LITHOTYPES OF ROCK-CARVED MONUMENTS IN PETRA/JORDAN - CLASSIFICATION AND PETROGRAPHICAL PROPERTIES

by

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Abstract

At the rock-carved monuments of Petra, damages of different types and intensities can be attributed to weathering. Systematic studies concerning damage diagnosis have been carried out. An important contribution to the damage diagnosis is a detailed lithological survey that has been made. All lithotypes have been studied with respect to their petrographical properties. A new lithostratigraphic classification and the first results of the petrographical analyses are presented.

Introduction

Many of Petra's stone monuments are endangered due to weathering. The working group "Natural stones and weathering" at the Geological Institute of the Aachen University of Technology has carried out studies in Petra within the framework of a research project, funded by DFG - Deutsche Forschungsgemeinschaft (Fitzner and Heinrichs 1998). These studies have focused on the systematic registration and evaluation of damages at the monuments, which today still represent the most conspicuous evidence of Nabataean culture in Petra. The research programme for this damage diagnosis has combined *in situ* investigation of monuments and laboratory analyses of all lithotypes. The *in situ* studies have included a lithological survey and the characterization, quantification and rating of the weathering state at the monuments considering the different lithotypes, monument characteristics - such as location, age, geometry and exposition - and environmental conditions. A methodological approach and first results of the *in situ* studies are presented in Fitzner and Heinrichs (1998; 1999) and in Heinrichs and Fitzner (1999; 2000). Petrographical stone properties have been investigated by means of modern analytical methods. In a first step, the properties of unweathered stone materials have been studied. In addition to the lithological survey made at the site, the results facilitate the differentiation and classification of lithotypes. In combination with the results obtained from studies at weathered stone materials, they allow the characterization and quantification of stone alteration. Consideration of results gathered from *in situ* studies and laboratory analyses is necessary for characterization, quantification and interpretation of weathering behaviour and development of damages at the monuments.

A detailed lithostratigraphical classification of stone types is presented for the rock-carved monuments together with the first results obtained from conducted studies at these lithotypes in their unweathered state. Results on mineral composition, grain size and further textural characteristics, bedding structure and porosity properties are presented.

Lithostratigraphic Classification

Jaser and Barjous (1992), and Pflüger (1990; 1995) have presented lithostratigraphic classifications for the rocks of the Petra region, and have defined major lithostratigraphic units. Regarding precise damage diagnosis for the rock-carved monuments, a more differentiated lithostratigraphic classification has been worked out. In Table 1 the lithostratigraphic classifications by Jaser and Barjous (1992), Pflüger (1990; 1995) and the authors are compared with regard to the Cambro-Ordovician sedimentary bedrocks in Petra. The nomenclature used by

Table 1. Lithostratigraphy of middle Cambrian to early Ordovician. Petra / Jordan.

<table>
<tr><th></th><th colspan="3">JASER & BARJOUS (1992)</th><th>PFLÜGER (1990, 1995)</th><th colspan="2">HEINRICHS & FITZNER</th></tr>
<tr><td>LATE CAMBRIAN TO ORDOVICIAN</td><td rowspan="5">↑
Ram-Sandstone Group
↓</td><td colspan="2">Disi Sandstone Formation (DI)</td><td>Disi Sandstone</td><td colspan="2">Disi Sandstone Formation:
white, mainly medium-grained, massive sandstone (DI-w-mSd)</td></tr>
<tr><td rowspan="4">MIDDLE TO LATE CAMBRIAN</td><td rowspan="4">Umm Ishrin Sandstone Formation</td><td rowspan="2">Upper part (uIN)</td><td>Ed-Deir Sandstone</td><td rowspan="4">Umm Ishrin Sandstone Formation</td><td rowspan="2">Upper part (uIN):
multicoloured, mainly medium-grained, massive sandstone (uIN-m-mSd)
with following sublithotypes:
- white, mainly medium-grained sandstone (uIN-m/w-mSd)
- yellow, mainly medium-grained sandstone (uIN-m/y-mSd)
- grey, mainly medium-grained sandstone (uIN-m/g-mSd)
- red, mainly medium-grained sandstone (uIN-m/r-mSd)
white, medium-grained, massive sandstone (uIN-w-mSd)
multicoloured, clayish, very fine-grained sandstone (uIN-m-ffSd)
white to pale grey, clayish, very fine-grained sandstone (uIN-wg-ffSd)
yellow-brown, clayish, hard, very fine-grained sandstone (uIN-y-ffSd)
violet, clayish, hard, very fine-grained sandstone (uIN-v-ffSd)
yellow-brown, very clayish siltstone (uIN-y-St)
violet, very clayish siltstone (uIN-v-St)</td></tr>
<tr><td>Habis Sandstone</td></tr>
<tr><td>Middle part (mIN)</td><td rowspan="2">Temple Sandstone</td><td>Middle part:
multicoloured, mainly fine-grained, massive sandstone (mIN-m-fSd)
with following sublithotypes:
- white, mainly fine-grained sandstone (mIN-m/w-fSd)
-grey, mainly fine-grained sandstone (mN-m/g-fSd)
- red, mainly fine-grained sandstone (mIN-m/r-fSd)
- yellow-brown, mainly fine-grained sandstone (mIN-m/y-fSd)
- violet, mainly fine-grained sandstone (mIN-m/v-fSd)
white-grey to pale violet, colour-banded, clayish, very fine-grained sandstone (mIN-m-ffSd)
white, clayish, hard, very fine-grained sandstone (mIN-w-ffSd)
yellow-brown, clayish, hard, very fine-grained sandstone (mIN-y-ffSd)
violet, clayish, hard, very fine-grained sandstone (mIN-v-ffSd)
yellow-brown, very clayish siltstone (mIN-y-St)
violet, very clayish siltstone (mIN-v-St)</td></tr>
<tr><td>Lower part (lIN)</td><td>not considered</td></tr>
</table>

Jaser and Barjous (Umm 'Ishrīn Sandstone Formation, ad-Dīsī Sandstone Formation) has been applied for the new lithostratigraphic classification with the subdivision of the Umm 'Ishrīn Sandstone Formation into lower, middle and upper part. Sedimentary rocks of the lower part of the Umm 'Ishrīn Sandstone Formation have not been considered in this classification, as in this lithological layer there are no monuments present.

The new lithostratigrapic classification is presented in Tables 2 - 4. The classification of lithotypes follows stratigraphy, stone colour, grain size, stone type and structural characteristics. Symbols used are explained in Table 5. Twenty-five lithotypes have been distinguished, in particular sixteen main lithotypes and nine sublithotypes.

Lithotypes - Umm 'Ishrīn Sandstone Formation/Middle Part

Multicoloured, mainly fine-grained sandstones (mIN-m-fSd) represent the predominant lithotype in this stratigraphic unit, in which most of the rock-hewn Petra monuments can be found. In the massive sandstones, some gravel layers and scattered quartz pebbles occur. The sandstones are mainly cross-bedded. The colour banding is very characteristic, most frequently irregularly oriented to the bedding structure of sandstones. This indicates a post sedimentary origin of the colour banding. The intersection of colour bands indicates several phases of colour banding. In the case of narrow colour banding, further differentiation of this lithotype into *sublithotypes* is not suitable. In the case of larger units of uniform colour, a subdivision of five sublithotypes according to colour is proposed: *mIN-m/w-fSd* (white), *mIN-m/g-fSd* (grey), *mIN-m/r-fSd* (red), *mIN-m/y-fSd* (yellow-brown) and *mIN-m/v-fSd* (violet). According to the field survey, the proportion of these sublithotypes can be stated as follows: *mIN-m/r-fSd* >> *mIN-m/w-fSd* and *mIN-m/g-fSd* >> *mIN-m/y-fSd* > *mIN-m/v-fSd*. Red, white and grey sublithotypes can occur with thicknesses up to one metre-range, whereas the yellow and violet sublithotypes only occur in thin layers.

In the series of the multicoloured, mainly fine-grained sandstones (mIN-m-fSd), six further lithotypes are interbedded.

White-grey to pale violet, colour-banded, clayish, very fine-grained sandstones (mIN-m-ffSd) occur in single, medium to thick beds. Frequently, the beds thin out. Horizontal bedding, colour banding following the bedding structure and separation planes parallel to bedding are characteristic.

The mainly white, rarely white-grey to pale violet, clayish, hard, very fine-grained sandstones (mIN-w-ffSd) occur in single, medium to thick beds. Horizontal bedding and thinning-out of beds are characteristic, and rarely pale colour banding can be stated. The hardness of this lithotype is striking.

The yellow-brown and the violet, clayish, hard, very fine-grained sandstones (mIN-y-ffSd, mIN-v-ffSd) differ in stone colour. Both lithotypes are characterized by horizontal bedding. They occur mainly in thin beds, and the thinning-out of beds can be observed. Frequently, these lithotypes can be found at the base or at the top of the two lithotypes listed before (mIN-m-ffSd, mIN-w-ffSd).

The lithotypes mIN-y-St and mIN-v-St comprise yellow-brown respectively violet, very clayish, laminated siltstones with horizontal bedding. These lithotypes occur in thin to medium beds. Thinning-out of beds can be observed very often. Separation planes parallel to the bedding as well as narrow jointing are very characteristic.

In Fitzner and Heinrichs (1998) a preliminary naming of the lithotypes by means of symbols was used and has now been revised (see Tables 2-5).

Lithotypes - Umm 'Ishrīn Sandstone Formation/Upper Part

Multicoloured, mainly medium-grained,

Table 2. Lithotypes. Umm 'Ishrīn Sandstone Formation - middle part.

<table>
<tr><td rowspan="12">UMM ISHRIN SANDSTONE FORMATION – middle part</td><td colspan="3">LITHOTYPES</td><td colspan="2">SYMBOLS</td></tr>
<tr><td rowspan="5">Multicoloured, mainly fine-grained, massive sandstone
planar, trough or overturned cross-bedding
partly with gravel layers along foresets and scattered quartz pebbles
colour banding characteristically</td><td rowspan="5">In case of larger units of uniform colour, division of sublithotypes according to stone colour:</td><td>White, mainly fine-grained sandstone</td><td rowspan="5">mIN-m-fSd</td><td>mIN-m/w-fSd</td></tr>
<tr><td>Grey, mainly fine-grained sandstone</td><td>mIN-m/g-fSd</td></tr>
<tr><td>Red, mainly fine-grained sandstone</td><td>mIN-m/r-fSd</td></tr>
<tr><td>Yellow-brown, mainly fine-grained sandstone</td><td>mIN-m/y-fSd</td></tr>
<tr><td>Violet, iron-rich, hard, mainly fine-grained sandstone</td><td>mIN-m/v-fSd</td></tr>
<tr><td colspan="3">White-grey to pale violet, colour-banded, clayish, very fine-grained sandstone
single medium to thick beds, horizontal bedding, colour banding, frequently thinning-out of beds, separation planes parallel to bedding</td><td colspan="2">mIN-m-ffSd</td></tr>
<tr><td colspan="3">White, rarely white-grey to pale violet, clayish, hard, very fine-grained sandstone
single medium to thick beds, horizontal bedding, rarely pale colour banding, frequently thinning-out of beds</td><td colspan="2">mIN-w-ffSd</td></tr>
<tr><td colspan="3">Yellow-brown, clayish, hard, very fine-grained sandstone
mainly thin single beds, horizontal bedding, frequently thinning-out of beds</td><td colspan="2">mIN-y-ffSd</td></tr>
<tr><td colspan="3">Violet, clayish, hard, very fine-grained sandstone
mainly thin single beds, horizontal bedding, frequently thinning-out of beds</td><td colspan="2">mIN-v-ffSd</td></tr>
<tr><td colspan="3">Yellow-brown, very clayish siltstone
single thin to medium beds, laminated, horizontal bedding, frequently thinning-out of beds, separation planes parallel to bedding</td><td colspan="2">mIN-y-St</td></tr>
<tr><td colspan="3">Violet, very clayish siltstone
single thin to medium beds, laminated, horizontal bedding, frequently thinning-out of beds, separation planes parallel to bedding</td><td colspan="2">mIN-v-St</td></tr>
</table>

Table 3. Lithotypes. Umm ‘Ishrīn Sandstone Formation - upper part.

