or unroofing. All the same, it is not to be expected that such processes would totally remove every sign of eventually pressure solution or depth of burial in the Azagador Member. In addition, breakage of grains is hardly observed in quartz. This could indicate cementation that would hold back compaction and/or a limited depth of burial. All things considered, the observed features suggest a maximum depth of burial of the Azagador Member to a few hundred meters.

7.1.3. Porosity

The average porosity in the investigated samples of the Azagador Member is 10,8 percent. Some of this is primary, some is secondary. By coincidence, the average amount of calcite cement is also 10,8 percent (appendix). Furthermore, apart from the molluscs, all of the bioclastic allochems of the Azagador Member are calcitic. Therefore, the potential for secondary porosity to develop is poor. This is in contrast to the more aragonite dominated parts of the Photozoan Assemblage (Lønøy, Norsk Hydro Research Centre, pers. com. 2002).

Nicolaides and Wallace (1997) observe a drop in porosity and increase in the amount of cement in the skeletal grainstone of the Clifton Formation between 430 and 550 meters. Porosity drops dramatically from 14 to 1,5 percent whereas the amount of cement increases from approximately one to almost 10 percent. By comparison, Schmoker and Halley (1982) report (from borehole results) an average of approximately 30 percent porosity in (pure warm water) carbonates at the depth of 550 meters. However, single porosity results range from 20 to more than 40 percent at this depth. At the depth of 3500 meters the best fitted porosity curve shows an average porosity of 20 percent, even though single porosity results as low as ten percent are observed as shallow as 1500 meters of burial. Schmoker et al. (1985) found that only 15 percent of limestone reservoirs in the United States are buried to less than 600 meters (at the present stage). Scholle et al. (1983) predict porosity close to 40 percent or more in carbonates buried to less than 1000 meters from porosity-depth trends in North America and Europe. Schmoker et al. (1985) also noted that the depth-thermal maturity curve may be a better way to illustrate diagenetic effects, especially if treated logarithmically. Lack of early cementation would for example affect such a curve. Nevertheless, all these results deviate from the porosity observed both in the Azagador Member and the Clifton Formation. The porosity-depth curve of the latter does not fit a single exponential function (Nicolaides and Wallace 1997) (fig.7.2)

One reason for this is a probable *threshold interval* of burial cement between 430 and 550 meters, a condition also reported by Nelson et al. (1988) in non-tropical carbonates on New Zealand. Increased pressure solution and related cementation may explain this sudden increase in interparticle cement. A close relationship between extensive pressure solution and cementation has been suggested by several researchers (e.g. Nelson et al. (1988) and Choquette and James (1990)).

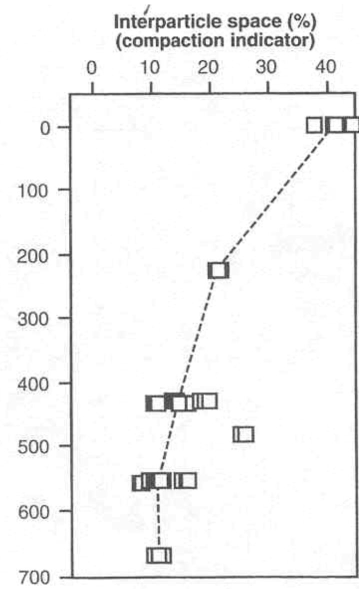

Fig.7.2. *Porosity-depth curve (interparticle space equals pore space plus cement) from the Clifton Formation. Figures plotted are from point counting of bore hole samples. The curve does not fit a simple exponential function. Note the interval from 430 and 550 meters, where both a drop in interparticle porosity and increase in interparticle cement occurs. Depth in meters. After Nicolaides and Wallace (1997).*

Compared to the Azagador Member the Clifton Formation has a much lower porosity but a similar amount of cement. However, if secondary porosity is neglected, the porosity in the Azagador Member would have been even less than 10,8 percent, perhaps more in line with the data from the Clifton Formation. The origin of the secondary porosity in the Azagador Member is not obvious. Depth of burial to only a few hundred meters is suggested in this discussion (see also chapter six). This is very shallow compared to the rock record. Thus, opposite to deeper buried rocks, it is possible that meteoric waters may have penetrated down to the Azagador Member at some stage. As mentioned, a mixture of diverse subsurface fluids (e.g. brines and meteoric water) may be undersaturated with respect to $CaCO_3$, and this could lead to creation of secondary porosity (Morse et al. 1997). Nevertheless, the 10,8 percent of porosity in the Azagador Member is a very low figure compared to the results from other researchers. This indicates, with the possible modification introduced by the compressional regime of the Azagador Member, that the Member has passed some kind of diagenetic threshold limit, similar to what is observed in the Clifton Formation between 430 and 550 meters (fig.7.2). It appears that mixed siliciclastic-allochems behave in a similar fashion to cool-water carbonates like the Clifton Formation during deep burial. In addition, the porosity data support the suggested depth of burial to a few hundred meters. These results also suggest that mixed siliciclastic-allochems have a poorer reservoir potential when buried deeper than the threshold limit and not subjected to extensive creation of secondary porosity.

