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Models for evaporite, selenite and gypsum microbialite deposition in ancient saline basins

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ABSTRACT:

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A group of integrated hydrological and sedimentary qualitative models is introduced for evaporite and selenite (coarse-crystalline gypsum) deposition in ancient drawdown saline basins (salinas). The general model of a salina basin as a framework for intrabasinal models of selenite and gypsum microbialite (a variety of fine-grained gypsum) sedimentation is given. Selected aspects of evaporite, selenite and gypsum microbialite deposition are reviewed and discussed.
A salina basin is a depression supplied with marine water by seepage and occasional surface inflows. The intrabasinal environments comprise: (i) ephemeral saline pans, evaporite shoals, and the peculiar majanna environment (recognised in the Recent MacLeod salina, Australia); and (ii) perennial saline pans. The sedimentary dynamic of these environments is controlled largely by seasonal brine level and groundwater table level fluctuations. The perennial saline pans are characterised by three basic hydrological states: (i) meromixis – with a permanent pycnocline, (ii) monomixis to polymixis – with a seasonal or periodic pycnocline, and (iii) polymixis - without a constant pycnocline. Monomictic saline pans showing stratification in the wet period (during seasonal highstand) and mixis in the dry period of the year (during seasonal lowstand) are the most significant for subaqueous evaporite and selenite deposition. Evaporite deposition takes place mainly during a mixis period coinciding with a dry season lowstand and increased evaporation. Within intrabasinal environments selenite crusts can be occasionally deposited from permanent brine sheets on evaporite shoals or majanna flats, but are mainly the product of bottom crystallisation in the hypolimnion of the monomictic (and/or polymictic) saline pans. Shallow-brine and deep-brine selenite pans are distinguished from each other on the basis of the relationship of the seasonally fluctuating pycnocline to the bottom of the pan. Selenite deposition in the mixolimnion of a deep meromictic basin is also possible. The qualitative models can be used for sedimentological analyses of ancient selenite-evaporite basins.

Key words: Evaporites, Drawdown salina basin, Saline water, Hypersaline environment, Cyanobacteria, Microbial mats, Selenite crystals, Gypsum microbialites, Monomictic, Pycnocline.

INTRODUCTION

Calcium sulphate deposits are one of the most widespread evaporite facies in the geological record and selenites are one of the most typical primary Ca sulphate facies in modern and Cenozoic deposits (SCHREIBER 1978, GEISLER-CUSSEY 1997). Pseudomorphs and ghosts of selenite crystals are recognized in many Phanerozoic diagenetically altered sulphate evaporites (NURMI & FRIEDMAN 1977, KENDALL 1984). Selenite deposits are found in many recent shallow evaporite settings like coastal salinas and salt lakes but the ancient selenite crystals and selenite-evaporite basins have no modern analogue comparable in size and variability of depositional processes. Many ancient selenite facies represent environments which are yet not satisfactorily explained. Ancient environments of selenite deposition were discussed by many authors and several depositional models were suggested (HARDIE & EUGSTER 1971; VAI & RICCI LUCCHI 1977; EUGSTER & HARDIE 1978a; ROUCHY 1982; WARREN 1982, 1999; KENDALL 1984; ORTÍ & *al*. 1984). All these models are highly simplified and do not cover all aspects of selenite deposition, for example, they do not explain the observed differentiation within selenite facies and the relationships to other associated facies such as gypsum microbialite deposits (ROUCHY & MONTY 2000). In particular, the hydrodynamic of stratified basinal brines and their influence on subaqueous evaporite crystallisation were not taken into consideration.

The main aim of this paper is to introduce an integrated group of new (or revised) qualitative models of selenite deposition with emphasis on the hydrochemistry of an evolving saline basin, associated gypsum facies, and the mechanisms of subaqueous evaporite deposition. These models are placed within the framework of a single, comprehensive model of the evaporite basin, in which selenites are only one particular chemical facies. The classic model of evaporite basin, known as a salina or drawdown basin (see BĄBEL 2004 in press), is explored. For full understanding of the new models and their interrelationships, a review of the main aspects of evaporite deposition in a salina basin is presented. In addition, the typical selenite and associated gypsum facies and particularly the gypsum microbialites are described. Conditions of selenite and gypsum microbialite deposition are characterised in detail to show the limitations of the presented models in which these two types of sediments play a crucial role.

The paper is composed of three chapters. Chapters 1 and 2 include critical reviews of the existing opinions on evaporite, selenite, and gypsum microbialite deposition in a salina basin environment. The new models are presented in chapter 3.

The models are inspired by the Middle Miocene (Badenian) selenite facies of the northern Carpathian Foredeep studied by the author (BĄBEL 1999a, b; 2004a in press, 2004b in press), but are based mainly on numerous other studies of both modern and ancient evaporite deposits and environments, particularly of monomictic coastal salinas and salt lakes.

The reviews, discussions and models principally concern selenite and gypsum microbialite deposition in a salina-type basin. However the material presented includes many more general aspects of evaporite deposition and therefore can be helpful for the study of other evaporite deposits and environments as well.

Terminology

The basic terminology for the hydrology of brine in a salina basin follows HUTCHINSON (1975), LEWIS (1983) and HORNE & GOLDMAN 1994). However, because some of the well known terms are used here in a slightly modified way, they are defined briefly below. Some other important terms are also described.

Brine sheet – body of free brine that is not topographically confined, 'up to 30 cm deep, averaging about 3 cm', and 'up to hundreds of square kilometers in area' (LOGAN 1987, p. 23). They are 'fed by seepage discharge or outflow from ponds' (LOGAN 1987, p. 2). Brine sheets are permanent elements in the MacLeod salina, the Kara Bogaz Gol (LEPESHKOV & *al*. 1981, pp. 186-187; LEVINE 1998) and Lake Tyrrell (TELLER & *al*. 1982, LONGMORE & *al*. 1986). They flow downslope from seepage areas or outflow from permanent ponds when brine level is rising. Brine sheets also are driven out of pond closures by wind and may become detached, forming migratory brine sheets which can flow high upslope. In Lake Tyrrell 'it is not unusual for the north end of the basin to contain water, while the south end, which lies as much as 2 metres lower, is dry' (TELLER & *al*. 1982, p. 169). Brine sheets dwindle by seepage and evaporation commonly leaving the evaporite deposits, or may drain into depressions forming permanent or ephemeral ponds. Similar 'roving' water sheets are common in playa lakes and were modelled by TORGERSEN (1984)

Epilimnion – according to the original definition: the 'upper region of more or less uniformly warm, circulating, and fairly turbulent water' appearing 'in all lakes of sufficient depth, heating in the spring from a low temperature' (BIRGE 1910 in HUTCHINSON 1975, p. 427). In this paper epilimnion is defined as the upper layer of a seasonally stratified water body.

Gypsum microbialites, gypsum microbialite deposits, microbialitic gypsum – organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital gypsum sediments and/or forming the locus of gypsum precipitation (cf. BURNE & MOORE 1987).

Hypolimnion – according to the original definition: the 'deep, cold, and relatively undisturbed' region of water appearing 'in all lakes of sufficient depth, heating in the spring from a low temperature' (BIRGE 1910 in HUTCHINSON 1975, pp. 427-428). In this paper hypolimnion is defined as the lower layer of a seasonally stratified water body.

Majanna – dominant environment in the MacLeod salina (LOGAN 1987); evaporite flats 'lying below sea level in which seepage inflow is less than evaporative outflow' (LOGAN 1987, p. 2); with suppressed, seasonally and daily fluctuating brine table 0-2 m below the surface. The majanna surface is more or less parallel to the brine table and is modelled by migratory brine sheets, crystallisation and dissolution of evaporite minerals, flood sheets, deflation, accretion of microbial mats; etc. The position of the brine table defines phreatic (wet) majanna, with the brine table close to the surface; and vadose (dry) majanna, with the brine table below ca. 0.4 m from the surface (LOGAN 1987, p. 61).

Meromictic – m. lake; a stably stratified lake which mixes only partially i.e. in which some water remains partly or wholly unmixed with the main water mass during the annual mixing cycle (FINNDENEGG 1935 in HUTCHINSON 1975; HORNE & GOLDMAN 1994)

Mixolimnion – an upper or surface part of a meromictic lake 'in which free circulation periodically can occur' (HUTCHINSON 1937 in HUTCHINSON 1975, p. 480)

Monimolimnion – 'the perennially stagnant deep layer of a meromictic lake' (FINNDENEGG 1935 in HUTCHINSON 1975, p. 480, SONNENFELD 1984, p. 72)

Monomictic – m. lake; a lake which is stratified in one (winter or summer) season of the year and goes through free entire mixing in the remaining season (see HUTCHINSON 1975, pp. 438-439)

Polymictic – p. lake, a lake with frequent periods of mixing per year (see HUTCHINSON 1975, pp. 462, 535; HORNE & GOLDMAN 1994, p. 47). 'Lakes that mix at intervals of days to weeks' and 'more than once a year' are discontinuous polymictic lakes and lakes 'that mix daily or without interruption' are continuous polymictic lakes (LEWIS 1983, pp. 1783).

Saline pan – in this paper: topographically depressed area filled with saline water or brine (cf. brine pond by LOGAN 1987, p. 20)

Selenite – in this paper: large (over 2 mm; cf. WARREN 1982) primary (sensu INGERSON 1968 and DRONKERT 1985, p. 94) gypsum crystals grown from solution or brine on the bottom of the basin, or within the soft deposits, microbial mats, or organic sediments as displacive (see TWENHOFEL 1950, pp. 601-603) or incorporative crystals (LOWENSTEIN 1982).

SALINA EVAPORITE BASIN

The salina-type basin model is well known from many previous studies (general features of this model are reviewed and discussed elsewhere; BĄBEL 2004 in press). The salina basin shows the following basic features (Text-fig. 1): (1) the evaporite basin is a closed depression separated from the ocean by some morphologic barriers; (2) evaporation is the main reason for water deficit and for chemical sedimentation; (3) seawater enters the basin by

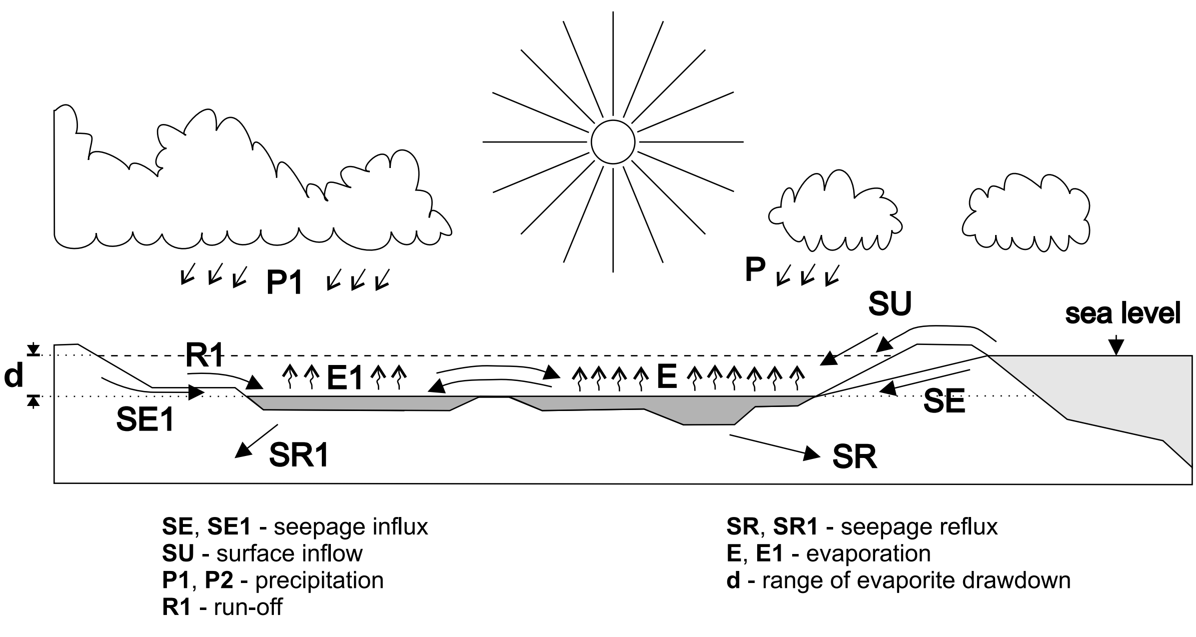

Fig. 1. A drawdown salina basin model of evaporite deposition

seepage and occasionally by direct inflows over the barriers (and is the main source of salts); and, (4) the basin is a system of interconnected subbasins which change in time and space depending on mean water level (and water budget). These subbasins, depending on depth, sizes and shapes, can be treated as separate subordinate smaller basins within a giant salina basin or as 'non-marine' bays separated from rest of the basin by shoals, islands and peninsulas.