<table>
<tr><td rowspan="13">UMM ISHRIN SANDSTONE FORMATION – upper part</td><th colspan="3">LITHOTYPES</th><th colspan="2">SYMBOLS</th></tr>
<tr><td rowspan="4">Multicoloured, mainly medium-grained, massive sandstone
planar, trough or overturned cross-bedding
colour banding characteristically</td><td rowspan="4">In case of larger units of uniform colour, division of sublithotypes according to stone colour</td><td>White, mainly medium-grained sandstone</td><td rowspan="4">uIN-m-mSd</td><td>uIN-m/w-mSd</td></tr>
<tr><td>Pale yellow, mainly medium-grained sandstone</td><td>uIN-m/y-mSd</td></tr>
<tr><td>Grey, mainly medium-grained sandstone</td><td>uIN-m/g-mSd</td></tr>
<tr><td>Red, mainly medium-grained sandstone</td><td>uIN-m/r-mSd</td></tr>
<tr><td colspan="3">White, medium-grained, massive sandstone
planar or trough cross-bedding, partly with gravel layers or scattered quartz pebbles</td><td colspan="2">uIN-w-mSd</td></tr>
<tr><td colspan="3">Multicoloured, clayish, very fine-grained sandstone
single medium to thick beds, horizontal bedding, colour banding, frequently thinning-out of beds, separation planes parallel to bedding</td><td colspan="2">uIN-m-ffSd</td></tr>
<tr><td colspan="3">White to pale grey, clayish, very fine-grained sandstone
single medium to thick beds, horizontal bedding, frequently thinning-out of beds</td><td colspan="2">uIN-wg-ffSd</td></tr>
<tr><td colspan="3">Yellow-brown, clayish, hard, very fine-grained sandstone
mainly thin single beds, horizontal bedding, frequently thinning-out of beds</td><td colspan="2">uIN-y-ffSd</td></tr>
<tr><td colspan="3">Violet, clayish, hard, very fine-grained sandstone
mainly thin single beds, horizontal bedding, frequently thinning-out of beds</td><td colspan="2">uIN-v-ffSd</td></tr>
<tr><td colspan="3">Yellow-brown, very clayish siltstone
single thin to medium beds, horizontal bedding, frequently thinning-out of beds, separation planes parallel to bedding</td><td colspan="2">uIN-y-St</td></tr>
<tr><td colspan="3">Violet, very clayish siltstone
single thin to medium beds, horizontal bedding, frequently thinning-out of beds, separation planes parallel to bedding</td><td colspan="2">uIN-v-St</td></tr>
</table>

Table 4. Lithotypes. ad-Dīsī Sandstone Formation.

	LITHOTYPE	SYMBOL
DISI SANDSTONE FORMATION	**White, mainly medium-grained, massive sandstone** *partly significant grain-size variation, large scale cross-bedding, frequently with gravel layers along foresets and with scattered well-rounded quartz pebbles*	DI-w-mSd

Table 5. Symbols for nomenclature of lithotypes.

STRATIGRAPHY		STONE COLOUR		GRAIN SIZE / STONE TYPE	
DI	Disi Sandstone Formation	w	white	mSd	medium-grained sandstone
uIN	Umm Ishrin Sandstone Formation - upper part -	g	grey	fSd	fine-grained sandstone
		r	red		
mIN	Umm Ishrin Sandstone Formation - middle part -	y	yellow, yellow-brown	ffSd	very fine-grained sandstone
		v	violet		
		m	multicoloured	St	siltstone

massive sandstones (uIN-m-mSd) represent the prevailing lithotype in the upper part of the Umm ʻIshrīn Sandstone Formation. These sandstones are coarser-grained than the multicoloured, mainly fine-grained sandstones in the middle part of the Umm ʻIshrīn Sandstone Formation (mIN-m-fSd). They show planar or trough, rarely overturned cross-bedding. Colour banding of the sandstones is characteristic. In the case of larger units of uniform stone colour, subdivision into four *sublithotypes* can be made: *uIN-m/w-mSd* (white), *uIN-m/y-mSd* (yellow), *uIN-m/g-mSd* (grey) and *uIN-m/r-mSd* (red). In contrast to the multicoloured, mainly fine-grained sandstones in the middle part of the Umm ʻIshrīn Sandstone Formation (mIN-m-fSd), also the yellow sublithotype here partly occurs with units up to one metre-range.

In the series of the multicoloured, mainly medium-grained sandstones (uIN-m-mSd) seven lithotypes are interbedded.

Locally, white, medium-grained, massive sandstones (uIN-w-mSd) occur. They are coarser-grained than the multicoloured sandstones (uIN-m-mSd). Cross-bedding is characteristic, and gravel layers or scattered quartz pebbles can be found. The sandstones can contain small black nodules of hematite.

The multicoloured, clayish, very fine-grained sandstones (uIN-m-ffSd) occur with medium to thick beds. Horizontal bedding, colour banding, thinning-out of beds and separation planes parallel to the bedding are characteristic.

Lithotype uIN-wg-ffSd comprises white to pale grey, clayish, hard, very fine-grained sandstones with horizontal bedding. The sandstones occur in medium to thick beds, frequently with thinning-out of the beds.

The yellow-brown and the violet, clayish, hard, very fine-grained sandstones (uIN-y-ffSd, uIN-v-ffSd) are similar to lithotypes mIN-y-ffSd and mIN-v-ffSd in the middle part of the Umm ʻIshrīn Sandstone Formation. The thickness of beds is sometimes higher. Horizontal bedding and thinning-out of beds are characteristic.

The lithotypes uIN-y-St and uIN-v-St comprise yellow-brown respectively violet, very clayish, laminated siltstones with horizontal bedding. These lithotypes occur in thin to medium beds. Thinning-out of beds can be observed. Separation planes parallel to bedding and narrow jointing are very characteristic. The lithotypes are comparable to the siltstones in the middle part of the Umm Ishrin Sandstone Formation (mIN-y-St, mIN-v-St).

Lithotype - ad-Dīsī Sandstone Formation

Ad-Dīsī Sandstone Formation consists of only one lithotype: white, mainly medium-grained, massive sandstones (DI-w-mSd). Compared to all lithotypes in the middle and upper part of the Umm ʻIshrīn Sandstone Formation, the sandstones are coarser-grained. They are characterized by large scale cross-bedding and grain-size variation. Gravel layers along foresets and scattered well-rounded quart pebbles occur.

Table 6 shows an outline of all lithotypes according to stone colour, stone type / grain size and bedding structure. The siltstones and all very fine-grained sandstones show horizontal bedding, whereas fine-grained sandstones and medium-grained sandstones are cross-bedded.

Table 6. Lithotypes according to stone colour, stone type / grain size and bedding structure.

<table>
<tr><td colspan="2" rowspan="4"></td><th colspan="5">BEDDING STRUCTURE</th></tr>
<tr><th colspan="2">Cross-bedding</th><th colspan="3">Horizontal bedding</th></tr>
<tr><th colspan="5">STONE TYPE, GRAIN SIZE</th></tr>
<tr><th>medium-grained sandstone</th><th>fine-grained sandstone</th><th colspan="2">very fine-grained sandstone</th><th>siltstone</th></tr>
<tr><th rowspan="6">STONE COLOUR</th><th>multi-coloured</th><td>uIN-m-mSd</td><td>mIN-m-fSd</td><td colspan="2">uIN-m-ffSd
mIN-m-ffSd</td><td>-</td></tr>
<tr><th>white</th><td>DI-w-mSd
uIN-m/w-mSd
uIN-w-mSd</td><td>mIN-m/w-fSd</td><td>mIN-w-ffSd</td><td rowspan="2">uIN-wg-ffSd</td><td>-</td></tr>
<tr><th>grey</th><td>uIN-m/g-mSd</td><td>mIN-m/g-fSd</td><td>-</td><td>-</td></tr>
<tr><th>red</th><td>uIN-m/r-mSd</td><td>mIN-m/r-fSd</td><td colspan="2">-</td><td>-</td></tr>
<tr><th>yellow, yellow-brown</th><td>uIN-m/y-mSd</td><td>mIN-m/y-fSd</td><td colspan="2">uIN-y-ffSd
mIN-y-ffSd</td><td>uIN-y-St
mIN-y-St</td></tr>
<tr><th>violet</th><td>-</td><td>mIN-m/v-fSd</td><td colspan="2">uIN-v-ffSd
mIN-v-ffSd</td><td>uIN-v-St
mIN-v-St</td></tr>
</table>

Mineral Composition

Mineral composition of the lithotypes has been studied by means of thin section microscopy and X-ray diffraction (XRD). For each lithotype a series of samples has been studied in order to ensure statistically reliable results. Table 7 shows the average mineral composition and visible porosity of the lithotypes. "Quartz" refers to monocrystalline quartz only, "rock fragments" in all lithotypes occur in the form of polycrystalline quartz. According to Pettijohn *et al.* (1987), "matrix" comprises all minerals with grain sizes less than 30 μm. The predominant clay mineral of all lithotypes is kaolinite, while minor clay mineral components in several lithotypes are dickite or illite. Goethite and limonite occur as iron-hydroxide minerals, and hematite occurs as iron-oxide mineral. Heavy minerals (tourmaline, zircon, rutile), chlorite, hornblende or augite can occur as accessory minerals. The microscopically visible pores will be called "large pores" in this section.

Lithotypes - Umm 'Ishrīn *Sandstone Formation/Middle Part*

Multicoloured, mainly fine-grained sandstone (mIN-m-fSd): Quartz is the main mineral. The multicoloured sandstones are matrix-rich with kaolinite as the main matrix mineral. Hematite represents the prevailing ferritic matrix mineral. Mica are rare.

Sublithotypes of mIN-m-fSd: The quartz content of the sublithotypes is similar. Matrix content and matrix-quartz-ratio increases and the proportion of large pores decreases from white sandstones (*mIN-m/w-fSd*) to grey sandstones (*mIN-m/g-fSd*), red sandstones and violet sandstones (*mIN-m/r-fSd, mIN-m/v-fSd*) to yellow-brown sandstones (*mIN-m/y-fSd*). Goethite occurs only

Table 7. Mineral composition and porosity. Thin section microscopy, X-ray diffraction analysis.