7.2. Calcarenitic deposits and the depositional environment of the Azagador Member

Braga et al. (2001) have interpreted the investigated channels of the Azagador Member to be erosion structures cutting through outer platform sediments. According to the authors, they mainly acted as bypass features, but significant amounts of platform sediments were removed by erosion from the walls of the incised channels and mobilized downslope. Once abandoned, they were filled with sediments from the surrounding platforms. Thrana (2002) has interpreted the channels to have been cut into a ramp in a narrow, current dominated strait located between the Sierra Cabrera and the Sierra de los Filabres (fig.7.3).

What Braga et al. define as a platform, Thrana has interpreted to be a ramp with dunes moving from west to east by strong currents. The combination of bottom currents, storms and tides sometimes acted together to create strong rip current events. These currents were responsible for the formation of the channel structures. Each level identified in the channels represents different preserved events. Decreasing current intensity created some upfining both inside and outside of the channels. When the next storm event occurred, finer pelagic sediments were eroded from outside the channels. Still, some were amalgamated and preserved inside the channels. However, in both the explanations of Braga and Thrana, the preserved sediments within and outside of the channels are essentially the same. This is confirmed by the findings in this thesis, where no systematic difference is observed between the two facies associations inside and outside the channels (see chapter six).

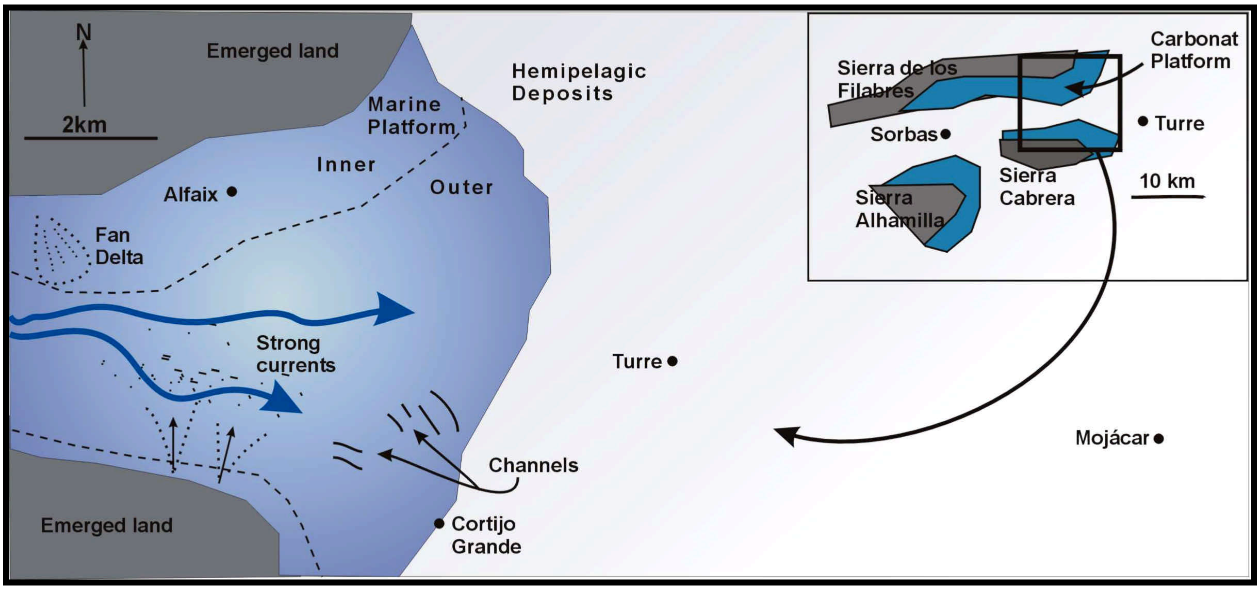

Fig.7.3. *Palaeogeographical reconstruction of the depositional system of the Azagador Member. Modified from Thrana (2002).*