Evaporation is a crucial factor in the depositional system of a salina basin. It plays three fundamental roles. First, it lowers the water level and builds the hydraulic head which forces the marine water to flow into the evaporite basin (Text-fig. 1). This water carries dissolved salts to a depositional site. Secondly, evaporation raises the salinity of the water in the basin resulting in the production of brine. The concentrations of particular ions in the brine increase together with the increase in salinity in a process known as evaporitic concentration. Third, when during this process a particular ionic compound attains a state of saturation, evaporation is the driving force which leads to the precipitation of salts. Strictly speaking, by removal of water to the atmosphere evaporation raises both the salinity and the concentration of given compounds to a state of oversaturation, which causes their precipitation. The other common ways of causing crystallisation of evaporite salts include temperature changes in saturated solutions (SLOSS 1969), mixing of brines known as salting-out or salination (RAUP 1982, SONNENFELD 1984), and brine freezing or freeze-drying (STRACHOV 1962, SONNENFELD 1984, MARION & *al*. 1999). In the models presented further in this paper evaporitic concentration is considered as the main driving force of chemical deposition.

A salina basin is technically a lake but it differs from a salt lake in at least two aspects. A salt lake is normally fed by meteoric water, which is very low in dissolved salts. In a salina basin the main source of water is marine water or marine-derived brine (or basinal brine inflowing from the adjacent saline pans or subbasins; Text-fig. 1). Such waters carry a considerable amount of salts. Therefore a salina basin, in a given climate and time span, 'produces' more salts than any salt lake – e.g. up to 30 times more Ca sulphate, on average (see DENISON & *al*. 1998, p. 3). A high content of calcium sulphate in the brine and its continuous supply is very important for the rapid growth of large gypsum crystals and therefore a salina basin is typical of selenite deposition.

Salt lake sedimentation is controlled mainly by climate and simply reflects dry and wet periods, whereas a salina basin is controlled also by marine water influx. The rate of this influx is not always constant and is difficult to predict. The seepage influx rate, among others, is controlled by the hydraulic head which depends on evaporite drawdown and thus on the depth of the salina basin (GOODALL & *al*. 1992). The influx through surface channels is controlled principally by eustasy, and also by tectonics in the barrier area, and the physical and morphological features of the barrier and channels (BORCHERT & MUIR 1964, LEPESHKOV & *al*. 1981, TUCKER in GOODALL & *al*. 1992). A large influx can refresh the brine, while a smaller influx can result in a salinity increase. This holds true only when there is no significant brine outflow from the basin by seepage reflux (SANFORD & WOOD 1991).

The importance of saline water inflow into the salina basin can be illustrated by the recent history of Kara Bogaz Gol. This salina is supplied with water from the Caspian Sea through a surface channel. Smaller influxes were directly related to sea-level falls in the Caspian Sea and caused a drastic increase in salinity and intensification of evaporite deposition (LEPESHKOV & *al*. 1981). Blocking the inflow channel by a dam in 1980 led to nearly complete drying out of the Kara Bogaz Gol over a period of only three years (LEVINE 1998).

Depositional environments of salina basin

In all Recent coastal salinas or salt lakes disconnected from the world oceans the water level may undergo seasonal fluctuations. Water level is low during a dry season and high in a wet one. The amplitude of these fluctuations depends on climatic factors but also on the sizes of drainage areas, the areal extent and depth of the basin, and the salinity of the brine (Tab. 1). It also depends on the rate of marine water seepage- or surface-inflow into a salina basin. The seasonal lowstand-highstand cycle is modified by wind-induced water level rises (wind tides) which in most lakes reach a few tens of cm on average, but some larger basins may reach as much as 2.5 m (LOGAN 1987, p. 115; RATKOVICH & IVANOVA 2001). Wind-induced water level changes are superimposed on the seasonal water level fluctuations and in sum the maximum span of these fluctuations is higher. The amplitude of water level fluctuations is an important measurable parameter enabling the definition and subdivision of the salina basin environments, as follows (Text-fig. 2).

In a salina basin, the whole area within the amplitude of seasonal (and periodic) water level fluctuations ('h' in Text-fig. 2) may undergo cyclic complete drying and flooding, and thus represents an **ephemeral** or **temporary saline pan** or **evaporite shoal** or other semi-emerged or emerged environments (HARDIE & *al*. 1978). Both the hydrological and sedimentary dynamics of these areas are extremely variable. The diagnostic features of such environments are mainly evidence of frequent emersions (see reviews of **salt pan** and **evaporite flat** facies by LOWENSTEIN & HARDIE 1985, KENDALL 1992). The specific environment of a salina basin is **majanna** - evaporite flats controlled by seepage inflow and evaporation outflow, with suppressed and seasonally fluctuating brine table (with amplitude ca. 0.2 m in the MacLeod salina; LOGAN 1987, p. 61), and common migratory brine sheets.

Those pans that are deeper than the maximum range of seasonal water level fluctuations are **perennial saline**

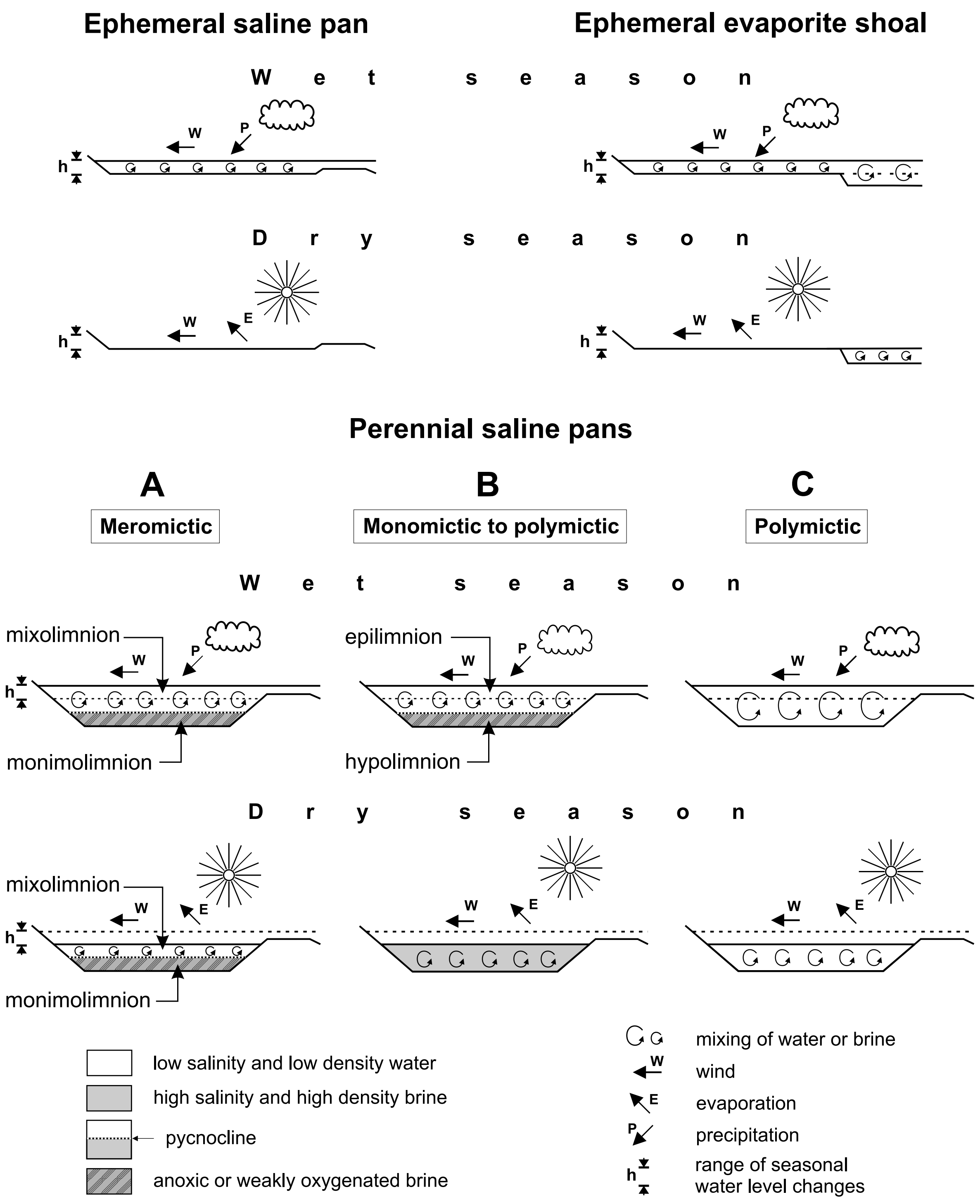

Fig. 2. Hydrological models of evaporite environments; further explanations in the text

NAME AND LOCATION OF THE BASIN	MAXIMUM SALINITY[1]	DEPTH	AMPLITUDE OF SEASONAL WATER LEVEL CHANGES	TYPE OF MIXING	PRESENCE AND TYPE OF GYPSUM SEDIMENTS[2]	REFERENCES
Dead Sea, Israel and Jordan	344‰	Northern basin: ca. 324 m. Southern basin: ca. 3 m.	Unstable, several tens of cm	Northern basin: meromictic (before 1979, in 1980-1984 and 1992-1995) and monomictic (in 1979-1980, 1985-1991, and after 1996). Southern basin: discontinuous polymictic.	G (precipitation only in monmolimnion-epilimnion zone, northern basin)	NEEV & EMERY 1967, GANOR & KATZ 1989, HEIM & *al.* 1997, NIEMI & *al.* 1997, ANATI 1998, IVANOV & *al.* 2002a, GERTMAN & *al.* 2003
Mono Lake, USA	94‰	45 m	Unstable, 0.1-2.7 m	Monomictic before 1983 and in 1990-1994; meromictic in 1983-1988, and after 1995; polymictic in transitional periods		MILLER & *al.* 1993, ROMERO & MELACK 1996, MELACK & JELLISON 1998, MACINTYRE & JELLISON 2001
Lake Balkhash, Kazakhstan	5.5‰	26.5 m	Up to 0.75 m	Polymictic		TARASOV 1961
Salton Sea, USA	45‰	15 m	Ca. 0.3 m	Discontinuous polymictic		WATTS & *al.* 2001
Great Salt Lake, USA	343‰	11 m	0.57 m on average, maximum 0.94 m	Meromictic and polymictic	S, G	STEPHENS & GILLESPIE 1976, GWYNN 1980
Solar Lake, Egypt	199‰	5 m	Up to 2.2 m	Monomictic	G (S in subsurface sediments)	ECKSTEIN 1970, COHEN & *al.* 1977, GAVISH 1980, GAVISH & *al.* 1985, ALI 1999; see also references in Tab. 2
Lago Pueblo, Venezuela	225‰	4.6 m	0.4-0.9 m	Meromictic (?)	S, G – only in mixolimnion	SONNENFELD & *al.* 1976, 1977; HUDEC & SONNENFELD 1978; SONNENFELD & HUDEC 1978; SONNENFELD 1984
Kara Bogaz Gol, Turkmenistan	310‰ and more	Ca. 3.5 m (1975 y)	Up to 0.5 m 0.8-1 m	Discontinuous polymictic	G	LEPESHKOV & al. 1981, LEVINE 1998
Lake Hayward, Australia	268‰	3 m		Monomictic	G	ROSEN & *al.* 1996, BURKE & KNOTT 1997
Lake Inneston, Australia	Gypsum saturated marine brine	3 m	Ca. 0.5 m	Meromictic or monomictic (?)	S, G	WARREN 1982
Cygnet and Ibis Ponds, MacLeod, Australia	190‰	1.5 m	Ca. 0.4 m	Polymictic	G, S	LOGAN 1987, fig. 57
Deep Lake, Australia	Gypsum saturated marine brine	1 m	Ca. 0.8 m	Discontinuous polymictic	S, G	WARREN 1982
Hutt Lagoon, Australia	Halite saturated marine brine	0.65-0.95 m	0.65-0.95 m	Polymictic	G, S	ARAKEL 1980, 1988; POST & *al.* 1983
Ras Muhammad Pool, Egypt	Gypsum saturated marine brine, up to 314‰	0.5 m	Less than 0.5 m	Polymictic	G (S in subsurface sediments)	GAVISH 1980, KUSHNIR 1981, FRIEDMAN & *al.* 1985

[1] all different original salinity units are roughly approximated to ‰
[2] S – selenites, G – fine-grained gypsum and/or gypsum microbialites

Tab. 1. Hydrological and sedimentological characteristics of selected modern saline basins

pans (Text-fig. 2). Shorelines of the perennial pans coincide with the mean low water level in the basin (cf. LAST 1993). Perennial pans can persist for many years without drying up and are traps for brine produced by evaporation. The present study focuses on perennial saline pans which are equivalents of subbasins in the salina basin model.

Hydrology of perennial saline pans

The hydrological structure and dynamics of perennial saline pans are crucial for understanding subaqueous evaporite (and selenite) deposition and can be characterised as follows.