Lithotypes	Quartz	Rock frag-ments	Matrix*					Others ***	Porosity	Minerals (XRD) ****
			Clay minerals **	Fe-oxide -hydroxide		Musco-vite	Calcite			
				Hematite	Goethite resp. Limonite					
	Composition in %									
DI-w-mSd	69.0	7.0	4.3	-	-	-	2.7	+	17.0	Q, K, C
uIN-m-mSd	Average composition, variation in dependence on proportion of corresponding *sublithotypes*									Q, K, (D,G,H,I)
	72.0	3.0	12.7	0.3		+	-	+	12.0	
uIN-m/w-mSd	73.4	3.0	12.5	0.1	-	+	-	+	11.0	Q, K, (D)
uIN-m/y-mSd	72.3	3.4	12.2	-	0.7	+	-	+	11.4	Q, K, (D,G,I)
uIN-m/g-mSd	72.3	2.7	12.1	0.4	-	+	-	+	12.5	Q, K, H
uIN-m/r-mSd	70.0	3.9	12.9	0.5	-	+	-	0.1	12.6	Q, K, H
uIN-w-mSd	66.8	4.1	5.8	+	-	-	3.2	+	20.1	Q, K, (D, C)
uIN-m-ffSd	63.2	1.6	33.0	0.5		0.3	-	0.1	1.3	Q, K, G, H, I, (D)
uIN-wg-ffSd	64.6	2.0	29.3	0.1	-	0.6	-	+	3.4	Q,K, (D, H, I, M)
uIN-y-ffSd	53.8	2.1	38.3	-	5.3	0.2	-	+	0.3	Q, K, G, (I)
uIN-v-ffSd	53.6	1.9	35.2	8.6	-	0.3	-	+	0.4	Q, K, H, (I, M)
uIN-y-St mIN-y-St	26.9	0.7	62.7	-	8.0	1.5	-	+	0.2	Q, K, G, I, (M)
uIN-v-St mIN-v-St	29.7	1.2	65.9	2.1	-	1.0	-	+	0.1	Q, K, H, I, (M)
mIN-m-fSd	Average composition, variation in dependence on proportion of corresponding *sublithotypes*									Q, K, (D,H,G)
	72.6	2.8	17.3	0.2		+	-	+	7.1	
mIN-m/w-fSd	70.6	3.6	12.9	+	-	+	-	0.1	12.8	Q, K, (D, H)
mIN-m/g-fSd	74.5	1.8	15.3	0.2	-	0.1	-	0.1	8.0	Q, K, H, (D)
mIN-m/r-fSd	72.6	2.9	20.5	0.3	-	+	-	+	3,7	Q, K, H, (D)
mIN-m/y-fSd	67.2	2.9	22.0	-	7.4	+	-	+	0.5	Q, K, G, (D)
mIN-m/v-fSd	68.6	4.3	7.3	12.9	-	+	-	+	6.9	Q, K, H
mIN-m-ffSd	64.3	2.1	30.4	0.2	-	0.5	-	0.1	2.4	Q, K, (D,H,I)
mIN-w-ffSd	60.9	2.2	35.6	0.1	-	0.2	-	+	1.0	Q, K, (D,H,I)
mIN-y-ffSd	54.1	2.2	36.4	-	6.3	0.2	-	0.1	0.7	Q, K, G, (D,I,M)
mIN-v-ffSd	56.6	2.6	27.5	12.9	-	0.1	-	+	0.3	Q, K, H, (D, I)

* Matrix : all minerals with grain sizes < 30 µm
** Clay minerals: kaolinite, dickite, illite
*** Accessory minerals like heavy minerals, chlorite, hornblende, augite
**** Q – quartz, K – kaolinite, D – dickite, H – hematite, G – goethite, C – calcite, M – muscovite, I – illite
( ) – not in all samples of the same lithotype
\+ < 0.1 %

in the yellow-brown sandstones. The lithotypes *mIN-m/y-fSd* and *mIN-m/v-fSd* are characterized by a high content of ferritic matrix minerals (goethite/limonite in *mIN-m/y-fSd*, hematite in *mIN-m/v-fSd*).

White-grey to pale violet, colour-banded, very fine-grained sandstone (mIN-m-ffSd); white, hard, very fine-grained sandstone (mIN-w-ffSd); yellow-brown, hard, very fine-grained sandstone (mIN-y-ffSd); violet, hard, very fine-grained sandstone (mIN-v-ffSd); yellow-brown siltstone (mIN-y-St) and violet siltstone(mIN-v-St): Compared to the multicoloured, mainly fine-grained sandstones (mIN-m-fSd), these six lithotypes are characterized by lower contents of quartz and rock fragments, higher contents of matrix and lower proportion of large pores.

Lithotypes mIN-m-ffSd and mIN-w-ffSd represent matrix-rich sandstones with kaolinite as the prevailing matrix mineral. Illite can occur as another clay mineral. Ferritic matrix minerals are rather rare. Lithotype mIN-m-ffSd shows a considerable content of mica.

Lithotypes mIN-y-ffSd and mIN-v-ffSd represent very matrix-rich sandstones. It can be stated that Kaolinite is the main matrix mineral and matrix minerals are ferritic (goethite / limonite in mIN-y-ffSd, hematite in mIN-v-ffSd). Illite can additionally occur in the matrix of the sandstones.

The yellow-brown siltstones in the middle and upper part of the Umm 'Ishrīn Sandstone Formation (mIN-y-St, uIN-y-St) and the violet siltstones in both parts of this Formation (mIN-v-St, uIN-v-St) are the most similar. The siltstones show very low quartz content and very high matrix content. Kaolinite is the main matrix mineral, illite occurs as a further characteristic clay mineral. Siltstones show high contents of ferritic matrix minerals (goethite / limonite in mIN-y-St/uIN-y-St, hematite in mIN-v-St(uIN-v-St) and mica.

Lithotypes - Umm 'Ishrīn Sandstone Formation/Upper Part

Compared to the multicoloured, mainly fine-grained sandstones in the middle part of the Umm 'Ishrīn Sandstone Formation (mIN-m-fSd), the multicoloured, mainly medium-grained sandstones in the upper part of this formation (uIN-m-mSd) show similar contents of quartz and rock fragements, lower matrix content and higher proportion of large pores. Clay minerals are the prevailing matrix minerals. Kaolinite represents the predominant clay mineral. Referring to the *sub-lithotypes* of uIN-m-mSd, only slight differences of mineral composition can be stated. A slight increase of matrix-content and matrix-quartz-ratio from *uIN-m/w-mSd* (white sandstones) to *uIN-m/g-mSd* (grey sandstones), *uIN-m/y-mSd* (yellow sandstones) and uIN-m/r-mSd (red sandstones) can be stated. Stone colour from white to grey and red corresponds to an increasing content of hematite. The yellow Colour of the sandstones is due to the presence of goethite/limonite.

White, medium-grained sandstone (uIN-m-mSd): This lithotype shows lower contents of quartz and matrix, but a higher proportion of large pores than the multicoloured, mainly medium-grained sandstones (uIN-m-mSd). Besides kaolinite, calcite can occur as a matrix mineral. The cementation by calcite occurred later than cementation by clay minerals.

Multicoloured, very fine-grained sandstone (uIN-m-ffSd); white to pale grey, very fine-grained sandstone (uIN-wg-ffSd); yellow-brown, hard, very fine-grained sandstone (uIN-y-ffSd); violet, hard, very fine-grained sandstone (uIN-v-ffSd); yellow-brown siltstone (uIN-y-St) and violet siltstone(uIN-v-St): These six lithotypes show lower contents of quartz and rock fragments, higher contents of matrix and a lower proportion of large pores than the multicoloured, mainly medium-grained sandstones (uIN-m-mSd).

Lithotypes uIN-m-ffSd and uIN-wg-ffSd represent matrix-rich sandstones with kaolinite as the prevailing matrix mineral. Illite occurs as a further clay mineral. Ferritic matrix minerals are rare. Lithotype uIN-wg-ffSd shows a considerable content of mica.

Lithotypes uIN-y-ffSd and uIN-v-ffSd represent very matrix-rich sandstones. Besides kaolinite as the main matrix mineral, high contents of ferritic matrix minerals can be stated (goethite / limonite in uIN-y-ffSd, hematite in uIN-v-ffSd). Illite can occur additionally in the matrix of the sandstones.

Lithotype - ad-Dīsī Sandstone Formation

Compared to all lithotypes in the middle and upper part of the Umm 'Ishrīn Sandstone Formation, the white, medium-grained sandstones of ad-Dīsī Sandstone Formation (DI-w-mSd) show - besides high quartz-content - the highest content of rock fragments and the lowest matrix-content. The matrix contains kaolinite and calcite. The cementation by calcite occurred later than cementation by clay minerals.

Textural and Structural Characteristics

Table 8 outlines studied textural and structural characteristics of the lithotypes. The description of texture considers geometric aspects like shape and size of grains, fabric and porosity characteristics. Porosity characteristics will be presented in the next section. The description of structure refers to the arrangement of stone components (internal structure) and is focused on the characterization of bedding characteristics at micro-scale. Shape, grain size characteristics, fabric and bedding characteristics have been studied by means of thin-section microscopy with an image analyzing system.

In Table 9, results on the shape of quartz grains as the main constituent of most lithotypes (exception: siltstones) are presented. Sphericity and roundness are taken as pa-

Table 8. Textural and structural characteristics.

TEXTURE	Shape of grains	*sphericity, degree of roundness*
	Grain size	*mean grain size, sorting, grain size distribution*
	Fabric	*grain-matrix-relation, type and number of grain contacts, cementing material*
	Porosity characteristics	*densities, total porosity, pore size distribution, pore surface*
STRUCTURE		*bedding characteristics, bedding index*

Table 9. Shape of grains (quartz).

Lithotype	Shape of grains		Lithotype	Shape of grains	
	Sphericity	Degree of roundness		Sphericity	Degree of roundness
mIN-m-fSd	low-moderate	3-5	uIN-m-mSd	moderate	4-6
mIN-m/w-fSd	low-moderate	3-5	*uIN-m/w-mSd*	moderate	4-6
mIN-m/g-fSd	low-moderate	3-5	*uIN-m/y-mSd*	moderate	4-6
mIN-m/r-fSd	low-moderate	3-5	*uIN-m/g-mSd*	moderate	4-6
mIN-m/y-fSd	low-moderate	3-5	*uIN-m/r-mSd*	moderate	4-6
mIN-m/v-fSd	low-moderate	3-5	uIN-w-mSd	moderate	4-6
mIN-m-ffSd	low	3-5	uIN-m-ffSd	low-moderate	3-5
mIN-w-ffSd	low	3-5	uIN-wg-ffSd	low-moderate	3-5
mIN-y-ffSd	low-moderate	3-5	uIN-y-ffSd	low-moderate	3-5
mIN-v-ffSd	low-moderate	3-5	uIN-v-ffSd	low-moderate	3-5
mIN-y-St	low	3-5	uIN-y-St	low	3-5
mIN-v-St	low	3-5	uIN-v-St	low	3-5
Degree of roundness (Tucker 1988)			DI-w-mSd	moderate-high	4-6
1 – very angular			*4 – subrounded*		
2 – angular			*5 – rounded*		
3 – subangular			*6 – well rounded*		

rameters to describe the shape of grains. Sphericity describes the degree to which the shape of a sedimentary particle approaches that of a sphere. Sphericity has been classified into five categories: very low, low, moderate, high, very high. Standard sets of grain images have been used to estimate the degree of roundness. Six categories have been distinguished: very angular, angular, subangular, subrounded, rounded, well rounded. In Table 10, grain size, sorting and grain size distribution of the lithotypes are presented. Table 11 shows fabric characteristics such as grain-matrix-relation, type and number of grain contacts and type of cementing material. Bedding characteristics at micro-scale are described for all lithotypes. Bedding indices have been determined by means of ultrasonic measurements. Summarizing the results of Tables 9 - 11, the lithotypes can be characterized as follows.

Lithotypes - Umm ʻIshrīn Sandstone Formation/Middle Part

Multicoloured sandstones (mIN-m-fSd): mainly fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of medium sand; grain-supported fabric with moderate number of long grain contacts, concavo-convex contacts or point contacts; mainly siliceous and clayish, subordinately ferritic cementing material; grain size variation and partly orientation of minerals (quartz) and variation of mineral composition (colour banding) as bedding characteristics; low bedding index.

Sublithotypes mIN-m/w-fSd (white sandstones), *mIN-m/g-fSd* (grey sandstones), *mIN-m/r-fSd* (red sandstones), *mIN-m/y-fSd* (yellow-brown sandstones) and *mIN-m/v-fSd* (violet sandstones):mainly fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of medium sand; grain-supported fabric with moderate number of long grain contacts, concavo-convex contacts or point contacts; *mIN-m/w-fSd* (white sandstones): siliceous and clayish cementing material, *mIN-m/g-fSd* (grey sandstones) and mIN-m/r-fSd (red sandstones): mainly siliceous and clayish cementing material, subordinately ferritic cementing material, *mIN-m/y-fSd* (yellow-brown sandstones) and *mIN-m/v-fSd* (violet sandstones): siliceous, clayish and ferritic cementing material; grain size variation and partly orientation of minerals (quartz) as bedding characteristics; *mIN-m/w-fSd* (white sandstones) and *mIN-m/g-fSd* (grey sandstones): moderate bedding index, *mIN-m/r-fSd* (red sandstones), *mIN-m/y-fSd* (yellow-brown sandstones) and *mIN-m/v-fSd* (violet sandstones): low bedding index.