This implies that 1) In contrast to warm water carbonates, cool water carbonates are easily remobilized and behave like siliciclastics. On a sequence-stratigraphic scale, an “ordinary” carbonate system has the likelihood of being exposed and undergoing extensive alteration. A subaqueous origin with no exposure events is the preferred explanation of Braga et al. (2001). Nevertheless, palaeosols are observed in certain facies of the Azagador Member. However, the palaeosols are only of a local character and are not believed to have covered the system as a whole. Furthermore, no typical signs of meteoric influence are observed. The Heterozoan Association also shares similarities with siliciclastics with respect to reservoir characteristics (Nelson 1988; James 1997; Lønøy, Norsk Hydro Research Centre, pers. com. 2002). 2) Due to redistribution of grains, both the amount of cement and porosity can vary greatly within different structures and probably also within the different facies. The distribution of grains seems to be somehow random within a given area. The variation in porosity might be due to local concentrations of bioclastic allochems, leading to selective porosity occlusion and/or creation of secondary porosity. As pointed out earlier, the ultimate porosity distribution seems to be controlled by the primary porosity. Presence of lime mud would affect permeability, intensifying the corroding effect of whatever pore fluid present at some levels and likewise reducing it at others.

Up until now little or virtually no work has been done on the porosity and permeability of mixed carbonate-siliciclastic systems. It is therefore also possible that the variations observed within the calcarenites of the Azagador Member are natural for such facies. To help clarifying the unanswered question with regards to the diagenesis of mixed calcarenitic deposits like the Azagador Member, more work has to be done. Some constraints can be placed on the burial depth, timing of porosity-related diagenetic events and even temperature by utilizing trace element and isotope geochemistry and two-phase fluid inclusions.

8. CONCLUSIONS

The main emphasis of this thesis has been to investigate the diagenesis and porosity of the Azagador Member.

- The term “mixed siliciclastic-carbonate system” has been given a new definition: Rocks that contain an intimately mixture of siliciclastic and bioclastic allochem-material. With regards to burial and diagenesis of the Azagador Member, and most probably also for similar mixed deposits, a carbonate approach is justified.

- A new classification scheme has been produced for mixed sediments. The simple triangular classification constitute the three end members of the Azagador Member: Siliciclastics, allochems and mud.

- The faunal assemblage is of the cool-water (temperate) carbonates of the Heterozoan Association-type (previous called Foramol Association).

- The two facies associations are distributed rather randomly between the Bioclastic Calcarenite and Quartzose Calcarenite rock types. In other words, the same sorts of rocks are identified both inside and outside the channels, and therefore do not appear to be related to facies associations.

- The investigated facies are interpreted to be of a purely marine origin, but virtually no marine cement has been identified. This is common for cool water carbonates, and seems to be the case for mixed deposits as well. This lack of early cement strongly influences the compaction history, promoting the mechanical compaction leading to pressure solution. The presence of quartz grains and/or shallow burial may have delayed compaction.

- Siliciclastics (e.g. quartz) have dissolved allochems by pressure solution. Quite a few allochems have been entirely dissolved, leaving behind oversized pores. Cements indicative for deep burial, such as coarse mosaic calcspar, have been identified. Occasions of tectonically-associated fracturing of grains may be related to the elevation of the Sierra Cabrera.

- The absence of extensive chemical dissolution suggests burial to not much deeper than of the order of 0,5 kilometres. The porosity results indicate that the Azagador Member has passed some kind of threshold limit, perhaps diagnostic for cool water carbonates.

- The pore spaces identified are both fabric- and non-fabric selective. Intra- and interparticle porosity are frequently observed. The primary porosity is partly or completely occluded by compaction and burial cement. The secondary porosity was mostly created by dissolution of bioclastic grains that created moldic and vuggy pores (oversized pores). The reduction of porosity is randomly distributed between the two facies associations.

- The porosity can vary greatly within different channel structures and also within the different facies associations. The origin of the secondary porosity is not obvious. Two processes are suggested as likely: 1) Updip migration of acid fluids from dewatering of shaley deposits at depth in the Vera Basin, and/or 2) Meteoric waters have reached down to the buried rock to create a mixture of brines and meteoric water undersaturated with respect to $CaCO_3$.

- It may be that the variations in porosity within the calcarenites of the Azagador Member are within an expected natural variation in such facies. More work has to be carried out to confirm or invalidate this.

- In chronological order, the main diagenetic events are supposed to have developed as follows (it is possible that the introduction of acid pore fluids and the accompanied creation of secondary porosity took place after the onset of erosion and uplift):

- Deposition and burial in a marine environment and with marine pore fluids but no early marine cements.
- Further burial, compaction and pressure dissolution, simultaneously with precipitation of burial cement(s).
- Introduction of acid pore fluids, perhaps through a flushing event, and creation of secondary porosity
- Burial to a few hundred meters and passing of some kind of threshold limit, arresting comprehensive creation of secondary porosity
- Erosion and uplift to present position, presumably accompanied by creation of some secondary porosity.