The water in a saline pan is normally denser than any water flowing into it. When density difference between the water in the pan and inflowing water reaches a critical value the waters mix poorly and stable density stratification can develop, with denser, more saline brine near the bottom, and less saline water at the surface. The water masses display not only different densities and salinities but often also differences in temperature and ionic composition. The interface zone between these water masses is characterised by their halocline (or chemocline; SONNENFELD 1984, p. 72) and pycnocline (HUTCHINSON 1975, p. 282). Rapid vertical change of temperature, a thermocline (term by BIRGE 1897, redefined by other authors; see HUTCHINSON 1975, p. 428; HORNE & GOLDMAN 1994), is commonly associated with this interface. During stratification these two water masses may mix independently of each other. The lower mass is usually more stagnant; whereas the upper one undergoes more vigorous mixing driven mainly by atmospheric influences. The stratification is not stable and can alternate with periods of mixis, when the temperature and salinity of the pan become homogeneous.

Depending on the pycnocline and the stratification behaviour during the seasonal highstand-lowstand cycle, three basic types of perennial saline pans can be distinguished (Text-fig. 2): meromictic, polymictic, and monomictic-polymictic. These types and corresponding hydrological states, i.e. meromixis, polymixis, and monomixis-polymixis (see HUTCHINSON 1975), are defined here by the frequency of mixing periods during the annual cycle (see LEWIS 1983).

The introduced classification is highly simplified. It is not based on the thermal structure of saline pans as suggested by the original meaning of monomixis and polymixis, although it is assumed that the thermocline more or less coincides with the pycnocline during stable stratification, which is true for many brine-filled basins. Periods of destabilisation and the onset of stratification, which are commonly characterised by the appearance and displacements of multiple temporary pycnoclines and thermoclines, are not shown in the models (Text-fig. 2).

The classification arbitrarily assumes that in monomictic pans the mixis period coincides with a seasonal lowstand and is caused mainly by the evaporation of the hypolimnetic waters, exactly as is observed in the shallow Solar Lake (COHEN & *al*. 1977, p. 605), Lake Hayward (ROSEN & *al*. 1996), and Australian selenite salinas (WARREN 1982; 1999, p. 14). All these basins (Tab. 1) show an unusually warm hypolimnion due to the heliothermal effect, contain Recent gypsum or selenite sediments, and, like most heliothermal lakes (SONNENFELD & HUDEC 1980, p. 96), are no more than 5 m deep. In contrast, in deeper monomictic saline lakes such as the Dead Sea or Mono Lake (Tab. 1), mixis takes place during the onset and the first phase of winter highstands (ANATI 1997, MELACK & JELLISON 1998).

Meromictic pans

Meromictic saline pans are permanently stratified (Text-fig. 2A). The monimolimnion always shows constant salinity, density and temperature. The mixolimnion is in a dynamic regime. It undergoes mixing and its salinity, density and temperature change during both wet and dry seasons. The pycnocline is said to act as a 'virtual bottom' because the brine properties below it do not change. The monimolimnion is permanently separated from the atmosphere and evaporative precipitation of salts within its brines is difficult or not possible (SLOSS 1969). A monimolimnion is commonly anoxic because the oxygen is consumed during decomposition of dead plankton and other organic debris settling from the upper water mass. Meromixis continues as long as the properties of the mixolimnion (density, temperature) support constant stratification of the system. GERTMAN & *al*. (2003) precisely formulated that 'a period is meromictic if it is longer than one seasonal cycle; it begins with the onset of stable stratification and terminates with the first overturn'. Meromixis is typical of many saline basins (Tab. 1). It passes commonly into monomixis during increased evaporation when the mixolimnion salinity rises and water level falls. Meromixis depends on the depth of the saline pan, density of brine and the weather conditions. The dense brines of Kara Bogaz Gol are normally mixed by winds only to 1-1.5 m depth (LEPESHKOV & *al*. 1981, p. 47). Shallow and low salinity pans are often mixed by strong winds down to the bottom (LEWIS 1983; GERDES & *al*. 2000b, p. 198).

Polymictic pans

In this state the water in the entire saline pan is permanently mixing during both wet and dry seasons and stratification appears only episodically (Text-fig. 2C). This state is characteristic of saline basins of relatively low salinity such as Hamelin Pool in western Australia, with waters of 53-72‰ (LOGAN 1987, p. 12), Salton Lake or Lake Balkhash (Tab. 1). Polymixis may also appear in shallow and even highly saline basins with a huge and constant inflow of fresher waters from one side, like Kara Bogaz Gol (LEPESHKOV & *al*. 1981) or the brine ponds of the MacLeod salina (LOGAN 1987, p. 21). In a very windy climate all shallow saline pans are mixed down to the bottom and can be considered as polymictic. Horizontal salinity gradients are common in shallow polymictic pans. In Kara Bogaz Gol the salinity changes from ca. 17‰, near the Caspian Sea water inflow channel, to 295‰ at the east coast (LEPESHKOV & *al*. 1981). The polymictic state is typical of the so-called isopycnal evaporite basins of LOGAN (1987).

Monomictic to polymictic pans

These pans show frequent and alternately changing stratified and homogeneous states (during a year or less; Text-fig. 2B). Monomictic saline pans are density stratified only in the wet season when a sheet of fresh or brackish water spreads over a more saline brine and mixes only with the upper part of this brine. A seasonal pycnocline is created at the boundary of the water masses. In a dry period evaporation increases the salinity and density of the upper mass and the stratified system looses its stability. The pycnocline disappears and the whole brine body in the pan is mixed down to the bottom, attaining a homogeneous state. In monomictic basins hypolimnetic anoxia commonly occurs during stratification and changes into full oxygenation during mixis (HORNE & GOLDMAN 1994). Stratified saline pans which undergo complete mixing once a year are termed monomictic, twice a year – dimictic (cf. HUTCHINSON 1975. p. 438), whereas those which undergo complete mixing several times a year, daily, or mix without interruption, are defined as discontinuous polymictic or continuous polymictic, depending on frequency of mixis (LEWIS 1983). Continuous polymictic pans that mix without interruption represent the 'polymictic pans', whereas discontinuos polymictic pans can only arbitrarily be considered as belonging to the 'monomictic-polymictic' or 'polymictic pans' (Text-fig. 2). Various physical processes are involved in destabilization of stratification, overturn and mixture of brine masses in saline pans (STERN 1980; STEINHORN 1985; GANOR & KATZ 1989; ANATI & STILLER 1991; ANATI & *al*. 1995; ROMERO & MELACK 1996; NIEMI & *al*. 1997; ANATI 1998; IVANOV & *al*. 2002a). Monomictic saline pans are relatively common (Tab. 1, HUTCHINSON 1975).

During monomictic, dimictic and discontinuous polymictic states with low frequency of mixis periods, unlike during permanent meromixis, the bottom brines experience seasonal temperature, density, salinity and oxygenation changes. All these changes can promote evaporite precipitation in the hypolimnion. Such a 'monomictic' precipitation of halite was observed in the Dead Sea (NIEMI & *al*. 1997, HERUT & *al*. 1998), and gypsum precipitation in Solar Lake (KRUMBEIN & COHEN 1974, 1977) and Lake Hayward (ROSEN & *al*. 1996, BURKE & KNOTT 1997).

Similarly as with freshwater lakes (LEWIS 1983) every sufficiently shallow saline pan becomes polymictic. The depth limit for the appearance of permanent polymixis depends on local conditions, like climate, salinity, fetch, etc., (HORNE & GOLDMAN 1994), and for pans not sheltered from winds may be arbitrarily placed between 1 and 3 m (Tab. 1).

Evaporite precipitation in perennial saline pans

Depending on environmental factors the hydrological states of saline pans change with time and the changes influence a course of evaporite deposition (and can be reconstructed from the ancient sedimentary record; KIRKLAND 2003).

During early stages of evaporative concentration and/or during drastic refreshments (like the one recently observed in Mar Chiquita; Argentina, MARTINEZ 1995) every hydrological state is possible (stratification can be maintained by the thermocline in the case of freshwater). At the beginning of evaporation, the salinity and density of the water are low and therefore the stability of originated pycnoclines is weak (e.g. ROMERO & MELACK 1996). Therefore, especially in shallow pans and in windy climate, polymixis is relatively frequent. When salinity rise allows the establishment of a constant pycnocline, meromixis or monomixis are the dominating hydrological states. During wetter years meromixis is the rule because the increased volume of fresh meteoric water added to the upper layer stabilises a pycnocline. During dry years permanent meromixis changes into a monomictic-polymictic state. Monomixis is the most important hydrological state responsible for abundant subaqueous evaporite deposition in perennial saline pans as recognised in Recent shallow coastal salinas and salt lakes (KRUMBEIN & COHEN 1974, 1977; ROSEN & *al*. 1996; BURKE & KNOTT 1997; WARREN

1999). Chemical deposition in such a state starts only when the brine is saturated with a given salt. Precipitation takes place mainly in dry seasons coinciding with lowstands and involves the whole brine body (Text-fig. 2). In some deep monomictic pans crystallisation of salts can take place during the whole year, i.e. can continue also during the wet seasons, from 'remnant supersaturation' within bottom hypolimnetic brines (see STILLER & *al*. 1997, p. 182). This mode of halite crystallisation was recorded in the hypolimnion of the Dead Sea during periods of stratification (ANATI & STILLER 1991, ANATI & *al*. 1995, NIEMI & *al*. 1997, HERUT & *al*. 1998, GERTMAN & *al*. 2003). The monomictic-polymictic state is reflected by cyclic precipitation or cyclic crystal growth of evaporite salts. Ideally, crystal growth zonation can represent successive periods of mixis; annual periods in the case of monomixis, and irregular shorter periods in the case of polymixis. Crystal growth zoning is visible in many evaporite gypsum crystals and clearly can be connected with monomixis (WARREN 1999). However the recently grown halite cubes from the hypolimnion of the Dead Sea, which are up to 2 cm in size, do not display any macroscopically visible zoning (HERUT & *al*. 1998), such as chevron halite crystals from shallow polymictic pans (HOLSER 1979, LOWENSTEIN & HARDIE 1985, HANDFORD 1991).

Gypsum precipitation is possible under a polymictic state, typical of a very low salinity, but only when the waters are saturated with Ca sulphate. Such a case is found in the Aral Sea, which contains Ca sulphate-enriched waters where gypsum is precipitated at salinity ca. 30‰ (LÉTOLLE & CHESTERIKOFF 1999), that is lower than the seawater salinity (35‰). Marine brine becomes saturated with Ca sulphate at salinity levels of ca. 150‰ when brine density is high enough to establish a stable pycnocline.

In any hydrological state evaporative precipitation theoretically can take place in any part of the brine body that is in contact with the atmosphere and is subjected to direct evaporation. Evaporative precipitation is not possible, or at least very difficult, when the monimolimnion of the meromictic pans is separated from the atmosphere (Text-fig. 2). Precipitation of salts is arrested in the monimolimnion but if the crystals remain under a cover of calm stagnating brine they are not dissolved, eroded or mechanically redeposited.

The mixolimnion in meromictic pans displays changeable water properties. Depending on the salinity and the concentration of a given salt, evaporative precipitation can occur there during the dry seasons and after dissolution of earlier precipitates during the wetter periods. Marginal zones of more diluted pans can be completely devoid of chemical precipitates because of the dissolution. In meromictic pans spontaneous precipitation can occur, forming 'whitings' within the mixolimnion, a 'rain' of tiny crystals that settle and accumulate on the bottom to form laminated deposits, such as the laminated gypsum in the Dead Sea (NEEV & EMERY 1967, HEIM & *al*. 1997). Perfectly laminated chemical sediments are not disturbed by bottom growth of evaporite crystals or early diagenetic crystallisation (like in the polymictic Ras Muhammad Pool in Sinai; KUSHIR 1981) because of the stagnant unchanging properties of the monimolimnion. When whitings occur once a year the sediments are true chemical varves. Whitings can be promoted by many processes (KIRKLAND 2003). Inflow of brines from other saline pans can lead to spontaneous salt precipitation due to mixing of different brines (see HOLSER 1979, RAUP 1982, BĄBEL 1999c). It is remarkable that laminated sediments are characteristic of many meromictic lakes, not only the saline ones (e.g. LOWE & *al*. 1997).

Summarising, optimum conditions for abundant salt precipitation are developed during increased aridity and evaporation in monomictic-polymictic saline pans. Monomixis is a fundamental hydrological state for subaqueous evaporite deposition in perennial saline pans. The Dead Sea and Mono Lake examples indicate, however, that this state is very sensitive to climatic changes and can alternate with meromixis during rainy years (NIEMI & *al*. 1997, MELACK & JELLISON 1998). Short-term meromictic periods against a background of long-term monomixis probably remain unrecorded in evaporite deposits.

Highstand, lowstand and brine transport in salina basin

Water-level changes in a salina basin are dependent on many interrelated factors. Irrespective of the reasons for these changes, there are two possible extreme states, the lowstand connected with evaporative water-level drop, and the highstand associated with deepening and expansion of the water surface.