White-grey to pale violet, colour-banded sandstones (mIN-m-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand; grain- to matrix-supported fabric with high number of mainly long grain contacts or point contacts; mainly clayish, subordinately siliceous and ferritic cementing material; grain size variation, orientation of minerals (quartz, mica) and variation of mineral composition (colour banding) as very significant bedding characteristics; moderate bedding index.

White, hard sandstones (mIN-w-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with very high number of mainly long grain contacts or concavo-convex contacts; clayish and siliceous cementing material; grain size variation and orientation of minerals (quartz, mica) as bedding characteristics;

Table 10. Grain size characteristics (quartz).

Lithotypes		Mean grain size *M** (mm)	Maximum grain size (mm)	Sorting So**		Grain size distribution (%)			
						Silt	Sand		
						coarse	very fine to fine	medium	coarse to very coarse
						0.020-0.063 mm	0.063-0.2 mm	0.2-0.63 mm	0.63-2.0 mm
Dl-w-mSd		0.305	1.185	1.45	moderate	2.0	24.2	69.5	4.3
ulN-m-mSd *ulN-m/w-mSd* *ulN-m/y-mSd* *ulN-m/g-mSd* *ulN-m/r-mSd*		0.210	0.700	1.55	moderate	7.3	44.5	47.7	0.5
ulN-w-mSd		0.265	0.870	1.44	moderate	1.7	30.2	66.8	1.3
ulN-m-ffSd		0.090	0.345	1.35	good	23.6	74.7	1.7	-
ulN-wg-ffSd		0.105	0.300	1.40	good	19.8	76.2	4.0	-
ulN-y-ffSd		0.100	0.320	1.45	moderate	25.4	71.0	3.6	-
ulN-v-ffSd		0.105	0.350	1.48	moderate	21.6	69.6	8.8	-
ulN-y-St	mlN-y-St	0.050	0.250	1.30	good	74.2	25.6	0.2	-
ulN-v-St	mlN-v-St	0.055	0.180	1.29	good	70.1	29.5	0.4	-
mlN-m-fSd *mlN-m/w-fSd* *mlN-m/g-fSd* *mlN-m/r-fSd* *mlN-m/y-fSd* *mlN-m/v-fSd*		0.170	0.615	1.37	good	6.7	60.8	32.2	0.3
mlN-m-ffSd		0.110	0.500	1.36	good	17.5	73.6	8.8	0.1
mlN-w-ffSd		0.085	0.290	1.33	good	33.4	63.8	2.8	-
mlN-y-ffSd		0.095	0.350	1.38	good	31.1	62.4	6.5	-
mlN-v-ffSd		0.095	0.310	1.37	good	29.2	64.7	6.1	-

* Mean grain size according to TRASK (in TUCKER 1988:): $M = \frac{P_{25} + P_{75}}{2}$

** Sorting according to TRASK (in TUCKER 1988): $So = \sqrt{\frac{P_{75}}{P_{25}}}$

1.00 - 1.23 very good
1.23 - 1.41 good
1.41 - 1.74 moderate
1.74 - 2.00 poor
> 2.00 very poor

Table 11. Fabric and bedding characteristics.

LITHOTYPES	FABRIC: Thin section microscopy				BEDDING	
						Ultrasonic measurements
	Grain-matrix-relation*	Type of grain contacts**	Grain contacts per cm^2	Cementing material***	Characteristics****	Index*****
DI-w-mSd	g	l, p, c	1400	(si, cl, ca)	1, 2-qz (partly)	1.08
uIN-m-mSd	g	l, c, (p)	3000	si, cl, (fe)	1, 2-qz (partly), 4	1.07
uIN-m/w-mSd	g	l, c, (p)		si, cl	1, 2-qz (partly)	1.09
uIN-m/y-mSd	g	l, c, (p)		si, cl, (fe)		1.07
uIN-m/g-mSd	g	l, c, (p)		si, cl, (fe)		1.07
uIN-m/r-mSd	g	l, c, (p)		si, cl, (fe)		1.06
uIN-w-mSd	g	l, p, c	1700	(si, cl, ca)	1, 2-qz (partly)	1.08
uIN-m-ffSd	g-m	l, p, c	11500	cl, (si, fe)	1, 2-qz/m (!), 3 (!)	1.16
uIN-wg-ffSd	g-m	l, p, c	10500	si, cl	2-qz/m (!)	1.15
uIN-y-ffSd	g-m	p, l, (c)	3500	cl, fe, (si)	1, 2-qz/m	1.03
uIN-v-ffSd	g-m	p, l, (c)	3500	cl, fe, (si)	1, 2-qz/m	1.03
uIN-y-St	m	(p, l, c)	grains mainly floating in matrix	cl, fe	2-qz/m (!)	1.24
uIN-v-St	m	(p, l, c)		cl, fe	2-qz/m (!)	1.25
mIN-m-fSd	g	l, c, p	4500	si, cl, (fe)	1, 2-qz (partly), 4	1.08
mIN-m/w-fSd	g	l, c, p		si, cl	1, 2-qz (partly)	1.12
mIN-m/g-fSd	g	l, c, p		si, cl, (fe)		1.12
mIN-m/r-fSd	g	l, c, p		si, cl, (fe)		1.06
mIN-m/y-fSd	g	l, c, p		si, cl, fe		1.07
mIN-m/v-fSd	g	l, c, p		si, cl, fe		1.07
mIN-m-ffSd	g-m	l, p, (c)	6000	cl, (si, fe)	1 (!), 2-qz/m (!) 3 (!)	1.14
mIN-w-ffSd	g-m	l, k, (p)	15000	cl, si	1, 2-qz/m	1.11
mIN-y-ffSd	g-m	p, l, (c)	3250	cl, fe, (si)	1, 2-qz/m	1.04
mIN-v-ffSd	g-m	p, l, (c)	3250	cl, fe, (si)	1, 2-qz/m	1.04
mIN-y-St	m	(p, l, c)	grains mainly floating in matrix	cl, fe	2-qz/m (!)	1.24
mIN-v-St	m	(p, l, c)		cl, fe	2-qz/m (!)	1.25

* g = grain-supported fabric, m = matrix-supported fabric, g-m = grain- to matrix-supported fabric

** p = point contacts, l = long contacts, c = concavo-convex contacts
listing in order of frequency, ( ) = subordinately

*** si = siliceous (quartz overgrowths), cl = clayish, fe = ferritic, ca = carbonatic ( ) = subordinately

**** Bedding characteristics at micro-scale
1 = grain size variation
2 = uniform orientation of minerals (qz = longish quartz grains, m = mica)
3 = colour banding parallel to bedding (= variation of mineral composition)
4 = colour banding partly parallel to bedding (!) = very significant characteristics

*****

$$\text{bedding index} = \frac{\text{ultrasonic velocity parallel to bedding}}{\text{ultrasonic velocity vertical to bedding}}$$

significance of bedding increases, as bedding index increases moderate bedding index.

Yellow-brown, hard sandstones (mIN-y-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with moderate number of mainly point contacts or long grain contacts; mainly clayish and ferritic cementing material; grain size variation and orientation of minerals (quartz, mica) as bedding characteristics; very low bedding index.

Violet, hard sandstones (mIN-v-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with moderate number of mainly point contacts or long grain contacts; mainly clayish and ferritic cementing material; grain size variation and orientation of minerals (quartz, mica) as bedding characteristics; very low bedding index.

Yellow-brown siltstones (mIN-y-St): siltstones with subangular to rounded quartz grains of low sphericity; good sorting; quartz grains mainly in the class of coarse silt, considerable proportion of grains in the class of very fine / fine sand; matrix-supported fabric, quartz grains mainly floating in matrix, therefore rare grain contacts; mainly clayish and ferritic cementing material; orientation of minerals (quartz, mica) as very significant bedding characteristics; very high bedding index.

Violet siltstones (mIN-v-St): siltstones with subangular to rounded quartz grains of low sphericity; good sorting; quartz grains mainly in the class of coarse silt, considerable proportion of grains in the class of very fine / fine sand; matrix-supported fabric, quartz grains mainly floating in matrix, therefore rare grain contacts; mainly clayish and ferritic cementing material; orientation of minerals (quartz, mica) as very significant bedding characteristics; very high bedding index.

Lithotypes - Umm 'Ishrīn Sandstone Formation/Upper Part

Multicoloured sandstones (uIN-m-mSd): mainly medium-grained sandstones with subrounded to well rounded quartz grains of moderate sphericity; moderate sorting; quartz grains mainly in the classes of very fine / fine sand and medium sand; grain-supported fabric with moderate number of mainly long grain contacts or concavo-convex contacts; mainly siliceous and clayish, subordinately ferritic cementing material; grain size variation, partly orientation of minerals (quartz) and partly variation of mineral composition (colour banding) as bedding characteristics; low bedding index.

Sublithotypes uIN-m/w-mSd (white sandstones), *uIN-m/y-mSd* (yellow sandstones), *uIN-m/g-mSd* (grey sandstones) and *uIN-m/r-mSd* (red sandstones): mainly medium-grained sandstones with subrounded to well rounded quartz grains of moderate sphericity; moderate sorting; quartz grains mainly in the classes of very fine / fine sand and medium sand; grain-supported fabric with moderate number of mainly long grain contacts or concavo-convex contacts; mainly siliceous and clayish cementing material. *uIN-m/y-mSd* (yellow sandstones), *uIN-m/g-mSd* (grey sandstones) and uIN-m/r-mSd (red sandstones): subordinately ferritic cementing material; grain size variation and partly orientation of minerals (quartz) as bedding characteristics; low bedding index.

White sandstones (uIN-m-mSd): medium-grained sandstones with subrounded to well rounded quartz grains of moderate sphericity; moderate sorting; quartz grains mainly in the class of medium sand, considerable proportion of grains in the class of very fine / fine sand; grain-supported fabric with low number of long grain contacts, concavo-convex contacts or point contacts; subordinately siliceous, clayish or carbonatic cementing material; grain size variation and partly orientation of minerals (quartz) as bedding characteristics; low bedding index.

Multicoloured sandstones (uIN-m-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with very high number of long grain contacts, concavo-convex contacts or point contacts; mainly clayish, subordinately siliceous and ferritic cementing material; grain size variation and especially orientation of minerals (quartz, mica) and variation of mineral composition (colour banding) as bedding characteristics; high bedding index.

White to pale grey sandstones (uIN-wg-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; good sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with very high number of long grain contacts, concavo-convex contacts or point contacts; mainly siliceous and clayish cementing material; orientation of minerals (quartz, mica) as very significant bedding characteristic; moderate to high bedding index.

Yellow-brown, hard sandstones (uIN-y-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; moderate sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with moderate number of mainly point contacts or long grain contacts; mainly clayish and ferritic cementing material; grain size variation and orientation of minerals (quartz, mica) as bedding characteristics; very low bedding index.

Violet, hard sandstones (uIN-v-ffSd): very fine-grained sandstones with subangular to rounded quartz grains of low to moderate sphericity; moderate sorting; quartz grains mainly in the class of very fine / fine sand, considerable proportion of grains in the class of coarse silt; grain- to matrix-supported fabric with moderate number of mainly point contacts or long grain contacts; mainly clayish and ferritic cementing material; grain size variation and orientation of minerals (quartz, mica) as bedding characteristics; very low bedding index.

Yellow-brown siltstones (uIN-y-St): siltstones with subangular to rounded quartz grains of low sphericity; good sorting; quartz grains mainly in the class of coarse silt, considerable proportion of grains in the class of very fine / fine sand; matrix-supported fabric, quartz grains mainly floating in matrix, therefore rare grain contacts; mainly clayish and ferritic cementing material; orientation of minerals (quartz, mica) as very significant bedding characteristics; very high bedding index.