REFERENCES

Adams, A. E. and MacKenzie, W. S., 1998. A colour atlas of carbonate sediments and rocks under the microscope. London, Manson Publishing, p.180.

Adams, A. E., MacKenzie, W. S. and Guilford, C., 1984. Atlas of sedimentary rocks under the microscope. New York, Longman Scientific & Technical, p.104.

Archie, G. E., 1952. Classification of carbonate reservoirs rocks and petrophysical considerations. American Association of Petroleum Geologists Bulletin 36(2): 145-152.

Bathurst, R.G.C, 1980. Deep crustal diagenesis in limestones. Revista del Instituto de Investigaciones Geologac de la Diputación de Barcelona (Universidad de Barcelona) 34: 89-100.

Bathurst, R.G.C, 1987. Diagenetically enhanced bedding in argillaceous platform limestones: stratified cementation and selective compaction. Sedimentology 34: 749-778.

Bathurst, R.G.C, 1991. Pressure-dissolution and limestone bedding: the influence of stratified cementation. In: Einsels, G., Ricken, W. and Seilacher, A.(Eds.), Cycles and events in stratigraphy. Springer Verlag:450-463.

Braga, J. C., Martin, J. M. and Wood, J. L., 2001. Submarine lobes and feeder channels of redeposited, temperate carbonate and mixed siliciclastic-carbonate platform deposits (Vera Basin, Almería, southern Spain). Sedimentology 48(1): 99-116.

Brown, A., 1997. Porosity variation in carbonates as a function of depth: Mississippian Madison Group; Williston Basin. Tulsa, The American Association of Petroleum Geologists, p.311.

Burley, S. D., Kantorowicz, J. D. and Waugh, B., 1985. Clastic diagenesis. In: Brenchly, P. J. and Williams, B. J. P.(Eds.), Sedimentology: recent developments and applied aspects. Geological Society of London Special Publications 18.:189-226.

Buxton, T. M and Sibley, D. F, 1981. Pressure solution features in shallow buried limestone. Journal of Sedimentary Petrology 51: 19-26.

Carannante, G., Esteban, M., Milliman, J. D. and Simone, L., 1988. Carbonate lithofaces as paleolatitude indicators: problems and limitations. Sedimentary Geology 60: 333-346.

Chave, K. E., 1967. Recent carbonate sediments -an unconventional view. Journal of Geological Education 15: 200-204.

Choquette, P. W. and James, N.P., 1990. Limestones - the burial diagenetic environment. In: McIlreath, I.A. and Morrow, D.W.(Eds.), Diagenesis. Geological Association of Canada:75-112.

Choquette, P. W. and Pray, L. C., 1970. Geological nomenclature and classification of porosity in sedimentary carbonates. American Association of Petroleum Geologists Bulletin 54(2): 207-250.

Dunham, R. J., 1962. Classification of carbonate rocks according to depositional textures. In: Ham, W. E.(Ed.), Classification of carbonate rocks. American Association of Petroleum Geologists Memoir 1:108-121.

Enos, P. and Sawatsky, L. H., 1981. Pore networks in Holocene carbonates sediments. Journal of Sedimentary Petrology 51: 961-986.

Folk, R. L., 1954. The distinction of grain size and mineral composition in sedimentary-rock nomenclature. Journal of Geology 62: 354-359.

Folk, R. L., 1959. Practical petrographic classification of limestones. American Association of Petroleum Geologists Bulletin 43: 1-38.

Fruth Jr., L. S., Orme, G. R. and Donath, F. A., 1966. Experimental compaction effects in carbonate sediments. Journal of Sedimentary Petrology 36: 747-754.

Haq, B. U., Hardenbol, J. and Vail, P. R., 1987. The chronology of fluctuating sea level since the Triassic. Science 235: 1156-1167.

Heyari, E., 2000. Porosity loss, fluid flow and mass transfer in limestone reservoirs: Application to the Upper Jurassic Smackover Formation. American Association of Petroleum Geologists Bulletin 84: 100-118.

James, N.P., 1997. The cool-water carbonate depositional realm. In: Noel, J. P. and Clarke, J. A. D.(Eds.), Cool-water carbonates. Society for Sedimentary Geology Special Publications 56:1-19.

James, N.P. and Bone, Y., 1991. Origin of cool water, Oligo-Miocene deep shelf limestone, Eucla Platform, Southern Australia. Sedimentology 38: 323-341.

James, N.P. and Choquette, P. W., 1990. Limestones - the sea-floor diagenetic environment. In: McIlreath, I.A. and Morrow, D.W.(Eds.), Diagenesis. Geological Association of Canada:13-34.