During highstands the barriers are flooded and saline pans are well connected by surface water (Text-fig. 3). Because highstands are usually periods of increased influx of meteoric and/or marine waters, and/or decreased evaporation, they are probably associated with meromixis and a lack of significant evaporite deposition. The brines of the separate subbasins supposedly do not mix but stagnate below sharp pycnoclines. Lateral brine transport and mixing between adjacent subbasins appear during the monomixis-polymixis but are limited by the size of the barriers. Brine transport and mixing is more

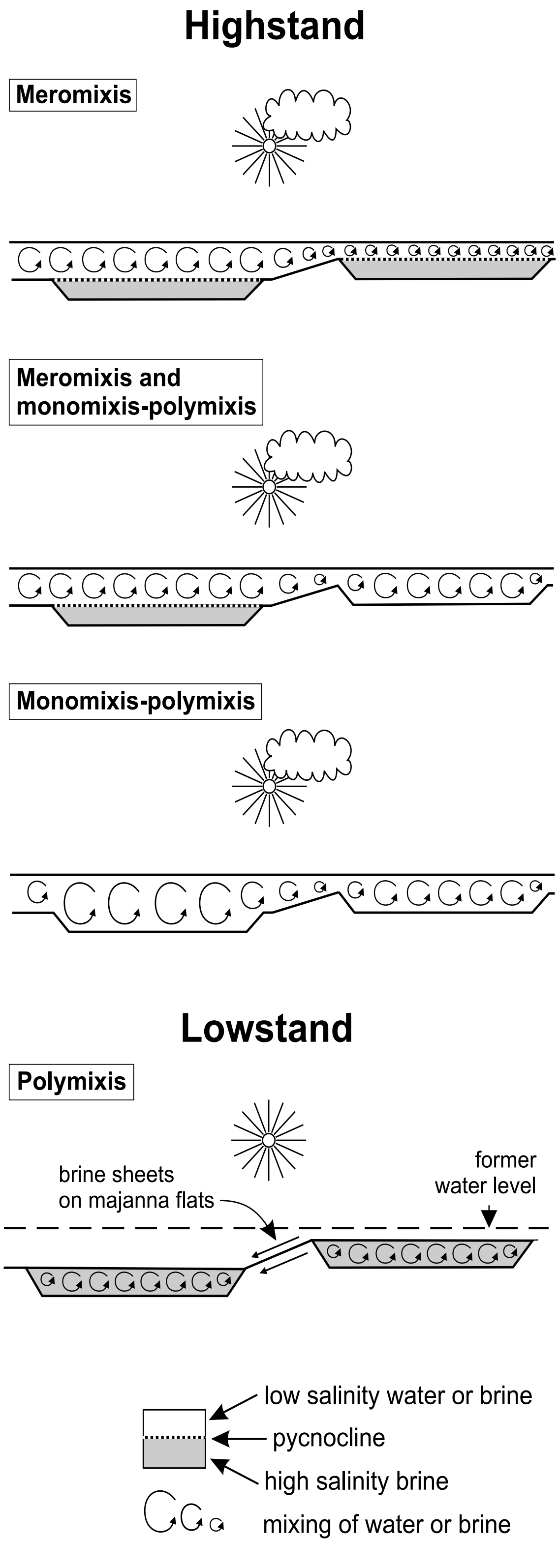

Fig. 3. Scheme showing hydrology of evaporite subbasins and saline pans during highstand and lowstand; detailed explanations in the text

complex when monomixis or polymixis occur in shallow subbasins and meromixis in deep subbasins (Text-fig. 3). When during long-term highstand the overall salinity is increasing, meromixis can pass into monomixis with associated evaporite deposition. Such deposition can be reflected by an onlapping pattern of evaporite facies on basin margins and on internal barriers and islands.

Lowstands are related to increased evaporation and/or decreased influx of marine and/or meteoric water. During lowstands large salina basins split into separate subbasins or small saline pans because of the uneven topography of the bottom (Text-fig. 3; as in the case of the recently drying out Aral Sea; ALADIN & *al.* 1998). The drying-out subbasins are separated by emerged or semi-emerged shoals, majanna flats or islands. When lowstand is prolonged the brines within each subbasin or saline pan can evolve in their own way, which leads to salinity differences and chemical and isotopic contrasts between adjacent basins (as documented in many shallowing salt lake systems; DARGAM 1995, FEDOROV & *al.* 1996, VALERO-GARCÉS & *al.* 1999).

The separated subbasins can show different water levels (Text-fig. 3). It is well known that water levels in adjacent lakes of different size and depth can fluctuate with different rates, and sometimes changes evolve in opposite directions (HUTCHINSON 1975, p. 248). For example the Great Salt Lake showed a 0.7-0.8 m difference in water level soon after it was divided by a dam (EUGSTER & HARDIE 1978b, GWYNN 1980). During drying out of the Aral Sea two subbasins formed and a dam was built to separate them in order to prevent water outflow from the northern, higher, Small Aral into the shrinking southern Great Aral basin (ALADIN & *al.* 1998). Inferred opposing water level changes in ancient salars in Bolivia led to water catchment and brine transport from high to low basins (RISACHER 1992, FORNARI & *al.* 2001). Similar processes can take place in a salina basin, particularly during lowstands or initial drawdown. During lowstand brine is drained into the deepest and lowest subbasins. Lowstands in a salina basin are thus periods of lateral brine transport between adjacent subbasins realised through rapid outflows, inflows, and slow seepage through barriers (Text-fig. 3). Except for more or less continuous seepage through the barriers the brine can flow constantly from one subbasin into the other as wind-driven migrating brine sheets or as brine streams in channels cut into barriers or the majanna flats (LOGAN 1987).

Catastrophic brine outflows can be recorded as an abrupt shallowing and/or emersion in one subbasin and flooding and water-level rise in the adjacent subbasin or saline pan. Such events can drastically change the hydrological structure and the brine chemistry in some subbasins. After catastrophic outflow of brines or complete drying out, the shallow subbasins can be transformed into sabkhas in a dry climate, or into brackish ephemeral lakes and mud flats in a wet climate. Evaporite deposition may cease because such a subbasin is cut off from any constant inflow of saline water carrying sufficient amounts of dissolved salts, like seawater or brine, from other subbasins. The following highstand can result in the return of the former saline pan environment, but sometimes the inflowing new brine can show a quite different chemical composition from that before. As a result of many repeated highstands and lowstands, multiple drying and flooding, salt dissolution and re-precipitation, higher salinity brine can be gradually transported by multiple mixing and outflows and can be accumulated in the lowermost subbasins or saline pans in a similar way as in the Qaidam salt lakes (DUAN & HU 2001). The lowermost subbasins are potential deposition sites of halite and K-Mg salts.

EVAPORITE GYPSUM SEDIMENTS

Gypsum is the first salt precipitated from a marine brine after calcium carbonate. Its crystallisation begins at a salinity of ca. 150‰, continues to ca. 320‰, and than ceases. Non-marine Ca sulphate-rich brines can show quite different salinity ranges for gypsum precipitation, as already exemplified by the Aral Sea. Phanerozoic seawaters permitted precipitation of evaporite salts according to Usiglio sequence and hence these waters were similar to recent seawater (HOLLAND 1984), although the contents of particular ions varied within some limits (HORITA & *al*. 2002). It seems that during initial gypsum crystallisation the brines in Phanerozoic salina basins, supplied mainly by seawaters, should not have differed very much from recent marine brine. This is particularly true for the Permian and Neogene salina basins because Permian and Neogene seawaters did not differ significantly from the recent seawater (HORITA & *al*. 2002).

Gypsum sediments deposited in a shallow salina basin are similar to those recognised in recent coastal salinas and in many other shallow water settings. A short list of characteristics of such deposits provides a background for further sedimentological modelling of salina basin environments.

Gypsum may precipitate in various portions of the brine bodies: (1) at the brine/air interface, (2) within the brine column, (3) directly on the floor of the evaporite basin, (4) in brine-soaked sediments or brine soaked organic mats as displacive crystals or pore-filling cements (SCHREIBER 1978, LOGAN 1987). Accumulations of such precipitated gypsum crystals can create several more or less distinct genetic groups of deposits: (1) subaqueous crystal cumulates, (2) subaqueous bottom precipitates, (3) intrasediment precipitates, and (4) clastic accumulations (see LOWENSTEIN 1982, LOGAN 1987, HANDFORD 1991, SMOOT & LOWENSTEIN 1991, KENDALL 1992). Recent and ancient gypsum evaporites are dominated by subaqueous bottom and intrasediment precipitates, and by clastic gypsum accumulations. In this paper, based on the average predominant crystal size, gypsum deposits are roughly subdivided into two main groups: fine-grained gypsum (crystals less than 2 mm) and selenite (crystals over 2 mm). Fine-grained gypsum is common in all evaporite environments. Coarse-crystalline gypsum crusts or selenites are typical and diagnostic of subaqueous deposition.

Fine-grained gypsum deposits

Fine-grained gypsum is common in shallow to semi-emerged evaporite environments such as ephemeral saline pans or evaporite shoals. On shoals this gypsum is precipitated from migratory brine sheets or, during emersions, as efflorescence in a capillary zone (LOGAN 1987). Fine-grained gypsum is crystallised from Ca sulphate-rich groundwater brines and forms pedogenic deposits (MAGEE 1991, AREF 2003a). Some fine-grained gypsum is produced by the destruction and redeposition of older gypsum rocks or sediments. It can form through settling and accumulation of tiny crystals precipitated at the brine/air interface or within the brine column. It is also a typical diagenetic product from the hydration of anhydrite.

In subaqueous shallow settings, fine-grained gypsum is commonly a microbialite deposit created during salinity rises by precipitation on the surface of, or within microbial mats, which are the locus of gypsum precipitation (see ROUCHY & MONTY 1981, 2000; BURNE & MOORE 1987; GERDES & *al*. 2000b). Crystallising gypsum can form a lamina which exactly reproduces the shape of a single mat (Pl. 1, Fig. 1). Periodic accretion of successive mats and gypsum laminae produces wavy laminated deposits known as mineralised (FULLER & PORTER 1969) or gypsified algal mats (ORTÍ & *al*. 1984; see also HARDIE & EUGSTER 1971; VAI & RICCI LUCCHI 1977; ROUCHY & MONTY 1981, 2000); or, more generally, as gypsum microbialites (see BURNE & MOORE 1987, BĄBEL 1999a, ROUCHY & MONTY 2000). Crystals growing within the mat destroy the original mat structure and create non-laminated gypsum microbialites displaying homogenous or micronodular structure (KRUMBEIN & COHEN 1977, ORTÍ & *al*. 1984).

Selenite deposits

Selenite deposits are represented by continuous coarse-crystalline crusts and beds or, less commonly, by isolated single or clustered gypsum crystals (Pl. 2, SCHREIBER 1978, DRONKERT 1985). Continuous selenite crusts form through direct crystallisation of gypsum on the whole sediment-brine interface in a way that is characteristic of crystal druses. Single selenite crusts and beds can be a few millimetres to several metres thick. Typically they are composed of vertically elongated crystals. Such a fabric is a product of competitive growth processes. The crystals grow syntaxially, in combination with seeding (nucleation) of new crystals on the surfaces of the pre-existing crystals. The fabric of the selenite crusts depends mostly on morphology, sizes and orientation of the component gypsum crystals. The crystals can be arranged in a palisade, radial, stellate, domal (Pl. 1, Fig. 2), or chaotic manner. Twinned crystals are very common.

Modern evaporite selenite crusts grow in shallow coastal salinas, saline lagoons, ephemeral and perennial saline lakes, and artificial salt pans (Tab. 2). Thin selenite crusts grow also on the surfaces of evaporite shoals from permanently flowing brine sheets (LOGAN 1987, pp. 23-24). Exceptionally, isolated, up to 0.5 m-large aggregates of gypsum crystals, which are not strictly related to an evaporite environment, were found in clays at the bottom of brine-filled depressions of the Ionian Sea at a depth of ca. 3.5 km (CORSELLI & AGHIB 1987).

Recent selenite crusts differ in some aspects from ancient selenites. Gypsum crystals in modern salinas are usually only mm and rarely cm in size. Ancient selenite crystals are commonly decimetres long, and may even attain several metres in length (BĄBEL 2002). Modern crusts show frequent dissolution surfaces and large intercrystalline pores. Ancient selenites are commonly massive and sometimes do not exhibit any dissolution features. The large size of the crystals corresponds to the scarcity of dissolution surfaces and to the great thickness of the selenite beds. The upright decimetre- to metre-sized crystals often form giant palisade structures that are unknown from recent deposits. Also, ancient selenite crystals display peculiar morphologies that are absent in recent settings (ORTÍ & SHEARMAN 1977, LO CICERO & CATALANO 1978, DRONKERT 1985, BĄBEL 1991, RODRÍGUEZ-ARANDA & *al*. 1995).

The distribution of selenites and associated fine-grained gypsum deposits in modern hypersaline environments is controlled by numerous interrelated factors. The most critical of these are discussed below.