Violet siltstones (uIN-v-St): siltstones with subangular to rounded quartz grains of low sphericity; good sorting; quartz grains mainly in the class of coarse silt, considerable proportion of grains in the class of very fine / fine sand; matrix-supported fabric, quartz grains mainly floating in matrix, therefore rare grain contacts; mainly clayish and ferritic cementing material; orientation of minerals (quartz, mica) as very significant bedding characteristics; very high bedding index.

Lithotype - ad-Dīsī Sandstone Formation

White sandstones (DI-w-mSd): medium-grained sandstones with subrounded to well rounded quartz grains of moderate to high sphericity; moderate sorting; quartz grains mainly in the class of medium sand, considerable proportion of grains in the class of very fine / fine sand; grain-supported fabric with low number of long grain contacts, concavo-convex contacts or point contacts; subordinately siliceous, clayish or carbonatic cementing material; grain size variation and orientation of minerals (quartz) as bedding characteristics; low bedding index.

Porosity Characteristics

Porosity characteristics are very important for the characterization of stone materials and for the interpretation of their weathering behaviour. It is essential for modeling water transport behaviour. The parameters include total porosity, pore size distribution and pore surface. Application of different measuring methods with joint evaluation of results is required for a realistic characterization of stone porosity. Direct methods and indirect methods can be distinguished (Fitzner 1994; Borelli 1999).

Studies of the twenty-five lithotypes have been made by means of thin-section microscopy in combination with an image analyzing system (direct method), mercury porosimetry and nitrogen sorption method (indirect methods). Joint evaluation of results obtained from these three methods allows realistic total porosity values and complete pore size distrubutions.

In Table 12 results on densities, total porosity and pore surface of the lithotypes are presented. For the rating of total porosity the following classification has been used: < 5% - very low porosity, 5-10% - low porosity, 10-15% - moderate porosity, 15-20% - high porosity, > 20% - very high porosity. Considering the range of pore surfaces of the lithotypes, the following informal classification has been used for relative rating: < 0.5 m^2/cm^3 - very small, 0.5-1 m^2/cm^3 - small, 1-2.5 m^2/cm^3 - medium, 2.5-5 m^2/cm^3 - large, > 5 m^2/cm^3 - very large. Information on pore radii distribution and median pore radius is shown in Table 13. The following classification of pore radii (r) has been used: r = 0.001-0.01 µm - extremely fine pores, r = 0.01-0.1 µm - very fine pores, r = 0.1-1 µm - fine pores, r = 1-10 µm - medium pores, r = 10-100 µm - coarse pores, r = 100-1000 µm - very coarse pores. Figures 1 - 4 illustrate pore radii distribution of all lithotypes by means of histograms. The range of pore radii from 0.001 - 1000 µm is subdivided into twenty-four radii classes following logarithmic scale. Summarizing the results on porosity properties, the lithotypes can be characterized as follows.

Lithotypes - Umm 'Ishrīn Sandstone Formation/Middle Part

Multicoloured, mainly fine-grained sandstones (mIN-m-fSd): sandstones with high total porosity; main porosity in the classes of medium pores and coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 32-56 µm and minor peak in the radii class 1.8-3.2 µm; median pore radius in the lowermost range of coarse pores; small pore surface.

Sublithotype mIN-m/w-fSd (white sandstones): sandstones with high total porosity; main porosity in the classes of coarse pores and very coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 56-100 µm and minor peak in the radii class 0.56-1.0 µm; median pore radius in the medium range of coarse pores; small pore surface.

Sublithotype mIN-m/g-fSd (grey sandstones): sandstones with high total porosity; main porosity in the classes of medium pores and coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 18-32 µm and minor peak in the radii class 1.0 -1.8 µm; median pore radius in the lower range of coarse pores; small pore surface.

Sublithotype mIN-m/r-fSd (red sandstones): sandstones with high total porosity; main porosity in the classes of medium pores and coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 5.6-10 µm and minor peak in the radii class 1.8-3.2 µm; median pore radius in

Table 12. Porosity characteristics - densities, total porosity, pore surface.

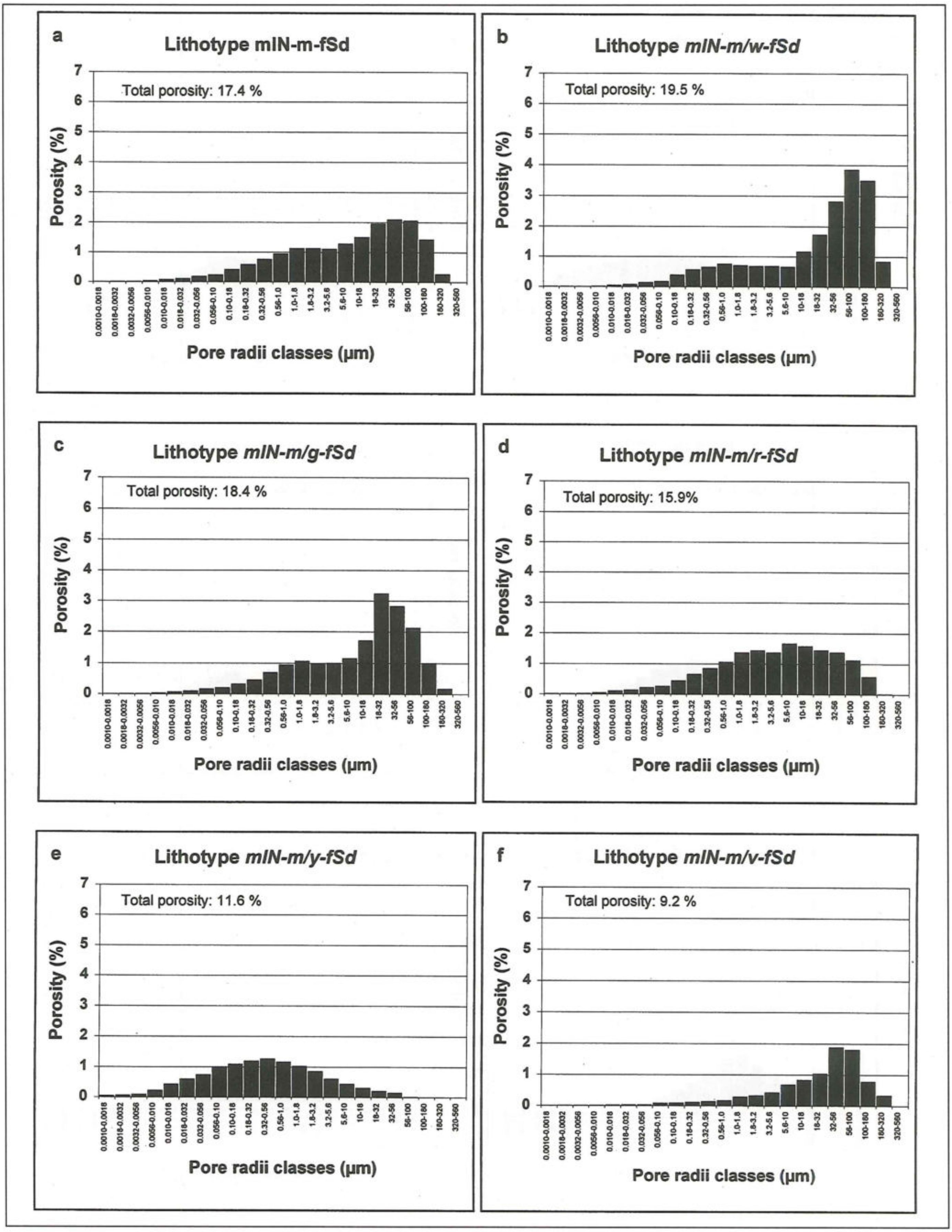
LITHOTYPES	Mercury porosimetry		Joint evaluation - mercury porosimetry - nitrogen sorption microscopy / image analysis		Nitrogen sorption (BET)	
	Bulk density (g / cm^3)	Density (g / cm^3)	Total porosity		Pore surface	
			Vol.-%	Classification*	(m^2 / g)	(m^2 / cm^3)
Dl-w-mSd	2.0831	2.6472	21.3	very high	0.14	0.28
ulN-m-mSd	Average values – ulN-m-mSd, variation in dependence on proportion of corresponding *sublithotypes*					
	2.1416	2.6621	19.6	high	0.24	0.52
ulN-m/w-mSd	2.1164	2.6577	20.4	very high	0.24	0.51
ulN-m/y-mSd	2.1670	2.6600	18.5	high	0.29	0.64
ulN-m/g-mSd	2.1664	2.6646	18.7	high	0.17	0.38
ulN-m/r-mSd	2.1164	2.6660	20.6	very high	0.26	0.55
ulN-w-mSd	2.1351	2.6580	19.7	high	0.17	0.37
ulN-m-ffSd	2.4469	2.6608	8.1	low	0.92	2.25
ulN-wg-ffSd	2.3799	2.6510	10.2	moderate	0.49	1.16
ulN-y-ffSd	2.5346	2.7224	7.0	low	1.34	3.43
ulN-v-ffSd	2.7548	2.8753	4.2	very low	0.97	2.66
ulN-y-St / mlN-y-St	2.5091	2.7608	9.2	low	2.27	5.70
ulN-v-St / mlN-v-St	2.5361	2.7042	6.3	low	1.25	3.17
mlN-m-fSd	Average values – mlN-m-fSd, variation in dependence on proportion of corresponding *sublithotypes*					
	2.1929	2.6553	17.4	high	0.36	0.79
mlN-m/w-fSd	2.1334	2.6502	19.5	high	0.26	0.54
mlN-m/g-fSd	2.1656	2.6558	18.4	high	0.33	0.72
mlN-m/r-fSd	2.2362	2.6575	15.9	high	0.42	0.95
mlN-m/y-fSd	2.4329	2.7500	11.6	moderate	1.47	3.59
mlN-m/v-fSd	2.7332	3.0108	9.2	low	0.25	0.69
mlN-m-ffSd	2.3620	2.6540	10.9	moderate	0.67	1.58
mlN-w-ffSd	2.4509	2.6539	7.7	low	0.78	1.92
mlN-y-ffSd	2.4664	2.7356	9.9	low	1.46	3.60
mlN-v-ffSd	2.8343	2.9860	5.1	low	1.02	2.89