Kupecz, J. A., Gluyas, J. and Bloch, S. (Eds.), 1997. Reservoir quality prediction in sandstones and carbonates: An overview. Tulsa, The American Association of Petroleum Geologists Memoir 69, p. 311.

Lees, A., 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. Marine Geology 19: 159-198.

Lees, A. and Buller, A. T., 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Marine Geology 13: M67-M73.

Lomando, A. J. and Harris, P. M., 1991. Mixed siliciclastic-carbonate system. Mixed siliciclastic-carbonate system, Dallas, Society of Sedimentary Geology Core Work Shop 15, p. 569

Lucia, F. J., 1983. Petrophysical parameters estimated from visual description of carbonate rocks: a field classification of carbonate pore space. Journal of Petroleum Technology 35: 626-637.

Lucia, F. J., 1995. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. American Association of Petroleum Geologists Bulletin 79(9): 1275-1300.

Lucia, F. J., 1999. Carbonate reservoir characterization. Berlin Heidelberg, Springer Verlag, p.226.

Lønøy, A., 2000. Carbonate grains, texture, cements and porosity (Report). Norsk Hydro Research Centre, Bergen.

Martín, J. M. and Braga, J. C., 1994. Messinian events in the Sorbas Basin in southeastern Spain and their implications in the recent history of the Mediterranean. Sedimentary Geology 90: 257-268.

Martín, J. M. and Braga, J. C., 1996. Tectonic signals in the Messinian stratigraphy of the Sorbas basin (Almería, SE Spain). In: Friend, P. F. and Dabrio, C. J.(Eds.), Tertiary basins of Spain: the stratigraphic record of crustal kinematics. Cambridge University Press:387-391.

Martín, J. M. and Braga, J. C., 2001. Shallow marine Sedimentation. In: Mather, A. E., Martín, J. M., Harvey, A. M. and Braga, J. C.(Eds.), A field guide to the Neogene sedimentary basins of the Almería Province, South-East Spain. Blackwell Science:134-185.

Martindale, W. and Boreen, T., 1997. Temperature-stratified Mississippian Carbonates as hydrocarbon reservoirs-examples from the foothill of the Canadian Rockies. In: James, N.P. and Clarke, J. A. D(Eds.), Cool-water carbonates. Society for Sedimentary Geology Special Publications 56:391-409.

McBride, E. F., 1963. A classification of common sandstones. Journal of Sedimentary Petrology 33: 664-669.

Meyers, W. J., 1980. Compaction in Mississippian skeletal limestones, southwestern New Mexico. Journal of Sedimentary Petrology 50: 457-474.

Meyers, W. J. and Hill, B. E., 1983. Quantitative studies of compaction in Mississippian skeletal limestone, New Mexico. Journal of Sedimentary Petrology 53: 231-242.

Miller, J., 1988. Cathodoluminescence microscopy. In: Tucker, M. E.(Ed.), Techniques in Sedimentology. Blackwell Scientific Publications:174-190.

Montenat, C. and D'estevou, P. Ott, 1996. Late Neogene basins evolving in the Eastern Betic transcurrent fault zone: an illustrated review. In: Friend, P. F. and Dabrio, C. J.(Eds.), Tertiary basins of Spain: the stratigraphic record of crustal kinematics. Cambridge University Press:372-386.

Montenat, C., Ott D'Estevou, P. and Masse, P., 1987. Tectonic-sedimentary characters of the Betic Neogene basins evolving in a crustal transcurrent shear zone (SE Spain). Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine 11(1): 1-22.

Moore, C. H., 2001. Carbonate reservoir porosity evolution and diagenesis in a sequence stratigraphic framework. Los Angeles, Elsevier, p.444.

Morad, S., Ketzer, J. M. and De Ros, L. F., 2000. Spatial and temporal distribution of diagenetic alterations in siliciclastic rocks: implications for mass transfer in sedimentary basins. Sedimentology 47 (Suppl.1): 95-120.

Morse, J., Hanor, J. and He, S., 1997. The role of mixing and migration of basina waters in carbonate mineral mass transport. In: Montanez, I. P., Gregg, J. M. and Shelton, K. L(Eds.), Basin wide diagenetic patterns: Integrated petrologic, geochemical, and hydrologic considerations. Society for Sedimentary Geology Special:41-50.

Mount, J., 1985. Mixed siliciclastic and carbonate sediments: a proposed first-order textural and compositional classification. Sedimentology(32): 435-442.

Nelson, C. S., 1988. An introductory perspective on non-tropical shelf carbonates. Sedimentary Geology 60: 3-12.