Salinity and deposition of gypsum microbialites and selenites

Observations in marine saltworks showed that thick microbial mats and associated fine-grained gypsum microbialites occur in low salinity pans, and coarse crystals and coherent selenite crusts in pans of higher salinity (JAVOR 1983; ORTÍ & *al*. 1984; GEISLER-CUSSEY 1986, 1997). Although exceptions occur (REINECK & *al*. 1990), salinity-controlled distribution of gypsum microbialite and selenite deposits seems to be a general rule. In many recent evaporite environments, including the Bocana de Virrilá lagoon, Peru, the size of the gypsum crystals and the thickness of the selenite crusts increase more or less distinctly along a salinity gradient (BRANTLEY & *al*. 1984, Tab. 1; SHUMILIN & *al*. 2002, Tab. 1). Fine-grained gypsum is found invariably in lower salinity environments, and is particularly common in areas which experience salinity drops far below the level of gypsum saturation – ca. 150‰ for seawater (GUNATILAKA 1975, PERTHUISOT & JAUZEIN 1978, KUSHNIR 1981, DULAU 1983 in CORNÉE 1984, FRIEDMAN & *al*. 1985, TRICHET & *al*. 2001). In marine saltworks, gypsified laminated microbial mats occur commonly in salinities of around 150‰, non-laminated gypsum microbialites in salinities of around 200‰, and selenite crusts in salinities of 200-300‰, with the thickest crusts in salinities of between 250 and 300‰ (Text-fig. 4; ORTÍ & *al*. 1984; GEISLER-CUSSEY 1986, 1997). The way salinity controls the distribution of selenite and gypsum microbialite deposits is not clear. The occurrence of the thickest crusts coincides with the maximum thickness of the gypsum sediments produced in the successive pans (ORTÍ & *al*. 1984, fig. 2A). However, the difference in size of crystals present in selenite and gypsum microbialite pans is much higher (several cm to less than 1 mm) then the difference in sediment thickness between these pans (from 3:1 to 5:1; see ORTÍ & *al*. 1984, fig. 2A), which means that some other factors, not only the rate of 'gypsum production', control the distribution of selenite and gypsum microbialite deposits. GEISLER-CUSSEY (1986, pp. 89-90; 1997), and earlier FERSMAN (1919) and KRUMBEIN & COHEN (1977, fig. 7), suggested that the growth of gypsum crystals is frequently inhibited and suppressed by covers of cyanobacterial mats (microbial mats dominated by cyanobacteria) developing when new water is supplied to low-salinity pans. When cyanobacterial mats are thick, the oversaturated fluids have difficulties in reaching the growth surfaces of the gypsum crystals below the mats and the new gypsum crystals nucleate on the upper surface of the mats. The crystals grow up until the point where a salinity drop, caused by new water inflow, followed by new cyanobacterial mat development inhibits their growth, and the process repeats. In the higher-salinity pans 'cyanobacterial growth becomes less important' (GEISLER-CUSSEY (1997, p. 23; see also FRIEDMAN & *al*. 1985, pp. 235-236) and there the gypsum crystals can grow without interruption, i.e. syntaxially, attaining larger sizes and creating selenite crusts.

In saltwork pans cyanobacteria colonize the selenite crusts relatively slowly although cyanobacterial mats grow thicker on selenites than on other substrates (ROUX 1996). Sometimes cyanobacteria develop under or within the crusts, not on the selenite tops (OREN & *al*. 1995). In such cases syntaxial growth of selenites is expected during the periods of increased salinity and concentration, even in the low-salinity brine.

The distribution of microbial and cyanobacterial communities along a salinity gradient and the presumed decline of cyanobacterial growth in the high salinity zone is discussed below.

Cyanobacteria and salinity

Microbial communities in the solar saltwork pans apparently change along a salinity gradient and a similar pattern of changes is recorded in many geographically different sites (CORNÉE 1988, GIANI & *al*. 1989, GARCIA-PICHEL & *al*. 1999). In marine brine at salinities of up to 100‰ the biota are similar to coastal marine communities; at salinities of 100-150‰ microbial communities are dominated by cyanobacteria, green algae and diatoms; at 200-250‰ the communities are dominated by halophilic archeans, halophilic bacteria, the green alga *Dunaliella*, and the flagellates; and at salinities of over 300‰ they comprise only halophilic archeans, halophilic bacteria and *Dunaliella* (PEDRÓS-ALIÓ & *al*. 2000, SANDAA & *al*. 2003). The thickest and most cohesive cyanobacterial mats occur in salinities of 70-150‰, before the onset of gypsum precipitation (JAVOR 1983, THOMAS 1984).

Maximum salinity tolerance of cyanobacteria is ca. 350‰ (Text-fig. 4, GERDES & *al*. 1985, KNOLL & BAULD 1989) or even slightly higher (374‰ and 393.9‰ in the Wadi Natrum soda lakes; IMHOFF & *al*. 1979 in CORNÉE 1988). However, most cyanobacteria grow optimally under moderate salinities (KNOLL & BAULD 1989). Laboratory studies revealed that many cyanobacteria species (or morphospecies) do not survive salinities above 210-250‰ and those that survive display decreased growth rate (GIANI & *al*. 1989, tab. 2; GARCIA-PICHEL & *al*. 1998, fig. 3). In natural environments, a salinity limit for many cyanobacteria is also about 210-250‰ (EHRLICH & DOR 1985). Thus, despite the great halotolerance (350-394‰), at salinities higher than ca. 180-250‰ cyanobacteria do not dominate the natural microbial communities, and do not contribute to the thick microbial mats (Text-fig. 4; HAMMER & *al*. 1983; POST & *al*. 1983, p. 9).

GERDES & *al*. (2000b) claimed that distribution of cyanobacterial mats in nature correlates with complex interactions of several factors, rather than a single factor like salinity. For example, development of thick cyanobacterial mats in saltern pans is stimulated by moderate contents of nutrients in inflowing water (DAVIES 1978, 1980 in THOMAS 1984; ROUX 1996; JAVOR 2002, fig. 1). High contents of nutrients lead to eutrophication and limit the growth of benthic cyanobacteria because planktonic micro-organisms shade the bottom (GERDES & *al*. 2000b, JAVOR 2002). In natural environments cyanobacteria usually occupy some ecological niches within certain range of salinity outside their optimum range, as revealed by laboratory growth (KNOLL & BAULD 1989, fig. 2; NÜBEL & *al*. 2000).

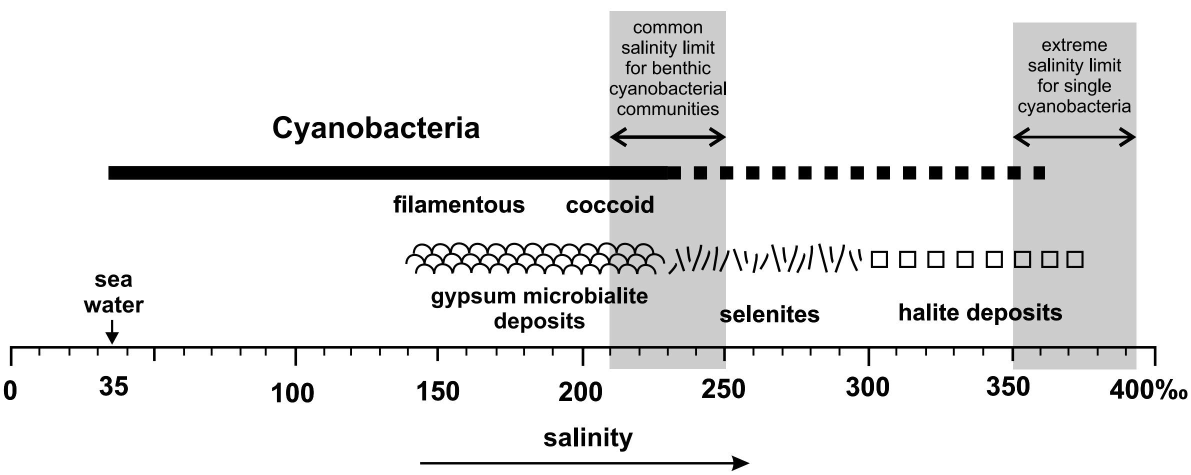

Fig. 4. Scheme showing distribution of evaporite facies and cyanobacteria along the salinity gradient; further explanations in the text

LOCALITY	GENERAL FEATURES	DEPTH AND SIZE	CHARACTERISTICS OF GYPSUM SEDIMENTS	SIZE OF GYPSUM CRYSTALS	RATE OF GYPSUM CRYSTAL GROWTH	REMARKS	REFERENCES
Saline lagoon: Bocana de Virrilá, Peru	Narrow and shallow marine lagoon which shows horizontal salinity gradient from seawater (35‰) to halite saturated brine (355‰); rare sheet floods occur in rainy years; surface water temperature is 23-27°C and rises with salinity	20 km long and up to 2 km wide, slightly below sea level, depth from 3 m at mouth to less than 15 cm at the inland end; divided by small shoals and islands	Near seaside: gypsum (mm-sized crystals) mixed with clastics, often dissolved by influxes of seawater. Close to halite precipitation area: up to 10 cm thick selenite crusts forming domes up to tens cm high.	3 cm in surface crusts; 2.5 cm in subfossil crust in halite area; mm-sized crystals dominate			MORRIS & DICKEY 1957, BRANTLEY & *al.* 1984
Small coastal salina: Solar Lake, Sinai, Egypt	Marine salina, which is monomictic, stratified and heliothermal during winter highstand, fully mixed during summer lowstand; epilimnion: 45-90‰, hypolimnion: 140-199‰ and up to 60°C; marine water seeping at depth 1.2-2.5 m through 60 m wide bar; very poor influx of meteoric water	140 m long, 60 m wide, maximum depth 5 m	Laminated gypsum-carbonate microbialite sediments on shoals and unordered aggregates of gypsum crystals growing within brine soaked organic sediments in deeper zones	Up to over 4 cm, but mm-sized crystals dominate	5-6 mm/5 years	Gypsum precipitates during summer lowstand and mixis	ECKSTEIN 1970; FRIEDMAN & *al.* 1973; KRUMBEIN & COHEN 1974, 1977; COHEN & *al.* 1977; KRUMBEIN & *al.* 1977; GAVISH 1980; GAVISH & *al.* 1985; ALI 1999
Large coastal salina: MacLeod, Australia	Complex marine salina basin; basin floor is mostly evaporite flat (wet and dry majanna), with two permanent (polymictic) and some ephemeral brine ponds; specific features of majanna flats are driven by winds and local gradients brine sheets (permanent and migratory); brine level and groudwater table level oscillate seasonally, seawater seeps through 3-15 km wide carbonate barrier and appears on seeping faces along the barrier base; rains and sheet floods are common in winter	80 km long, up to 45 km wide; basin floor 0-4.3 m below sea level, permanent brine ponds up to 1.5 m deep	Clastic gypsum (sand, gravel, pebble, to cobble-sized) dominating on majanna flats, 1-4 cm thick selenite crusts occurring in permanent brine ponds	Up to several cm, but sand -sized crystals dominate			LOGAN 1987
Gypsum pans in solar saltworks: marine coasts in warm climate zone	Controlled precipitation of salts from marine water follows the Usiglio sequence; seawater (35‰) passes through system of evaporation (polymictic) pans and attains halite saturation (over 300‰); gypsum precipitates in salinity ca. 140-325‰ and average temperature 35-40°C	Depth commonly less than 0.5 m	Fine-grained gypsum and gypsum microbialites in low salinity pans; a few mm to several cm thick selenite crusts with domal structures in high salinity pans	Mm-sized crystals in low salinity pans, up to several cm in selenite crusts from high salinity pans	Growth rate commonly 1-2 cm/year; maximum 4 cm/year	Gypsum precipitates during increased evaporation in summer	FERSMAN 1919; SCHREIBER & KINSMAN 1975; SCHREIBER & *al.* 1977; DULAU & TRAUTH 1982; ORTÍ & *al.* 1984; DRONKERT 1985; GEISLER -CUSSEY 1986, 1997

Tab. 2. Selected examples of recent environments of selenite deposition

The most common salinity limit (210-250‰) for many cyanobacteria and for thick cyanobacterial mats apparently coincides with the border between microbialite and selenite gypsum deposition recognised in saltworks (Text-fig. 4; ORTÍ & *al*. 1984; GEISLER-CUSSEY 1986, 1997), supporting the view that the presence of benthic cyanobacteria influences the type of gypsum sediments as described above.