* Classification of total porosity

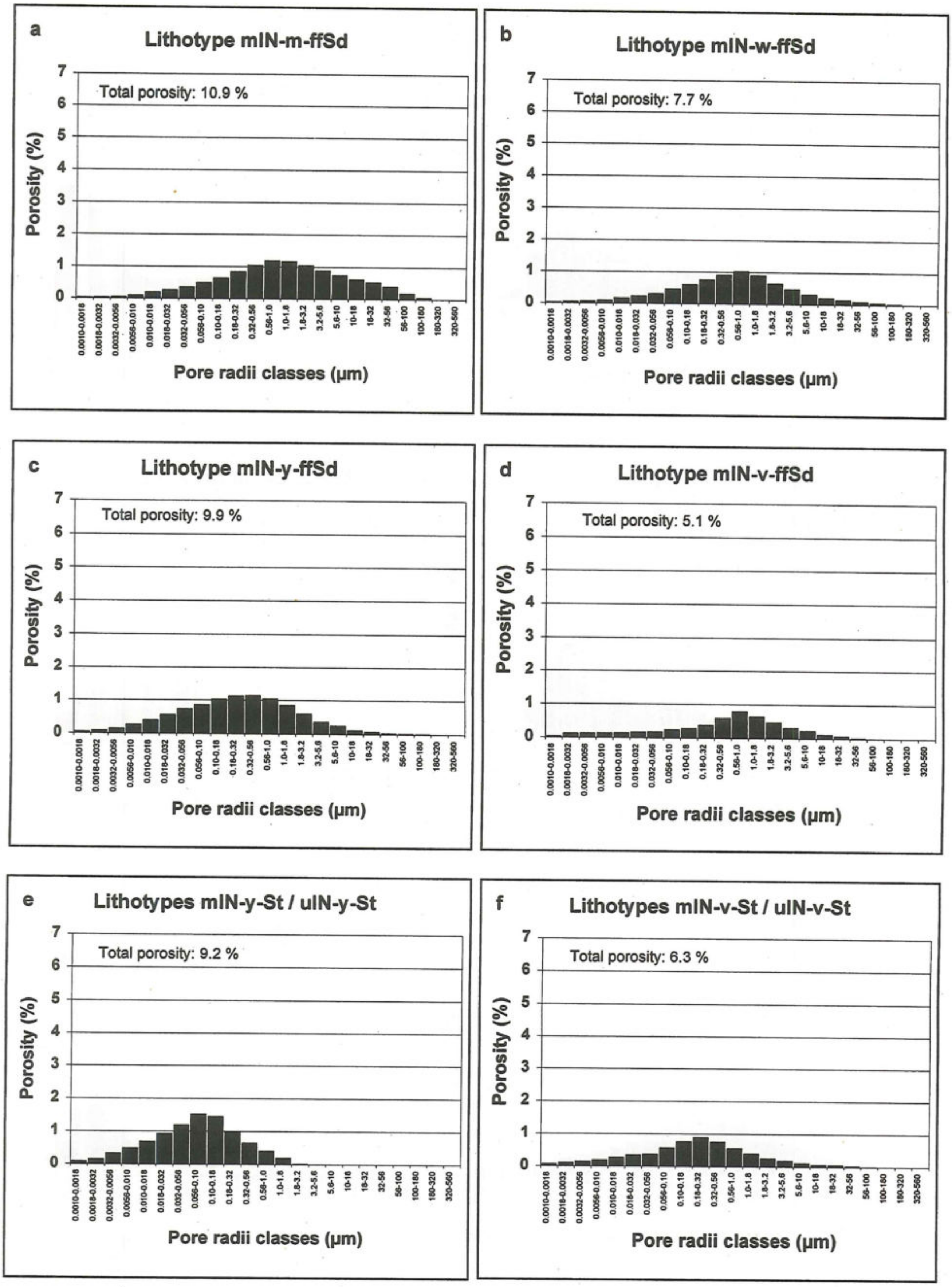
< 5%	very low porosity
5 – 10%	low porosity
10 – 15 %	moderate porosity
15 – 20%	high porosity
> 20%	very high porosity

Table 13. Porosity characteristics - Pore radii distribution, median pore radius.

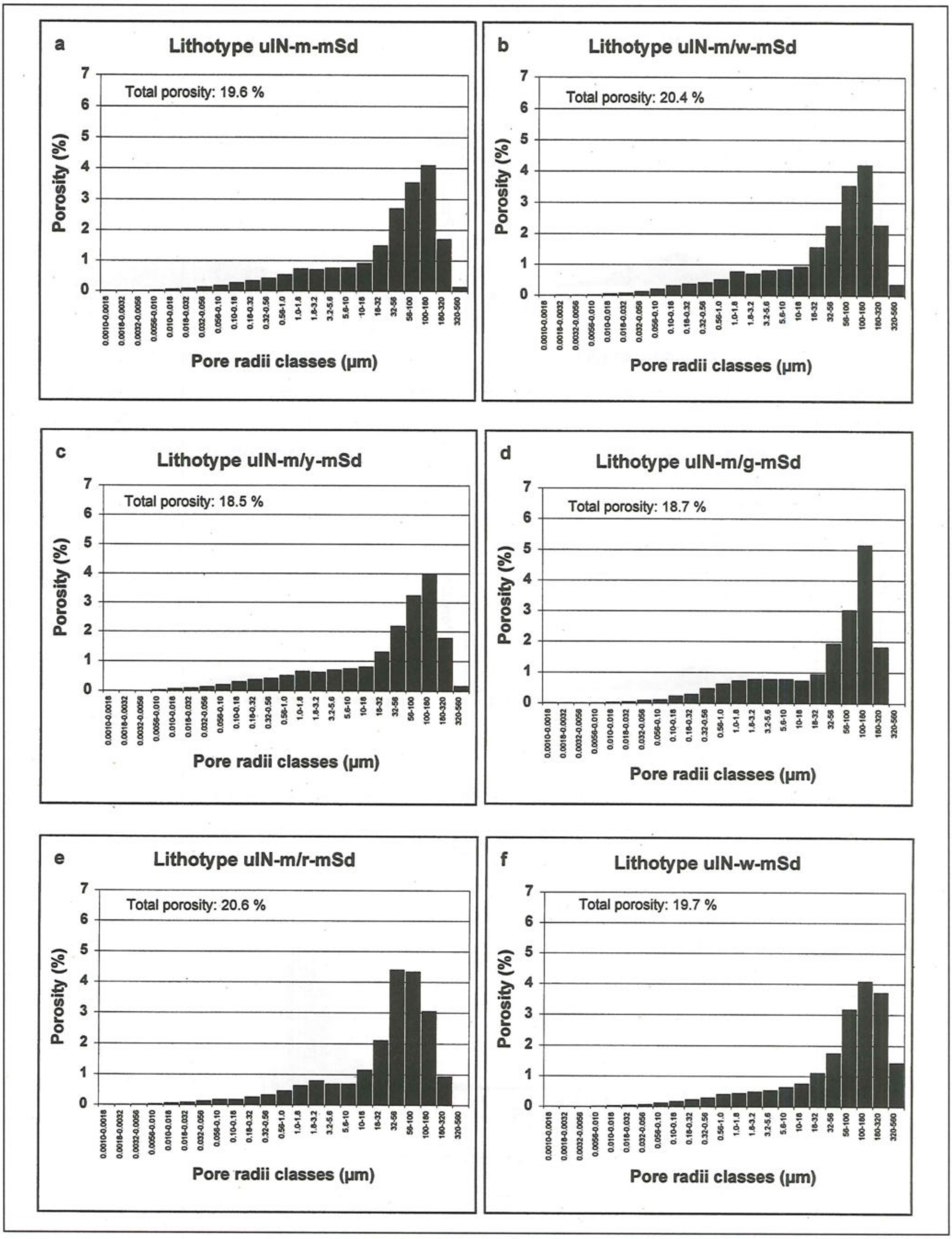
LITHOTYPES		Joint evaluation - mercury porosimetry, nitrogen sorption, microscopy/image analysis						
		Pore radii distribution						Median pore radius (µm)
		Porosity (%) in radii classes						
		extremely fine pores 0.001 - 0.01 µm	very fine pores 0.01 - 0.1 µm	fine pores 0.1 - 1 µm	medium pores 1 - 10 µm	coarse pores 10 - 100 µm	very coarse pores 100 - 1000 µm	
Dl-w-mSd		0.02	0.21	0.68	1.23	7.19	11.98	115.0
ulN-m-mSd		Average values – ulN-m-mSd, variation in dependence on proportion of corresponding *sublithotypes*						
		0.05	0.44	1.54	2.96	8.64	5.94	55.0
ulN-m/w-mSd		0.05	0.47	1.61	3.13	8.28	6.84	62.0
ulN-m/y-mSd		0.06	0.53	1.63	2.77	7.58	5.96	57.0
ulN-m/g-mSd		0.03	0.29	1.67	3.09	6.66	6.98	60.0
ulN-m/r-mSd		0.06	0.47	1.26	2.84	12.01	4.00	46.0
ulN-w-mSd		0.04	0.28	1.14	2.15	6.82	9.25	93.0
ulN-m-ffSd		0.36	1.52	3.61	2.41	0.20	-	0.47
ulN-wg-ffSd		0.14	1.07	2.78	3.62	2.30	0.31	2.05
ulN-y-ffSd		0.63	2.23	2.99	1.05	0.09	-	0.16
ulN-v-ffSd		0.34	0.81	1.96	1.03	0.08	-	0.34
ulN-y-St	mlN-y-St	1.09	4.37	3.51	0.23	-	-	0.08
ulN-v-St	mlN-v-St	0.54	1.60	3.01	0.98	0.18	-	0.21
mlN-m-fSd		Average values – mlN-m-fSd, variation in dependence on proportion of corresponding *sublithotypes*						
		0.08	0.63	2.72	4.65	7.65	1.69	13.0
mlN-m/w-fSd		0.04	0.45	2.36	2.72	9.58	4.36	41.0
mlN-m/g-fSd		0.07	0.56	2.45	4.23	9.94	1.19	19.0
mlN-m/r-fSd		0.11	0.76	3.04	5.82	5.53	0.61	5.5
mlN-m/y-fSd		0.45	2.79	4.74	2.95	0.70	-	0.38
mlN-m/v-fSd		0.05	0.16	0.54	1.76	5.59	1.13	34.0
mlN-m-ffSd		0.21	1.33	3.74	3.85	1.75	0.07	1.7
mlN-w-ffSd		0.25	1.20	3.33	2.36	0.52	0.03	0.63
mlN-y-ffSd		0.57	2.60	4.38	2.09	0.25	0.01	0.27
mlN-v-ffSd		0.43	0.73	2.06	1.67	0.24	-	0.65



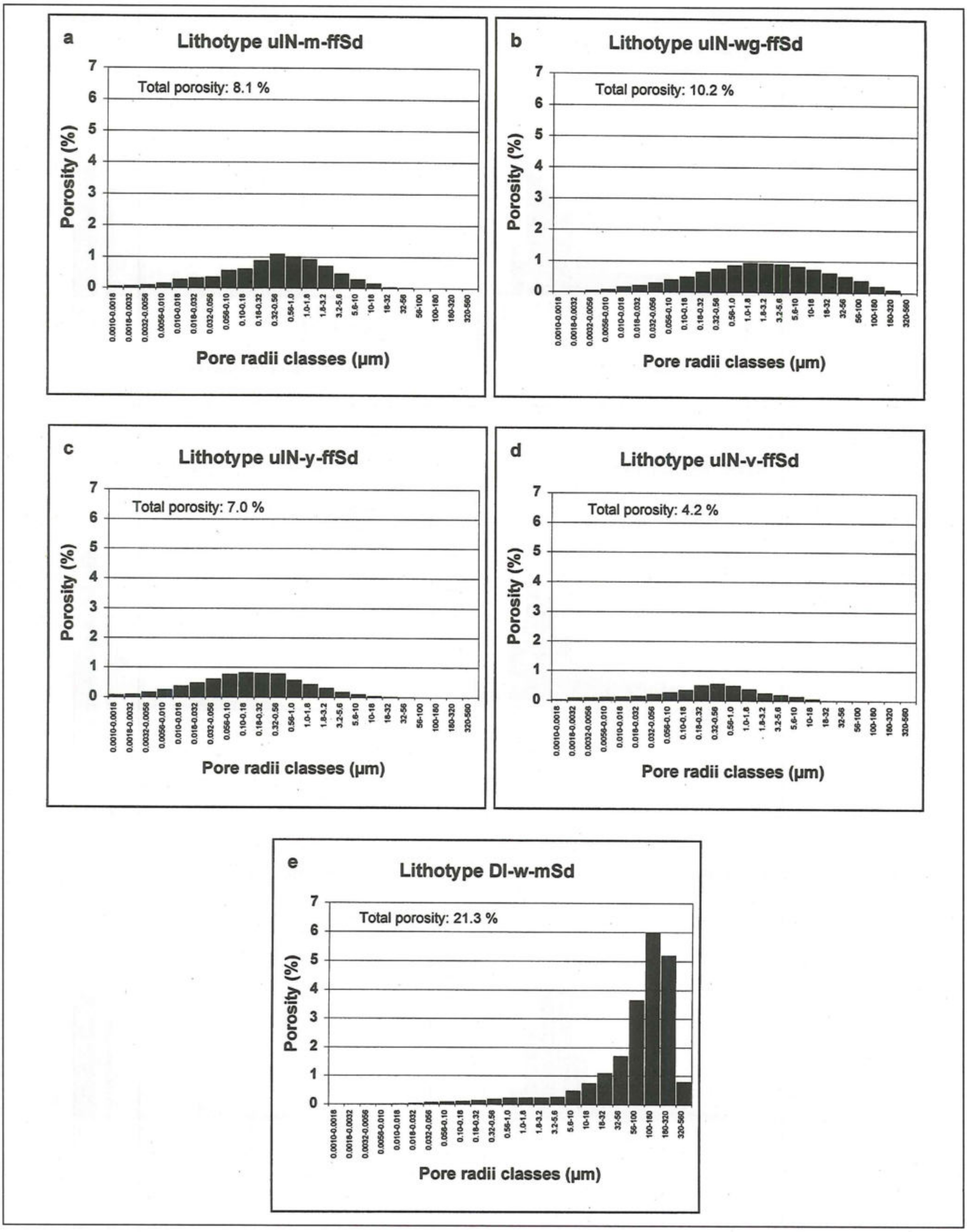
1. a-f: Pore radii distribution of lithotypes. Umm 'Ishrīn Sandstone Formation - middle part. Joint evaluation of results obtained from mercury porosimetry, nitrogen sorption and microscopy / image analysis.