Nelson, C. S., Harris, G. J. and Young, H. R., 1988. Burial-dominated cementation in non-tropical carbonates of the Oligocene Te Kuiti Group, New Zealand. Sedimentary Geology 60: 233-250.

Nicolaides, S. and Wallace, M. W., 1997. Pressure-dissolution and cementation in an Oligo-Miocene non-tropical limestone (Clifton Formation), Otway basin, Australia. In: James, N.P. and Clarke, J. A. D(Eds.), Cool-water carbonates. Society for Sedimentary Geology Special Publications 56:249-261.

Nijhuis, H. J. 1964. Plurifacial alpine metamorphism in the south-eastern Sierra de los Filabres South of Lubrín, SE Spain (PhD.). University of Amsterdam, Amsterdam.

Pedley, M. and Grasso, M., 2002. Lithofacies modelling and sequence stratigraphy in microtidal cool-water carbonates: a case study from the Pleistocene of Sicily, Italy. Sedimentology 49(3): 533-553.

Penela, A. J. P. and Barragán, G., 1995. Silification of carbonate clasts in marine environment (Upper Miocene, Vera Basin, SE Spain). Sedimentary Geology 97: 21-32.

Pettijohn, F. J., Potter, P. E. and Siever, R. (Eds.), 1987. Sand and sandstone. New York, Springer-Verlag, p. 553.

Pray, L. C. and Choquette, P. W., 1966. Genesis of carbonate reservoir facies (abstract). American Association of Petroleum Geologists Bulletin 50: 632.

Rondeel, H. E. 1965. Geological Investigations in the Western Sierra Cabrera and Adjoining Areas, South-Eastern Spain (PhD.). University of Amsterdam, Amsterdam, p.155.

Sanz de Galdeano, C. M. and Rodríguez-Fernández, J., 1996. Neogene palaegeography of the Betic Cordillera: an attempt at reconstruction. In: Friend, P. F. and Dabrio, C. J.(Eds.), Tertiary basins of Spain: the stratigraphic record of crustal kinematics. Cabridge University Press:323-329.

Schmoker, J. W. and Halley, R. B., 1982. Carbonate porosity versus depth: A predictable relation for South Florida. American Association of Petroleum Geologists Bulletin 66(12): 2561-2570.

Schmoker, J. W., Krystinik, K. B. and Halley, R. B., 1985. Selected characteristics of limestone and dolomite reservoirs in the United States. American Association of Petroleum Geologists Bulletin 69: 733-741.

Scholle, P. A., Arthur, M. A. and Ekdale, A. A., 1983. Pelagic environment. In: Scholle, P. A., Bebout, D. G. and Moore, C. H.(Eds.), Carbonate Depositional Environments. American Association of Petroleum Geologists Memoir 33:619-691.

Scholle, P. A. and Halley, R. B., 1985. Burial diagenesis: out of sight, out of mind! In: Schneidermann, N. and Harris, P. M.(Eds.), Carbonate cements. Society of Economic Paleontologists and Mineralogists Special Publications 36:309-334.

Tada, R. and Siever, R., 1989. Pressure solution during diagenesis. Annual Review of Earth and Planetary Sciences 17: 89-118.

Talbot, M .R., 1971. Calcite cements in the Corallian Beds (Upper Oxfordian) of southern England. Journal of Sedimentary Petrology 41: 261-273.

Thrana, C., 2002. Facies and depositional environment of the Azagador Member (Hovedfag/Master Thesis), University of Bergen, Bergen, p.110.

Tobin, R. C., 1997. Porosity prediction in frontier basins: A systematic approach to estimating subsurface reservoir quality from outcrop samples. In: Kupecz, J. A., et al.(Ed.), Reservoir quality prediction in sandstones and carbonates. The American Association of Petroleum Geologists 69:311.

Trewin, N., 1988. Use of scanning electron microscope in sedimentology. In: Tucker, M. E.(Ed.), Techniques in Sedimentology. Blackwell Science:229-273.

Tucker, M. E., 2001. Sedimentary petrology. Oxford, Blackwell Science, p.263.

Tucker, M. E. and Wright, V. P., 1990. Carbonate sedimentology. Oxford, Blackwell Science, p.482.

Völk, H. R. 1967. Zur Geologie und Stratigraphie des Neogenbeckens von Vera, Südost-Spanien (PhD.). The University of Amsterdam, Amsterdam, p.159.

Völk, H. R. and Rondeel, H. E., 1964. Zur gliederung des Jungtertiärs im becken von Vera, Südostspanien. Geologie en Mijnbouw 43: 310-315.

Weijermars, R., Roep, T. B., van der Eeckhout, B., Postma, G. and Kleverlaan, K., 1985. Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almería, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain). Geologie en Mijnbouw 64: 397-411.