Benthic microbial communities and growth of selenite crusts

The two main morphogroups of cyanobacteria are the filamentous and the coccoid. At lower salinities filamentous cyanobacteria dominate, at higher coccoid forms are common, although there are also exceptions (GERDES & *al*. 1985, GARCIA-PICHEL & *al*. 1998). At the upper range of salinity cyanobacterial mats are usually less densely colonized, embedded in soft slime and apparently less compact (GARCIA-PICHEL & *al*. 1999, p. 237). Coccoid cyanobacteria, like the most common morphospecies *Aphanothece halophytica* (GARCIA-PICHEL & *al*. 1998), produce large amounts of extracellular polymeric substances and form soft flocculose mats (EHRLICH & DOR 1985, OREN & *al*. 1995, ROUX 1996, JAVOR 2002) whereas filamentous cyanobacteria are responsible for the creation of very cohesive rubber-like laminated mats (THOMAS 1984). Filamentous cyanobacteria which normally dominate in less saline brine form thick cohesive mats that are weakly permeable to brine (LIU & *al*. 2002). Such mats can apparently isolate the gypsum crystals from the brine column above and stop their syntaxial growth (FERSMAN 1919), and the salinity increases lead to incrustation of cohesive mats by new gypsum crystal seeds. This effect is presumably weaker or absent in the case of more permeable mats composed of coccoid cyanobacteria or flocculous archeal-bacterial 'mats' not bound to the substrate (described below), which are both typical of higher salinities.

Living cyanobacteria, together with the diatoms in the uppermost part, create the external growth surface of microbial mats; bacteria and archeans live in the underlying mat (FENCHEL & *al*. 1998, SCHOPF 1999). In brines closer to halite saturation (300-320‰) the halophilic archeans and halobacteria predominate and create benthic communities devoid of a surface growth layer composed of cyanobacteria. The cohesion of such archeal-bacterial masses is created only by extracellular polymeric substances produced by the archeans and bacteria and is weak (PFLÜGER & GRESSE 1996). Because of the very weak cohesion such microbial communities cannot be called 'microbial mats' in a strict sense because a mat by definition should be 'cohesive' (BURNE & MOORE 1987). Such archeal-bacterial masses fit rather to the definition of biofilms (FENCHEL & *al*. 1998, pp. 142, 157; GERDES & *al*. 2000a; KRUMBEIN & *al*. 2003). These archeal-bacterial biofilms are flocculous, soft (REINECK & *al*. 1990), and sometimes even move together with currents (ROUX 1996). Brine can better penetrate such biofilms and easily sinks into the substrate below. An increase in salinity leads to syntaxial growth of the gypsum crystals covered with the archeal-bacterial communities and rarely induces the growth of gypsum crystals within them. Therefore selenite crusts predominate in the high-salinity areas.

The described regularities in the distribution of cyanobacteria, gypsum microbialites and selenites along a salinity gradient are not universal and numerous exceptions are possible. One is represented by ancient selenites containing horizontal internal lamination composed of dense cyanobacterial filaments that are remnants of benthic mats (VAI & RICCI LUCCHI 1977, ROUCHY & MONTY 1981). This specific facies appears to represent a low salinity zone (ROUCHY & MONTY 2000). It is important to emphasise that, because of the common deviations of ancient brines from the composition of recent seawater brine, the ancient environments could show salinity limits for the precipitation of gypsum and halite that are more or less different from those predicted for recent seawater (Text-fig. 4).

Depth of selenite deposition

GERDES & *al*. (2000b) suggested that the distribution of cyanobacterial mats in recent hypersaline environments is related to brine depth. They believed that in extremely shallow brines cyanobacterial mats occur in almost all salinities up to over 300‰, like in the Gavish Sabkha, but, in brines only a few decimetres deeper, the distribution of mats is limited to salinities of up to 140-160‰ (GERDES & *al*. 2000b, p. 199). However, cyanobacterial mats can exceed this 160‰ limit in some oligotrophic saline pans that are very poor in nutrients, like the 3.0 m deep Lake Hayward (BURKE & KNOTT 1997). The lack of cyanobacterial mats in deep brine favours the development of selenite crusts.

The lack of cyanobacterial mats in deeper saline pans can be attributed to the effect of the shading. In the deep, high-salinity pans archeal, bacterial, or *Dunaliella* phytoplankton blooms are very common (MARÍN & *al*. 1998), especially in nutrient-enriched eutrophic brines (GERDES & *al*. 2000b, JAVOR 2002). Pigments: mainly α-baterioruberin produced by halobacteria and β-carotene – by *Dunaliella salina* (and some bacteria) – stain the brine red

(MARÍN & *al*. 1998, OREN & RODRÍGUEZ-VALERA 2001) and shade the bottom. Such shading causes the death of benthic mats composed of phototropic cyanobacteria or drastically limits their growth (cf. CORNÉE & *al*. 1992, BURKE & KNOTT 1997). The dead mats can be detached from the selenite crusts and can float free in the brine, additionally shading the bottom (KRUMBEIN & *al*. 1977, JAVOR 2002). The uncovered selenite crystals can continue syntaxial growth in the deep brine.

Selenite growth is also controlled by microtopography. On the 0-20 cm deep margins of the saline pans gypsum precipitation and growth of selenite crusts are more intensive than in the brine below 20 cm (DULAU & TRAUTH 1982, ROUCHY 1982, ORTÍ & *al*. 1984). During solar evaporation salinity increases more rapidly on the semi-emerged shoals than in the deep parts of saline pans apparently because of the very slow downslope outflow of saline (denser) waters. The brine shows higher salinity, larger temperature fluctuations (which closely follow air temperature), higher oxygenation and pH (due to activity of cyanobacteria) towards the margin of the pans (CORNÉE & *al*. 1992). A horizontal salinity gradient exists even at night when deeper zones of the pan may show oxygen deficit (CORNÉE & *al*. 1992). All these factors, especially nocturnal temperature drop in the saturated fluids, larger on shoals than in deep brine, favour selenite growth on the shoals. Higher temperature accelerates evaporation on the semi-emerged shoals, which is a direct driving force for gypsum precipitation.

In recent evaporite environments selenite deposits are largely restricted to 0-5 m depth (cf. SCHREIBER 1978, p. 52; KENDALL 1984, p. 279; see Tab. 1, 2). A few well known subfossil records extend this depth to 10 m (WARREN 1982). The scarcity of modern analogues of large deep evaporite basins makes estimation of the possible depth for selenite deposition very controversial. There is certainly some depth limit for selenite growth due to difficulties in continuous gypsum precipitation in deep brine. Tens to hundreds of metres deep brines are commonly stratified and show deep and very stable pycnoclines. Stagnating bottom brines are oxygen deficient because the oxygen is utilized for decomposition of the dead plankton and other organic detritus. Lack of oxygen and consequently, lack of, or very low concentration of SO_4^{2-} restricts precipitation of gypsum (unlikely as halite) to shallow depths (NURMI & FRIEDMAN 1977).

It is believed that selenite growth occurred largely or exclusively in the photic zone, where oxygen is produced by cyanobacteria (SONNENFELD & *al*. 1976, 1977; SCHREIBER & *al*. 1982; SONNENFELD 1984, p. 177). However, photosynthesis is only one of several ways of water oxygenation (IVANOV & *al*. 2002b, HIGASHINO & *al*. 2004). A more effective way in saline basins is vertical mixing of superficial well oxygenated waters with bottom weakly oxygenated brines (Text-fig. 2). Polymictic pans are typically well oxygenated and the degree of oxygenation depends on the intensity of brine mixing and on the duration of mixing periods. Monomictic basins are commonly fully oxygenated during mixis, although they show an anoxic hypolimnion during stratification (HORNE & GOLDMAN 1994). The monimolimnion of the meromictic pans is commonly permanently anoxic and therefore gypsum precipitation in monimolimnetic brines is not possible. However, it appears that in shallow oligotrophic meromictic pans the depth of the oxygenated zone can be extended into the monimolimnion due to the presence of cyanobacteria (see BĄBEL 2004b in press, with references). Oxygenation of monomictic pans seems to depend on the volume relation of the more oxygenated epilimnetic waters to the more anoxic hypolimnetic brines as well as on the degree of anoxia and the trophic state of the waters. In Mono Lake, anoxia of the entire water column appeared during mixis after the breakdown of long-term meromixis (MILLER & *al*. 1993). Similarly, the polymictic and highly eutrophic Salton Sea remained weakly oxygenated during mixis (see WATTS & *al*. 2001). In both these lakes oxygen was consumed during mixis by oxidation of sulphide rising from anoxic bottom waters. It seems that deep monomictic pans with a high volume of anoxic sulphide-rich hypolimnetic brine will not be well oxygenated right to the bottom during mixis. Therefore, abundant continuous crystallisation of large gypsum crystals forming selenite crusts is unlikely at the bottom of very deep monomictic basins. An additional feature limiting oxygenation of deep dense brines is their elevated salinity, because solubility of oxygen is lower in high-salinity brine (see SONNENFELD 1984, pp. 176-178; SHERWOOD & *al*. 1991).

There is certainly some depth limit for selenite deposition, and it appears that the greater the brine depth (over 10 m) the more unlikely is selenite crystallisation. The deepest water selenites in the Badenian basin of the Carpathian Foredeep appear to be represented not by selenite crusts but by isolated selenite aggregates (BĄBEL 1999a, pl. 2, fig. 2) similar to those described by CORSELLI & AGHIB (1987) from the Ionian Sea.

Most authors investigating ancient selenites unanimously accepted that the thickest and the coarsest crystalline selenite crusts and beds are typical of a deep brine (VAI & RICCI LUCCHI 1977; SCHREIBER 1978; ROUCHY 1982, fig. 67; DRONKERT 1985; YOUSSEF 1988; ROBERTSON & *al*. 1995; ROSELL & *al*. 1998, fig. 5D; WARREN 1999; AREF 2003b). However, contrary to this common view, Holocene selenite crusts from Marion Lake in Australia, with crystals 45 cm long and 15 cm wide, were interpreted by HARDIE & EUGSTER (1971) and EUGSTER &

HARDIE (1978a) as being periodically emerged and dissolved by floods of meteoric water. WARREN (1982) believed that these crusts are exclusively subaqueous deposits. He suggested that they grew in deeper monomictic salinas because of the lack of traces of subaerial karst pits along dissolution surfaces (WARREN 1999, pp. 14, 44).

The formation of ancient giant-crystalline crusts lacking dissolution surfaces (see e.g. HARDIE & EUGSTER 1971, VAI & RICCI LUCCHI 1977, SHEARMAN & ORTÍ 1978, ROUCHY 1982, DRONKET 1985, ROBERTSON & *al*. 1995) requires permanent cover of Ca sulphate-saturated brine, and vertical space and time for undisturbed syntaxial crystal growth. It seems that such crusts grew at relatively greater depths necessary for the continuous upward growth of giant crystals, or the vertical accretion of the crusts kept pace with the rise of brine level. Such conditions are found below a pycnocline on the bottom of deeper density-stratified perennial saline pans (in a salina basin) during both meromixis and monomixis-polymixis. Models for such selenite-depositing pans will be reviewed later in the text.

MODELS FOR SELENITE AND GYPSUM MICROBIALITE DEPOSITION

Two simple models are suggested below for the deposition of selenite crusts. Both models concern marine Ca sulphate-rich brine obeying Usiglio sequence of salt precipitation. The models can be easily placed in and connected with formerly recognised environments of salina basin (Text-figs 1-3). Salinity and concentration (e.g. HOLSER 1979) are discussed in both models, and it is important to emphasise that it is a concentration increase, not a salinity increase, which is directly responsible for precipitation of a given evaporite salt.

Selenite shoal

The selenite shoal model is a modification of the gypsum-halite basin scheme by ORTÍ & *al*. (1984, fig. 24) and the 'selenite flat' reconstructed by EUGSTER & HARDIE (1978a, fig. 4).

The model assumes the existence of a large, shallow water to submerged, shoal flooded with gypsum-saturated brine. On this evaporite shoal, like in a saltwork, a thin brine sheet is unidirectionally transported from the low-salinity zone (marked A in Text-fig. 5, left) into the high-salinity zone (B) and further out of the system towards the halite saturation area. The low-salinity area is periodically supplied with brine of lower salinity yet not saturated with gypsum – showing a relatively low concentration of Ca^{2+} and SO_4^{2-} ions. After an influx of such waters there is a drop in both salinity and concentration of Ca sulphate, which stops gypsum precipitation in the low-salinity zone or even dissolves the pre-existing gypsum sediments there. The salinity drop favours the bloom of microbial mats in the low-salinity zone, especially mats dominated by filamentous cyanobacteria. The return of gypsum precipitation in the low-salinity zone requires time for evaporation and for the salinity and Ca sulphate concentration to increase. After reaching Ca sulphate saturation, crystallisation of gypsum begins on or within the microbial mats, leading to the deposition of gypsum microbialites. Then Ca sulphate-saturated brine flows into the higher salinity zone (B) and a new influx of the low salinity brine begins the process again.

The low salinity zone A is characterised by salinity fluctuations at the beginning of the gypsum saturation stage (around 150‰ for marine brine). The growth of gypsum crystals is periodically interrupted and is not syntaxial, because of the development of thick cyanobacterial mats covering the surfaces of the crystals during salinity decreases. The higher salinity zone B is supplied with brine which is already saturated with gypsum although this brine is of lower salinity than the host brine in zone B. The influx of new brine causes a salinity decrease in zone B but does not disturb the growth of the gypsum crystals there because both inflowing and in situ brines are saturated with Ca sulphate. Gypsum crystals are precipitated in zone B continuously and crystal growth is syntaxial. Thick cyanobacterial mats disturbing the gypsum crystal growth are absent in high-salinity brines close to halite saturation (300-320‰ for marine brine) as discussed above.