2. a-f: Pore radii distribution of lithotypes. Umm ʻIshrīn Sandstone Formation - middle and upper part. Joint evaluation of results obtained from mercury porosimetry, nitrogen sorption and microscopy / image analysis.



3. a-f: Pore radii distribution of lithotypes. Umm 'Ishrīn Sandstone Formation - upper part. Joint evaluation of results obtained from mercury porosimetry, nitrogen sorption and microscopy / image analysis.



4. a-e: Pore radii distribution of lithotypes. Umm 'Ishrīn Sandstone Formation - upper part (a, b, c, d). Ad-Dīsī Sandstone Formation (e). Joint evaluation of results obtained from mercury porosimetry, nitrogen sorption and microscopy / image analysis.

the range of medium pores; small pore surface.

Sublithotype mlN-m/y-fSd (yellow-brown sandstones): sandstones with moderate total porosity; main porosity in the classes of fine pores and medium pores, no very coarse pores; unimodal pore radii distribution with main peak in the radii class 0.32-0.56 µm; median pore radius in the range of fine pores; large pore surface.

Sublithotype mlN-m/v-fSd (violet sandstones): sandstones with low total porosity; main porosity in the classes of medium pores and coarse pores; unimodal pore radii distribution with main peak in the radii class 32-56 µm; median pore radius in the lower range of coarse pores; small pore surface.

Comparing these *sublithotypes* of the multicoloured, mainly fine-grained sandstones (mlN-m-fSd), total porosity and median pore radius decrease and pore surface increases from *mlN-m/w-fSd* (white sandstones) to *mlN-m/g-fSd* (grey sandstones), *mlN-m/r-fSd* (red sandstones) and *mlN-m/y-fSd* (yellow-brown sandstones). Main porosity shifts from classes of larger pores to classes of smaller pores. *Sublithotype mlN-m/v-fSd* (violet sandstones) shows the lowest total porosity, however, comparably high proportion of larger pores rersulting in rather high median pore radius and low pore surface.

White-grey to pale violet, colour-banded, very fine-grained sandstones (mlN-m-ffSd): sandstones with moderate total porosity; main porosity in the classes of fine pores and medium pores; unimodal pore radii distribution with main peak in the radii class 0.56-1.0 µm; median pore radius in the lowermost range of medium pores; medium pore surface.

White, hard, very fine-grained sandstones (mlN-w-ffSd): sandstones with low total porosity; main porosity in the classes of fine pores and medium pores; unimodal pore radii distribution with main peak in the radii class 0.56-1.0 µm; median pore radius in the lowermost range of coarse pores; medium pore surface.

Yellow-brown, hard, very fine-grained sandstones (mlN-y-ffSd): sandstones with low total porosity; main porosity in the classes of very fine pores and fine pores; unimodal pore radii distribution with main peak in the radii class 0.32-0.56 µm; median pore radius in the lower range of fine pores; large pore surface.

Violet, hard, very fine-grained sandstones (mlN-v-ffSd): sandstones with low total porosity; main porosity in the classes of fine pores and medium pores, no very coarse pores; unimodal pore radii distribution with main peak in the radii class 0.56-1.0 µm; median pore radius in the upper range of fine pores; large pore surface.

Yellow-brown siltstones (mlN-y-St): siltstones with low total porosity; main porosity in the classes of very fine pores and fine pores, no coarse or very coarse pores; unimodal pore radii distribution with main peak in the radii class 0.056-0.1 µm; median pore radius in the upper range of very fine pores; very large pore surface.

Violet siltstones (mlN-v-St): siltstones with low total porosity; main porosity in the classes of very fine pores and fine pores; unimodal pore radii distribution with main peak in the radii class 0.18-0.32 µm; median pore radius in the lower range of fine pores; large pore surface.

The yellow-brown siltstones in the middle and upper part of the Umm Ishrin Sandstone Formatiòn (mlN-y-St, ulN-y-St) are most similar, as well as the violet siltstones in both parts of this Formation (mlN-v-St, ulN-v-St). Therefore, results on porosity characteristics are jointed for mlN-y-St/ulN-y-St and mlN-v-St/ulN-v-St.

Lithotypes - 'Umm 'Ishrīn Sandstone Formation/Upper Part

Multicoloured, mainly medium-grained sandstones (ulN-m-mSd): sandstones with high total porosity; main porosity in the classes of coarse pores and very coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 100-180 µm and minor peak in the radii class 1.0-1.8 µm; median pore radius in the medium range of coarse pores; small pore surface.

Sublithotype uIN-m/w-mSd (white sandstones): sandstones with very high total porosity; main porosity in the classes of coarse pores and very coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 100-180 µm and minor peak in the radii class 1.0-1.8 µm; median pore radius in the medium range of coarse pores; small pore surface.

Sublithotype uIN-m/y-mSd (yellow sandstones): sandstones with high total porosity; main porosity in the classes of coarse pores and very coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 100-180 µm and minor peak in the radii class 1.0-1.8 µm; median pore radius in the medium range of coarse pores; small pore surface.

Sublithotype uIN-m/g-mSd (grey sandstones): sandstones with high total porosity; main porosity in the classes of coarse pores and very coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 100-180 µm and minor peak in the radii class 1.8-3.2 µm; median pore radius in the medium range of coarse pores; very small pore surface.

Sublithotype uIN-m/r-mSd (red sandstones): sandstones with very high total porosity; main porosity in the classes of coarse pores and very coarse pores; slightly bimodal pore radii distribution with main peak in the radii class 32-56 µm and minor peak in the radii class 1.8-3.2 µm; median pore radius in the medium range of coarse pores; small pore surface.

With respect to their porosity characteristics, the *sublithotypes* of the multicoloured, mainly medium-grained sandstones (uIN-m-mSd) are rather simular. Ratio of very coarse pores to coarse pores and median pore radius decreases from *uIN-m/w-mSd* (white sandstones) and *uIN-m/g-mSd* (grey sandstones) to *uIN-m/y-mSd* (yellow sandstones) and finally *uIN-m/r-mSd* (red sandstones).

White, medium-grained sandstones (uIN-m-mSd): sandstones with high total porosity; main porosity in the classes of coarse pores and very coarse pores; unimodal pore radii distribution with main peak in the radii class 100-180 µm; median pore radius in the uppermost most range of coarse pores; very small pore surface.

Multicoloured, very fine-grained sandstones (uIN-m-ffSd): sandstones with low total porosity; main porosity in the classes of fine pores and medium pores, no very coarse pores; unimodal pore radii distribution with main peak in the radii class 0.32-0.56 µm; median pore radius in the medium range of fine pores; medium pore surface.

White to pale grey, very fine-grained sandstones (uIN-wg-ffSd): sandstones with moderate total porosity; main porosity in the classes of fine pores and medium pores; unimodal pore radii distribution with main peak in the radii class 1.0-1.8 µm; median pore radius in the lowermost range of medium pores; medium pore surface.

Yellow-brown, hard, very fine-grained sandstones (uIN-y-ffSd): sandstones with low total porosity; main porosity in the classes of very fine pores and fine pores, no very coarse pores; unimodal pore radii distribution with main peak in the radii class 0.1-0.18 µm; median pore radius in the lowermost range of fine pores; very large pore surface.

Violet, hard, very fine-grained sandstones (uIN-v-ffSd): sandstones with very low total porosity; main porosity in the classes of fine pores and medium pores, no very coarse pores; unimodal pore radii distribution with main peak in the radii class 0.32-0.56 µm; median pore radius in the lower range of fine pores; small pore surface.

Lithotype - ad-Dīsī Sandstone Formation

White, medium-grained sandstones (DI-w-mSd): sandstones with very high total porosity; main porosity in the classes of coarse pores and very coarse pores; unimodal pore radii distribution with main peak in the radii class 100-180 µm; median pore radius in the lowermost range of very coarse pores; very small pore surface.

Summary and Conclusions

As a fundamental contribution to scientific damage diagnosis of carved rock-monuments in Petra/Jordan, detailed studies of stone materials have been carried out including lithostratigraphic classification and analyses of petrographical properties. Twenty-five lithotypes have been distinguished referring to the stratigraphic units of the Umm 'Ishrīn Sandstone Formation (middle and upper part) and the ad-Dīsī Sandstone Formation. The complete lithostratigraphic classification has been presented as well as the results on the petrographical properties of the lithotypes, in particular on mineral composition, texture, micro-scale structure and porosity characteristics. In Table 14 the lithotypes are characterized according to several petrographic parameters. The presented rating system has been adjusted specially to the lithotypes for detailed relative comparison of data.

The results on petrographical properties reveal a significant range of lithotypes. This range of lithotypes concerns mineral composition (very quartz-rich lithotypes to very matrix-rich lithotypes, different composition of matrix), grain size (siltstones to medium-grained sandstones), grain size distribution, grain-matrix-relation (grain-supported fabric to matrix-supported fabric), type and number of grain contacts, type of cement (siliceous, clayish, ferritic or carbonatic cementing material), bedding characteristics at micro-scale, total porosity (very low to very high), median pore radii (very small to very large), pore radii distribution and pore surface (very small to very large).

Comparing the lithotypes, the following correlations of petrographical properties can be stated:

- Increasing grain size correlates with increasing quartz-matrix-ratio, increasing degree of roundness and sphericity of the quartz grains and with decreasing sorting of grains.
- Decreasing quartz-matrix-ratio correlates with transition from grain-supported fabric via grain- to matrix-supported fabric to matrix-supported fabric.
- Decreasing grain size correlates with increasing number of grain contacts in case of lithotypes with grain-supported fabric. With transition to matrix-supported fabric, number of grain contacts then decreases again due to increasing proportion of grains floating in matrix.
- Increasing grain size correlates with increasing total porosity and increasing proportions of coarse and very coarse pores.
- Increasing total porosity correlates with increasing median pore radius and decreasing pore surface.