Westra, G. 1969. Petrogenesis of a composite metamorphic facies series in an intricate fault-zone in the south-eastern Sierra Cabrera, SE Spain (PhD.). University of Amsterdam, Amsterdam.

Wilson, M. E. J., 2002. Cenozoic carbonates in Southeast Asia: implications for equatorial carbonate development. Sedimentary Geology 147: 133.

Zuffa, G. G., 1980. Hybrid Arenites: their composition and classification. Journal of Sedimentary Petrology 50(1): 21-29.

APPENDIX

Thin sections point count results – absolute numbers

Facies association	Facies	Sample Number	Quartz	Calcaeous red algae	Echinoids	Molluscs	Foramini-fers	Other bioclasts	(Total allochems)	Micritic matrix	Calcite cement	Unknown	Pores	N
Facies F3 (in-channels)	F3	I2	124	150	38	68	6	15	277	0	38	7	54	500
	F3	I127	132	85	6	86	5	103	285	1	23	0	59	500
	F3	I128	214	44	0	11	7	95	157	1	53	0	75	500
	F3	I130	237	22	17	17	14	62	132	3	99	0	29	500
	F3	I120	203	40	7	41	0	96	184	39	57	0	17	500
	F3	III133	93	70	37	46	17	112	282	24	67	0	34	500
	F3	III143	83	134	14	41	0	47	236	96	80	0	5	500
	F3	V17	191	37	11	54	4	59	165	25	53	4	62	500
	F3	V18	202	9	1	36	4	43	93	100	69	9	27	500
	F3	V19	183	9	14	34	10	50	117	104	62	7	27	500
	F3	V22	309	8	5	9	0	53	75	40	40	3	33	500
	F3	V21	163	9	4	32	0	91	136	147	35	2	17	500
	F3	VIII149	152	67	0	21	0	138	226	29	56	0	37	500
Comparison facies F2, F4 and F5 (outside-channels)	F2	I12	217	53	41	57	2	43	196	5	28	7	47	500
	F2	V114	63	180	19	44	3	64	310	44	65	1	17	500
	F2	V23	233	25	6	29	6	59	125	23	75	10	34	500
	F2	V135	209	16	14	34	11	52	127	112	36	0	16	500
	F2	V116	120	16	38	51	22	120	247	10	108	2	13	500
	F5	IX52	153	49	15	48	7	120	239	19	24	2	63	500
	F4	IX51	302	29	18	3	0	28	78	49	42	1	28	500
	F4	IX50	18	154	7	129	0	33	323	30	54	0	75	500
	F4	IX54	256	23	18	9	1	90	141	18	33	1	51	500
Reference samples	F6	V140	93	47	24	24	2	76	173	141	78	1	14	500
	F6	I119	119	6	6	19	11	99	141	195	29	0	16	500
	F5	V20	242	23	9	23	4	63	122	35	59	6	36	500
	F10	V138	345	5	0	4	0	42	51	0	91	0	13	500