It is evident that crystal growth in the high salinity zone B is more continuous than in the low salinity zone A because the crystals stay longer in brine saturated with gypsum. When the crystal growth rate is the same in both zones, more gypsum is deposited in the high salinity zone because the brine in this zone is nearly constantly saturated with Ca sulphate. Thus, although both the zones are influenced by the same climatic factors (air humidity, temperature, wind) selenite crusts will form in the zone of higher salinity (B) and gypsified microbial mats in the zone of lower salinity (A). Fluctuations in the rate of flow, volume and salinity of waters entering zones A and B cause lateral migrations of the microbialite and selenite facies on the evaporite shoal, reflecting oscillations of the boundary between the two zones.

The model relates the size of the gypsum crystals and the thickness of the selenite crusts to the duration of their effective growth, which is directly connected with the duration of calcium sulphate oversaturation. This time is much longer in the higher salinity zone B than in the lower salinity zone A. The oversaturation and crystal growth are driven by evaporation. In the model, the crystal size and thickness of selenite crusts are thus not directly connected with the 'current' rate of gypsum growth observed during periods of oversaturation. This rate is, or can be, different in zones A and B even when driven by the same evaporation rate. The rate of gypsum crystal growth is dependent on many factors, such as stoichiometry which is also different in the two zones. In reality, gypsum precipitation in saturated or oversaturated solutions can also be driven by temperature changes or mixing processes.

Both zones A and B can experience the influx of meteoric (rain) water (Text-fig. 5, left). This water does not bring any substantial amounts of new salts into the system. Meteoric water stops gypsum deposition and often dissolves gypsum grains in the lower salinity zone A and produces dissolution surfaces in selenite crusts in the higher salinity zone B. Meteoric water from surface runoff is commonly enriched in nutrients washed from soils and these nutrients can enhance the development of microbial or cyanobacterial mats (DAVIES 1978, 1980 in THOMAS 1984; ROUX 1996; JAVOR 2002), contributing to the deposition of gypsum microbialites, also in the high-salinity zone B.

A recent analogue of selenite shoal model is the Bocana de Virrilá lagoon, where the periodic influxes of sea water are controlled by seasonal or day-night differences in evaporation rate or possibly also by extremely high tides (BRANTLEY & *al*. 1984). The other analogue is provided by the gently inclined majanna flats with permanently flowing marine brine sheets in the MacLeod salina (LOGAN 1987, pp. 23-24). These unidirectional brine sheets show horizontal salinity gradients and are able to precipitate both gypsum microbialites and selenite crusts. 'In permanent brine sheets, there is a zonal distribution of both brine precipitation fields and precipitate phases away from the source in a pattern determined by flow rates and configuration' (LOGAN 1987, p. 23). In both environments, the main driving force for water flow is hydraulic head produced by evaporation and evaporite drawdown, which are typical and essential features of a salina basin. Brine sheets driven by constant winds were undoubtedly very common on giant evaporite flats of ancient salina basins. In particular, brine sheets appeared on shoals and majanna flats separating subbasins during lowstands (Text-fig. 3).

Monomictic selenite pan

The model of a functional selenite pan introduced below grows out of ideas on evaporite deposition from stratified brine proposed by SLOSS (1969) and supplements some views on selenite deposition expressed by KENDALL & HARWOOD (1996), PETRICHENKO & *al*. (1997), WARREN (1999, pp. 14, 44), and KIRKLAND (2003). It corresponds to the popular two-box model of stratified lakes and is based strictly on current hydrological and evaporite deposition processes recognised in recent monomictic coastal salinas and saline lakes: Solar Lake (ECKSTEIN 1970), the Dead Sea (STEINHORN 1985; ANATI 1997, 1998), Lake Hayward (ROSEN & *al*. 1996; BURKE & KNOTT 1997), and Mono Lake (MELACK & JELLISON 1998).

The model assumes a semi-closed system of a seasonally-stratified monomictic or polymictic saline pan (Text-fig. 5). Occasionally, for a period of some years, a pan can be also in a meromictic state, as occurred recently in the Dead Sea (GERTMAN & *al*. 2003), but this state is considered insignificant for evaporite deposition. In the model, for simplicity, it is treated as prolonged equivalent of seasonal stratification. The model expresses only a general pattern of selenite deposition. The influence of thermocline and temperature changes on the hydrological cycle and the course of gypsum precipitation are not considered.

A pan is density-stratified only during the wet period or season when a pycnocline separates two water masses; a low-salinity upper mass (epilimnion or mixolimnion, marked A in Text-fig. 5, right) and a high-salinity lower mass (hypolimnion or monimolimnion, designated B in Text-fig. 5, right). These brine masses are very rough equivalents of the brines from microbialite and selenite depositional zones A and B in the selenite shoal model (Text-fig. 5, left). During a wet period, brine B is saturated, brine A is undersaturated in respect of Ca sulphate. Both these brines mix together and create a single homogeneous brine during the dry period.

Stratification begins in a wet season when large amounts of meteoric water together with low-salinity water are supplied to the pan, inflowing from other areas of the evaporite basin. The inflowing waters are not yet saturated with gypsum. These waters spread over the denser brines of the pan and partly mix with them (like in Lago Pueblo; SONNENFELD & *al*. 1977; or Solar Lake; COHEN & *al*. 1977, p. 601), so a seasonal pycnocline separating the brine masses A and B is created. The upper brine A is undersaturated with Ca sulphate. The low salinity of brine A enables a bloom of cyanobacterial mats in the marginal zone of the pan, but not on its bottom covered with high salinity brine B (for the reasons discussed earlier). The ensuing increased evaporation in the dry season leads to an increase in the salinity and density of the upper brine A. This, and associated physical processes (see references to general discussion of a monomictic pan given above), gradually destabilises the pycnocline, causing the brine masses to overturn, and causes seasonal complete mixing and homogenisation of the brine. The continuing evaporation soon leads to oversaturation in Ca sulphate within the brine body and results in gypsum precipitation in the whole pan. However, the pattern of precipitation is different on shoals above the former pycnocline than on the deep bottom below it. The bottom below the pycnocline is covered with high-salinity brine practically all the time, similar to zone B in the previous model (Text-fig. 5). Therefore, for the same reasons, gypsum precipitates will never be dissolved there and will rarely be covered with thick cyanobacterial mats. Thus, gypsum crystals created there during the previous dry periods can grow syntaxially, forming a selenite crust (similarly as in selenite shoal model).

The manner of gypsum precipitation on the shoals and along the margins of the pan is different but is similar to precipitation in the zone of low salinity A in the previous model (Text-fig. 5). During a dry period, the thick cyanobacterial mats developed along the marginal shoals of the pan will be encrusted with fine-grained gypsum crystals and will become gypsum microbialites. In a following wet period, an increased influx of meteoric water to the system again will cause the re-establishment of a pycnocline and a seasonal stratification. In this state, the bottom brine B will still be saturated with gypsum; however, lack of evaporation will slow (or inhibit?) the growth of this mineral there (like in the case of halite crystals growing recently at the bottom of the Dead Sea; NIEMI & *al*. 1997, HERUT & *al*. 1998). The upper water mass A will show lower salinity and will be undersaturated with gypsum. Lower salinity will again cause the development of cyanobacterial mats. During extremely wet periods, marked drops in salinity and gypsum concentration in the upper water mass A can promote gypsum dissolution in the most shallow marginal zone of the pan. Depending on environmental factors controlling fluctuations in the

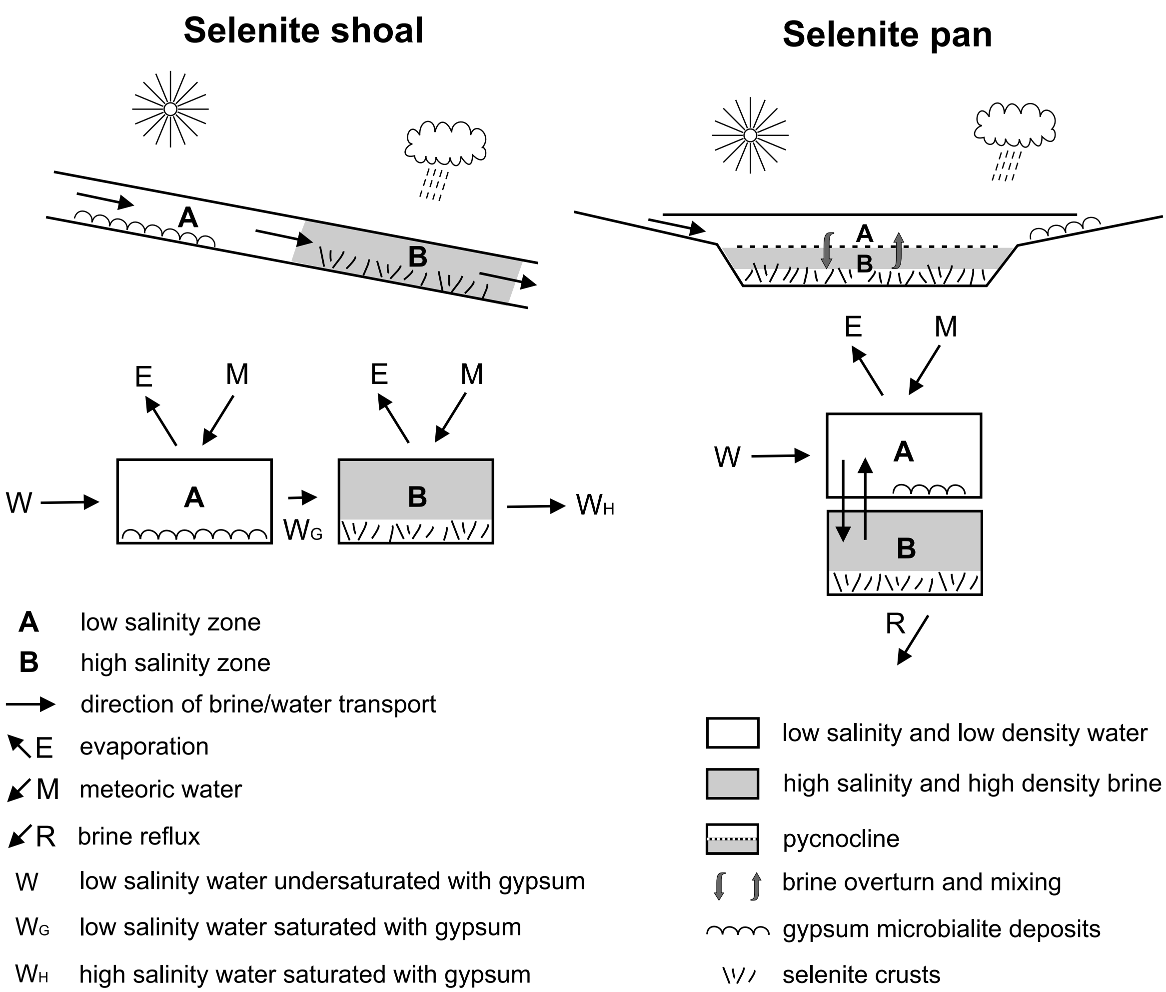

Fig. 5. Models of selenite deposition; further explanations in the text

water level in a saline pan and the level of the pycnocline, the boundaries between zones of dissolved gypsum, of gypsum microbialites, and of selenite crusts migrate along a saline pan slope, similarly as in the evaporite shoal model.

The two best analogues of selenite crystallisation in monomictic pans were indicated above: Solar Lake (KRUMBEIN & COHEN 1977) and Lake Hayward (ROSEN & *al*. 1996, BURKE & KNOTT 1997). Unfortunately, these pans do not contain selenite crusts but instead organic-carbonate-gypsum deposits with loose, very fine gypsum crystals. Both these pans are characterised by a relatively low salinity of the hypolimnion (maximum ca. 160-200‰) which is favourable for the growth of benthic cyanobacterial communities (see discussion of cyanobacteria-salinity relations above). Because of such a low salinity and the presence of cyanobacteria, the gypsum crystal growth at the bottom of these saline pans is highly restricted – they are suppressed by thick cyanobacterial mats (KRUMBEIN & *al*. 1977). The optimum pan model for the deposition of selenite crust from marine brine, should show a much higher salinity in the hypolimnion - the same as in selenite-depositing solar saltwork pans: 250-300‰ (ORTÍ & *al*. 1984). Such a salinity range can eliminate or depress benthic cyanobacterial communities and favour the development of selenite crusts (as discussed above). Alternatively, salinity can be low but some other factors could be involved in limiting benthic cyanobacteria development. One such factor is the shading effect in nutrient-rich eutrophic brine (see discussion above and remarks on the oligotrophic monomictic saline pan model in BĄBEL 2004b in press). Lago Pueblo in Venezuela is an interesting case of a meromictic saline pan where selenite and gypsum microbialite deposits were found only in the shallow photic zone at depths from 0.3 to ca. 1.5 m (Tab. 1; SONNENFELD & *al*. 1976, 1977; SONNENFELD & HUDEC 1978). The complete lack of gypsum within the monimolimnion at depths from 1.5 to 5 m clearly indicate that the monomictic state is necessary for selenite deposition in such deeper brines.