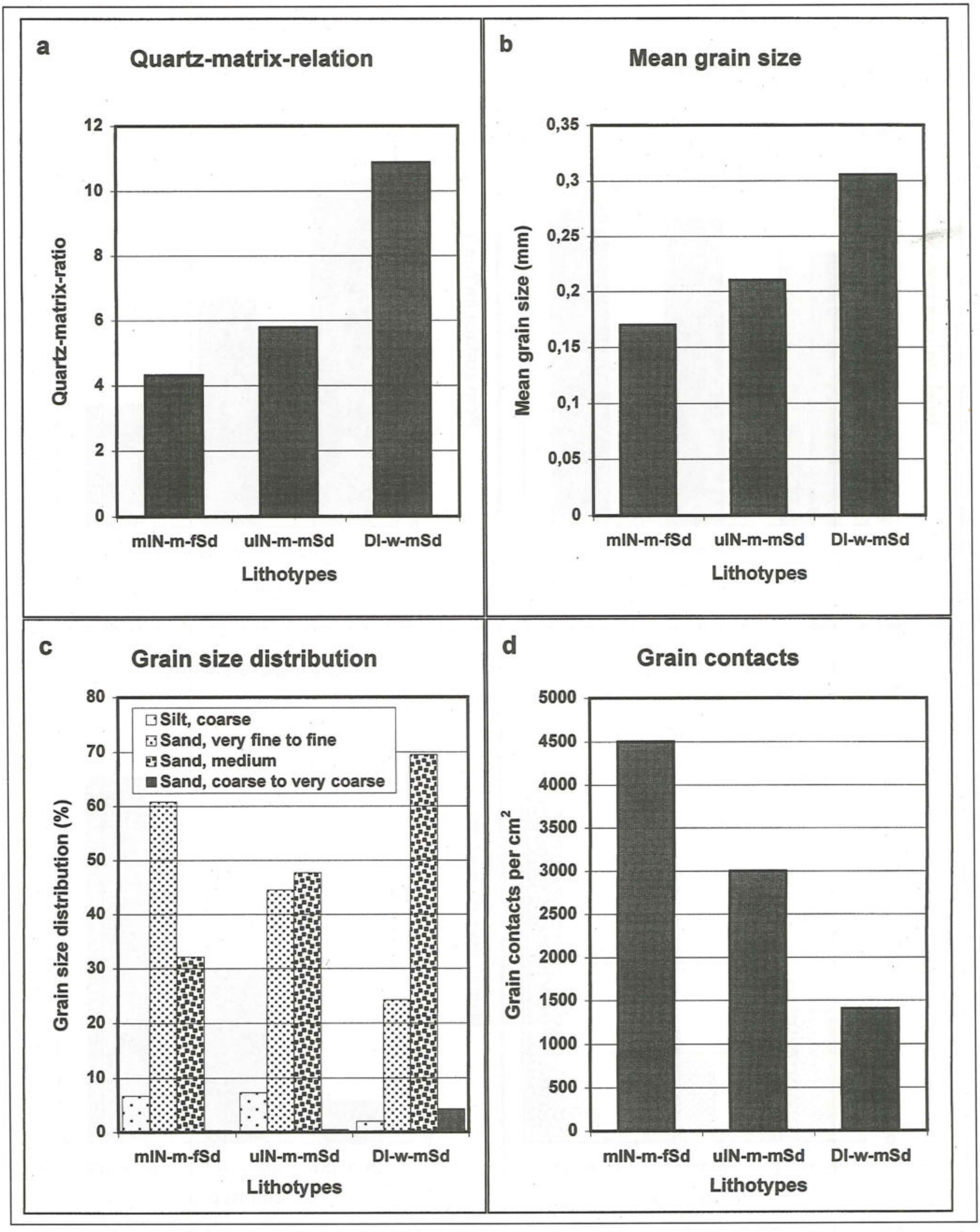
Multicoloured, mainly fine-grained sandstones (Umm 'Ishrīn Sandstone Formation - middle part), multicoloured, mainly medium-grained sandstones (Umm 'Ishrīn Sandstone Formation - upper part) and white, medium-grained sandstones (ad-Dīsī Sandstone Formation) represent the three prevailing lithotypes. In Figures 5 (a-d) and 6 (a-d) their petrographical proporties are summarized and compared. In the sequence of stratigraphically older to stratigraphically younger lithotypes:

- The quartz-matrix-relation increases (Fig. 5a),
- The mean grain size increases (Fig. 5b),
- The proportion of grains in the classes of coarse silt and very fine to fine sand decreases and the proportion of grains in the classes of medium sand and coarse to very coarse sand increases (Fig. 5c),
- The number of grain contacts decreases

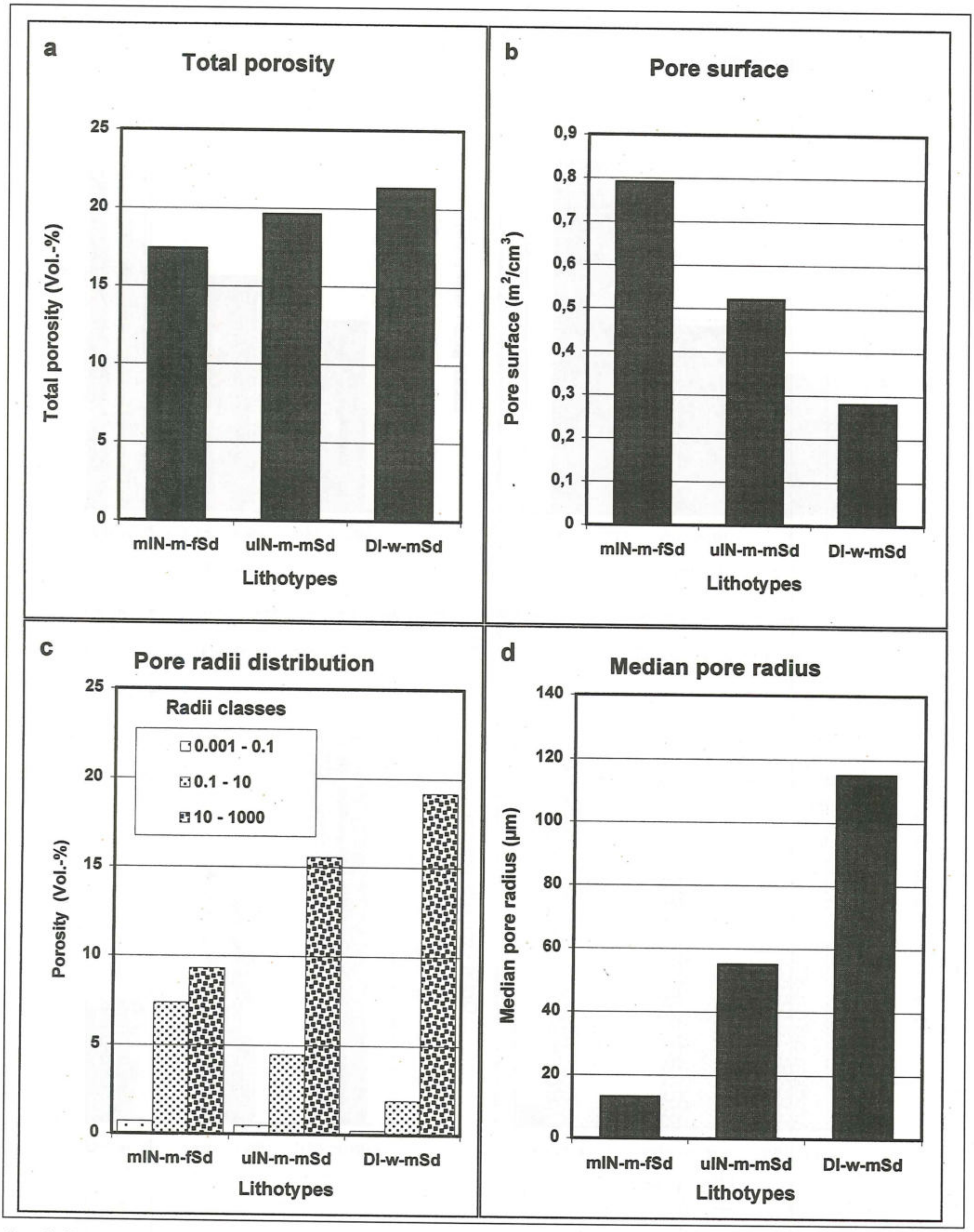
Table 14. Comparison and rating of petrographical properties.

Lithotypes	Quartz-matrix-ratio	Mean grain size	Number of grain contacts	Total porosity	Median pore radius	Pore surface
Dl-w-mSd	+ +	+	-	++	+ +	- -
ulN-m-mSd	+	+	- +	+	+	-
ulN-m/w-mSd	+	+	- +	++	+	-
ulN-m/y-mSd	+	+	- +	+	+	-
ulN-m/g-mSd	+	+	- +	+	+	- -
ulN-m/r-mSd	+	+	- +	++	- +	-
ulN-w-mSd	+	+	-	+	+	- -
ulN-m-ffSd	-	-	+ +	-	- -	- +
ulN-wg-ffSd	-	-	+ +	- +	-	- +
ulN-y-ffSd	-	-	- +	-	- -	+
ulN-v-ffSd	-	-	- +	- -	- -	+
ulN-y-St	- -	- -	- -	-	- -	+ +
ulN-v-St	- -	- -	- -	-	- -	+
mlN-m-fSd	- +	- +	- +	+	- +	-
mlN-m/w-fSd	+	- +	- +	+	- +	-
mlN-m/g-fSd	- +	- +	- +	+	- +	-
mlN-m/r-fSd	- +	- +	- +	+	-	-
mlN-m/y-fSd	-	- +	- +	- +	- -	+
mlN-m/v-fSd	- +	- +	- +	-	- +	-
mlN-m-ffSd	-	-	+	- +	-	- +
mlN-w-ffSd	-	-	++	-	- -	- +
mlN-y-ffSd	-	-	- +	-	- -	+
mlN-v-ffSd	-	-	- +	-	- -	+
mlN-y-St	- -	- -	- -	-	- -	+ +
mlN-v-St	- -	- -	- -	-	- -	+

Rating	Quartz-matrix-ratio	Grain size	Contacts per cm^2 (Thin section)	Vol.-%	µm	m^2/cm^3
++ very high	> 10	-	> 10.000	> 20	> 100	> 5
+ high	5 – 10	medium sand	5.000 – 10.000	15 – 20	50 – 100	2.5 - 5
-+ moderate	2.5 – 5	fine sand	2.500 – 5.000	10 – 15	10 – 50	1 – 2.5
- low	0.5 – 2.5	very fine sand	< 2.500	5 – 10	1 – 10	0.5 – 1
-- very low	< 0.5	silt	grains mainly floating in matrix	< 5	< 1	< 0.5



5. a-d: Comparison of multicoloured, mainly fine-grained sandstones (Umm ‘Ishrīn Sandstone Formation - middle part), multicoloured, mainly medium-grained sandstones (Umm ‘Ishrīn Sandstone Formation - upper part) and white, medium-grained sandstones (ad-Dīsī Sandstone Formation).



6. a-d: Comparison of multicoloured, mainly fine-grained sandstones (Umm 'Ishrīn Sandstone Formation - middle part), multicoloured, mainly medium-grained sandstones (Umm 'Ishrīn Sandstone Formation - upper part) and white, medium-grained sandstones (ad-Dīsī Sandstone Formation).

(Fig. 5d),
- The total porosity increases (Fig. 6a),
- The pore surface decreases (Fig. 6b),
- The proportion of porosity in the classes of extremely fine to very fine pores and fine to medium pores decreases and the proportion of porosity in the class of coarse to very coarse pores increases (Fig. 6c),
- The median pore radius increases (Fig. 6d).

The five *sublithotypes* of the multicoloured, mainly fine-grained sandstones in the middle part of the Umm 'Ishrīn Sandstone Formation show significant differences concerning their petrographical properties, whereas petrographical differences of the four *sublithotypes* of the multicoloured, mainly medium-grained sandstones in the upper part of this formation are less significant.

Compared to the multicoloured, mainly fine-grained sandstones in the middle part of the Umm 'Ishrīn Sandstone Formation, all lithotypes interbedded in this unit are characterized by a lower quartz-matrix-ratio, lower grain size, higher proportion of grains in the classes of silt and very fine to fine sand, lower proportion of grains in the class of medium sand, lower resp. missing proportion of grains in the class of coarse to very coarse sand, lower total porosity, lower median pore radius and higher pore surface.

Referring to the upper part of the Umm Ishrin Sandstone Formation, this concerns in the same way six lithotypes in relation to the multicoloured, mainly medium-grained sandstones.

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