Thin sections point count results – percent														
Facies association	**Facies**	**Sample Number**	**Quartz**	**Calcaeous red algae**	**Echinoids**	**Molluscs**	**Foraminifers**	**Other bioclasts**	**(Total allochems)**	**Micritic matrix**	**Calcite cement**	**Unknown**	**Pores**	**N**
Facies F3 (in-channels)	F3	I2	24.8	30	7.6	13.6	1.2	3	55.4	0	7.6	1.4	10.8	100
	F3	I127	26.4	17	1.2	17.2	1	20.6	57	0.2	4.6	0	11.8	100
	F3	I128	42.8	8.8	0	2.2	1.4	19	31.4	0.2	10.6	0	15	100
	F3	I130	47.4	4.4	3.4	3.4	2.8	12.4	26.4	0.6	19.8	0	5.8	100
	F3	I120	40.6	8	1.4	8.2	0	19.2	36.8	7.8	11.4	0	3.4	100
	F3	III133	18.6	14	7.4	9.2	3.4	22.4	56.4	4.8	13.4	0	6.8	100
	F3	III143	16.6	26.8	2.8	8.2	0	9.4	47.2	19.2	16	0	1	100
	F3	V17	38.2	7.4	2.2	10.8	0.8	11.8	33	5	10.6	0.8	12.4	100
	F3	V18	40.4	1.8	0.2	7.2	0.8	8.6	18.6	20	13.8	1.8	5.4	100
	F3	V19	36.6	1.8	2.8	6.8	2	10	23.4	20.8	12.4	1.4	5.4	100
	F3	V22	61.8	1.6	1	1.8	0	10.6	15	8	8	0.6	6.6	100
	F3	V21	32.6	1.8	0.8	6.4	0	18.2	27.2	29.4	7	0.4	3.4	100
	F3	VIII149	30.4	13.4	0	4.2	0	27.6	45.2	5.8	11.2	0	7.4	100
Comparison facies F2, F4 and F5 (outside-channels)	F2	I12	43.4	10.6	8.2	11.4	0.4	8.6	39.2	1	5.6	1.4	9.4	100
	F2	V114	12.6	36	3.8	8.8	0.6	12.8	62	8.8	13	0.2	3.4	100
	F2	V23	46.6	5	1.2	5.8	1.2	11.8	25	4.6	15	2	6.8	100
	F2	V135	41.8	3.2	2.8	6.8	2.2	10.4	25.4	22.4	7.2	0	3.2	100
	F2	V116	24	3.2	7.6	10.2	4.4	24	49.4	2	21.6	0.4	2.6	100
	F5	IX52	30.6	9.8	3	9.6	1.4	24	47.8	3.8	4.8	0.4	12.6	100
	F4	IX51	60.4	5.8	3.6	0.6	0	5.6	15.6	9.8	8.4	0.2	5.6	100
	F4	IX50	3.6	30.8	1.4	25.8	0	6.6	64.6	6	10.8	0	15	100
	F4	IX54	51.2	4.6	3.6	1.8	0.2	18	28.2	3.6	6.6	0.2	10.2	100
Reference samples	F6	V140	18.6	9.4	4.8	4.8	0.4	15.2	34.6	28.2	15.6	0.2	2.8	100
	F6	I119	23.8	1.2	1.2	3.8	2.2	19.8	28.2	39	5.8	0	3.2	100
	F5	V20	48.4	4.6	1.8	4.6	0.8	12.6	24.4	7	11.8	1.2	7.2	100
	F10	V138	69	1	0	0.8	0	8.4	10.2	0	18.2	0	2.6	100

Difference thin section SEM and point counting porosity results – percent

Facies association	Facies	Sample Number	SEM porosity #1	SEM porosity #2	SEM porosity #3	SEM porosity #4	SEM average	Point Counting	Difference SEM-porosity
Facies F3 (in-channels)	F3	I2	11.39	5.52	8.56	12.18	9.41	10.8	*1.39*
	F3	I127	11.66	8.96	9	4.99	8.65	11.8	*3.15*
	F3	I128	12.12	13.44	5.53	14.96	11.51	15	*3.49*
	F3	I130	14.96	16.84	11.84	7.25	12.72	5.8	*-6.92*
	F3	I120	4.58	3.67	missing	0.02	2.76	3.4	*0.64*
	F3	III133	8.62	4.48	1.71	6.72	5.38	6.8	*1.42*
	F3	III143	1.3	2.7	0.17	0.09	1.07	1	*-0.06*
	F3	V17	10.89	11.25	8.47	13.4	11.00	12.4	*1.40*
	F3	V18	8.63	1.34	3.43	5.34	4.69	5.4	*0.72*
	F3	V19	8	4.81	2.34	4.16	4.83	5.4	*0.57*
	F3	V22	4.38	2.47	7.91	2.26	4.26	6.6	*2.35*
	F3	V21	7.11	3.96	3.66	4.5	4.81	3.4	*-1.41*
	F3	VIII149	5.52	1.71	3.74	4.72	3.92	7.4	*3.48*
Comparison facies F2, F4 and F5 (outside-channels)	F2	I12	16.26	13.65	7.07	7.39	11.09	9.4	*-1.69*
	F2	V114	1.61	2.72	10.41	3.63	4.59	3.4	*-1.19*
	F2	V23	4.34	4.02	2.05	0.04	2.61	6.8	*4.19*
	F2	V135	0.06	0.81	6.26	4.35	2.87	3.2	*0.33*
	F2	V116	1.4	1.86	2.99	6.73	3.25	2.6	*-0.65*
	F5	IX52	1.97	15.57	13.98	9.2	10.18	12.6	*2.42*
	F4	IX51	3.09	9.43	13.02	6.12	7.92	5.6	*-2.32*
	F4	IX50	21.23	6.45	7.01	22.66	14.34	15	*0.66*
	F4	IX54	11.04	3.63	9.28	14.38	9.58	10.2	*0.62*
Reference samples	F6	V140	3.03	missing	0.03	1.02	1.36	2.8	*1.44*
	F6	I119	0.43	3.03	0.9	0.15	1.13	3.2	*2.07*
	F5	V20	7.48	8.46	7.37	6.43	7.44	7.2	*-0.24*
	F10	V138	13.98	6.87	5.58	19.5	11.48	2.6	*-8.88*