The presented selenite pan model is considered as fundamental for selenite deposition in a salina basin. It is developed below into several ancillary models.

Discussion of selenite shoal and pan models

The necessary condition for gypsum deposition in both the selenite pan and selenite shoal models is inflow of saline water, which is already close to the gypsum saturation level. It should not be normal marine water but brine produced from marine water by evaporitic concentration or any other Ca sulphate-rich water inflowing from interior areas of the evaporite basin. The system thus requires the existence of some evaporite shoals or intermediate saline pans for the evaporation of marine or other waters to the stage of gypsum saturation before these waters will inflow into a selenite pan or shoal.

In both models, deposition of gypsum microbialites and selenites is related to different salinities and the selenites crystallise in higher salinity brine. Selenite deposition in the evaporite shoal model is not dependent on depth, which is in agreement with observations from saltwork pans, where both gypsum microbialite and selenite deposits are found at the same depth - less than 0.5 m. In the saline pan model, selenite deposition is controlled by depth and is dependent on the position of a seasonal or periodic pycnocline. The first model is hydrologically open. It assumes an impermeable substrate which excludes brine escape by seepage. Brine passes through the shoal, leaving gypsum precipitates, and flows away before reaching halite saturation (Text-fig. 5, left). The second model is hydrologically semi-closed. The brine partly escapes from the system by seepage reflux (Text-fig. 5, right). However, unlike in the shoal model, some components not involved in gypsum precipitation, like Na^+, K^+, Mg^{2+}, Cl^-, and not fully used for this precipitation, like SO_4^{2-}, can accumulate in the brine body and can be utilized for future deposition of higher evaporite salts in the same pan. The semi-closed system evolves with time and the composition of brine changes. When the salinity of brine is rising, the system has a great potential for the precipitation of the next evaporite minerals following the Usiglio sequence – halite and K-Mg salts. This however depends strongly on the rate of seepage outflow (LOGAN 1987, KENDALL & HARWOOD 1996).

Selenite crusts in both models are expected to be different. The selenites on evaporite shoals show common dissolution surfaces, are thin and are intercalated with fine-grained pedogenic, microbialite and clastic gypsum (and other) deposits typical of evaporite shoals. Such crusts have very low preservation potential. Selenites from deep monomictic pans are separated from the direct influence of meteoric water and therefore they rarely show dissolution surfaces. Such selenites have greater preservation potential. The growth of selenite crusts on evaporite shoals take place under relatively stable conditions and persists for prolonged periods. The growth of deeper-water selenites is periodically interrupted and a prolonged period is necessary for reestablishment of oversaturation within the brine body.

The selenite growth in the monomictic pan is caused by evaporation of the epilimnion. This is just one of the four basic pathways of evaporite deposition from stratified brine considered by SLOSS (1969). The other way, suggested by SLOSS (1969) as the most effective, was connected with strong unidirectional wind action which led to inclination of a pycnocline and partial exposure of the hypolimnetic brine to atmosphere and to evaporation. However, such a state may be achieved only in sufficiently shallow and large pans and is relatively unstable (HUTCHINSON 1975, SONNENFELD 1984). In shallow pans, the continuous action of strong wind after exposure of the pycnocline soon leads to overturn and mixture of the water bodies. Such a condition corresponds strictly to a polymictic saline pan and thus to the previous fundamental way of selenite deposition. Exposure of the pycnocline by storm winds was not observed in the deeper basins like the Great Salt Lake, the Dead Sea and Mono Lake (Tab. 1), with pycnoclines at depths below 8 m (STEPHENS & GILLESPIE 1976, NIEMI & *al.* 1997, MACINTYRE & JELLISON 2001; see also SONNENFELD 1984, pp. 53-55).

Shallow versus deep selenite pans

Saline pans in a saline basin are divided into ephemeral and perennial (Text-fig. 2) and this division also applies to selenite pans (cf. LOWENSTEIN & HARDIE 1985). Ephemeral selenite pans pass through a repeated seasonal cycle: flooding → evaporitic concentration → desiccation. Flooding, drying, emersion and dissolution produce mainly fine-grained clastic varieties of gypsum. Selenite crusts of ephemeral pans are thin and show features of meteoric dissolution and reworking. They are well known from many recent and subfossil examples (ARAKEL 1980, BOWLER & TELLER 1986, MAGGE 1991).

Perennial selenite pans represent more stable, albeit very variable environments. In such pans, most traces of emersion, karst and pedogenesis are lacking; however, dissolution features are not uncommon. Two simple facies models of perennial shallow and deep selenite pans are introduced below. In the sedimentary record they can be distinguished mainly by lateral facies relations. The models presented here do not cover all the possible perennial gypsum pans.

It is not easy to find diagnostic sedimentary features of the ancient shallow and deep perennial selenite pans and to define unequivocally what is meant by shallow and deep. The depths of selenite pans in salina basins can vary remarkably over fairly short time intervals. Like in salt lakes the position of the pycnocline in such pans is supposedly more stable than the water level (LOWE & *al.* 1997). Therefore, the distinction between shallow and deep selenite pans is based below on the relationship between the seasonally fluctuating pycnocline and the bottom of the pan – not on the vertical distance of the seasonally fluctuating water level to the bottom.

Shallow-brine flat-bottom selenite pan

In this type of pan, selenite crust growth is controlled by seasonal pycnocline fluctuations which uncover the apices of growing gypsum crystals and expose them to the influence of low-salinity surface waters (Text-fig. 6). Because a pycnocline is horizontal, the top of the selenite crust is found throughout the pan at the same topographic level. The selenite crusts commonly display palisade-like, grass-like and domal structures, and are arranged into even, parallel layers. The tops of vertical selenite crystals are often rounded or flattened by dissolution. Extensive flat dissolution surfaces are common. They cross-cut selenite crusts and can disappear laterally due to the syntaxial growth of the gypsum crystals. Larger and longer falls in water level and/or pycnocline result in major horizontal dissolution surfaces commonly covered with fine-grained gypsum (often microbialitic and clastic). Selenite crusts pass laterally into ephemeral shoal facies represented by fine-grained (microbialitic, clastic or pedogenic) gypsum. On the other hand, selenite crusts do not pass laterally into any other facies showing deeper brine characteristic (as described below). Laterally continuous stacked palisade-like or grass-like selenite crusts with thin, laterally continuous, shallow-water fine-grained gypsum intercalations are typical facies in the sedimentary record. Small flat-topped selenite domes and gypsified cyanobacterial mats are common in this facies.

Deep-brine selenite pan

Deep pans display a large slope area and an uneven bottom (Text-fig. 6) with possible subordinate subbasins separated by underwater highs. Selenites grow on the entire morphologically differentiated bottom below the pycnocline. Therefore, unlike as in the shallow pans, the isochronous selenite crusts can occur at different topographic levels. Because of the greater depth, the range of possible pycnocline fluctuations is larger. A pycnocline is normally high above the bottom and its fluctuations do not reach the lowest areas of the bottom. Pycnocline fluctuations are reflected only on marginal slopes and subaqueous uplifts by the presence of dissolution surfaces. Selenite crystals with rounded tops occur in these areas. The selenites from the deepest areas of the pan do not display dissolution surfaces and are devoid of any flat layering. Because the syntaxial growth of these selenites is uninterrupted, the crystals attain large decimetre and metre sizes. Giant selenite domes can grew in such deep areas.

Within the zone defined by an average range of pycnocline fluctuations, there are slope or ridge facies determined by frequent and drastic environmental changes promoted by these fluctuations. Specific microbialite-selenite facies is deposited there (like in the upper slopes of Solar Lake; KRUMBEIN & *al*. 1977). Typical of such facies are gypsum microbialites with randomly scattered selenite clusters, described in more details in BĄBEL (2004a in press, 2004b in press). This facies can pass into a purely selenite facies composed of a network of horizontal and mutually intergrown crystals. In shallower zones, like in the shallow pans previously described, fine-grained (microbialitic, clastic or pedogenic) gypsum is deposited. Deep selenite pans often contain large volume of low-salinity or brackish water above a pycnocline and therefore the evaporite shoals around such pans are usually covered with thick living microbial (cyanobacterial) mats. Because of the dominance of fresher water, unlike those in the shallow pans, these mats rarely undergo gypsification. The shallowest marginal zones of deep pans are commonly devoid of any gypsum sediments because the inflowing surface meteoric waters completely dissolve earlier gypsum precipitates. Therefore, some deep selenite pans commonly lack the marginal gypsum microbialite belt.

The other prevalent facies of deep selenite pans are formed during long-term lowstand. During lowstand, the marginal fine-grained gypsum deposits and selenite crusts covering the slopes of the pan are exposed and subjected to karst dissolution and atmospheric weathering. This leads to the formation of the clastic selenite debris facies along a shoreline (like in Marion Lake; see references to selenite debris facies in BĄBEL 2004b in press). The facies of deep selenite pans are generally more differentiated than those of the shallow pans.

Stratigraphic record of the shallow-brine and deep-brine pans

The following simple model illustrates the hypothetical response of the shallow-brine and deep-brine selenite pans to water level fluctuations, which are expected to be

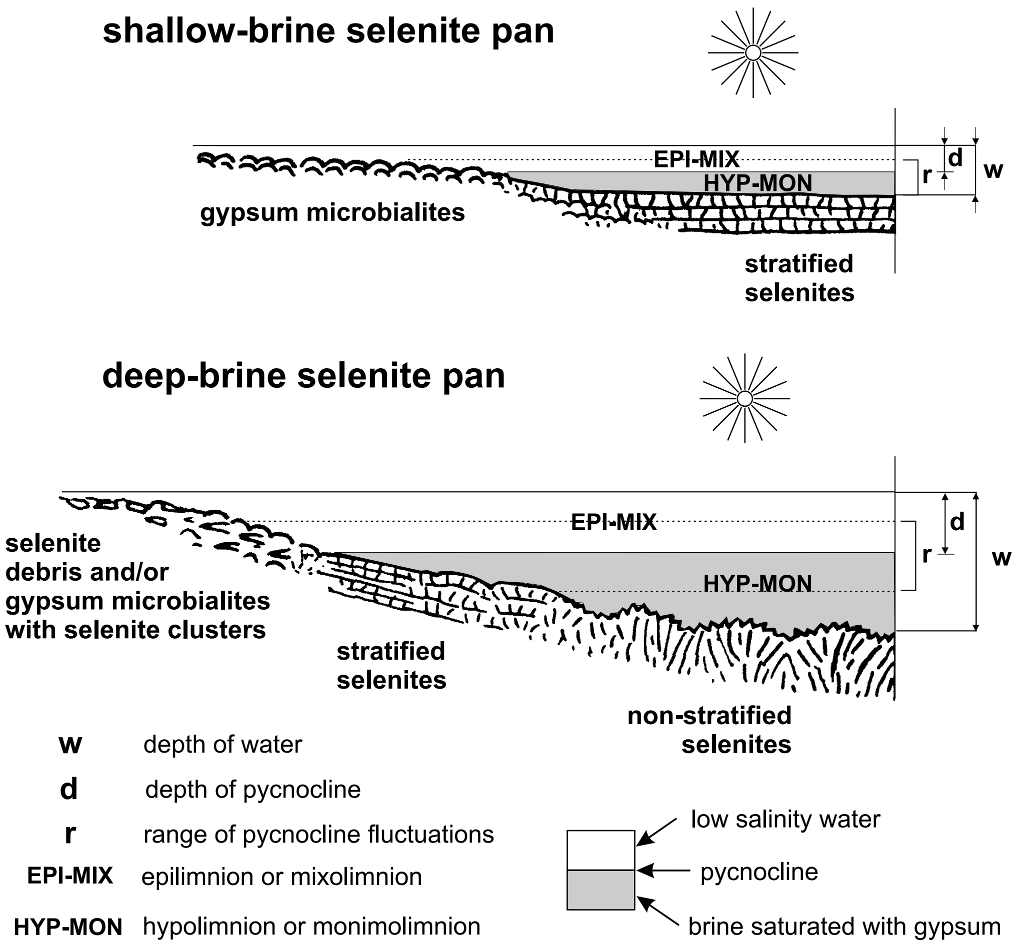

Fig. 6. Depositional models of shallow-brine and deep-brine selenite pans

rapid and frequent in a salina basin (Text-fig. 7). For simplicity, it is assumed that fluctuations of the water level are more frequent and rapid than fluctuations of the pycnocline (cf. LOWE & *al*. 1997) and any long-term trend of water level changes coincides with fluctuations of a pycnocline (as interpreted by VERSCHUREN 1999). The bottom of a saline pan above the pycnocline is characterised by multiple seasonal or periodic rises and falls of salinity

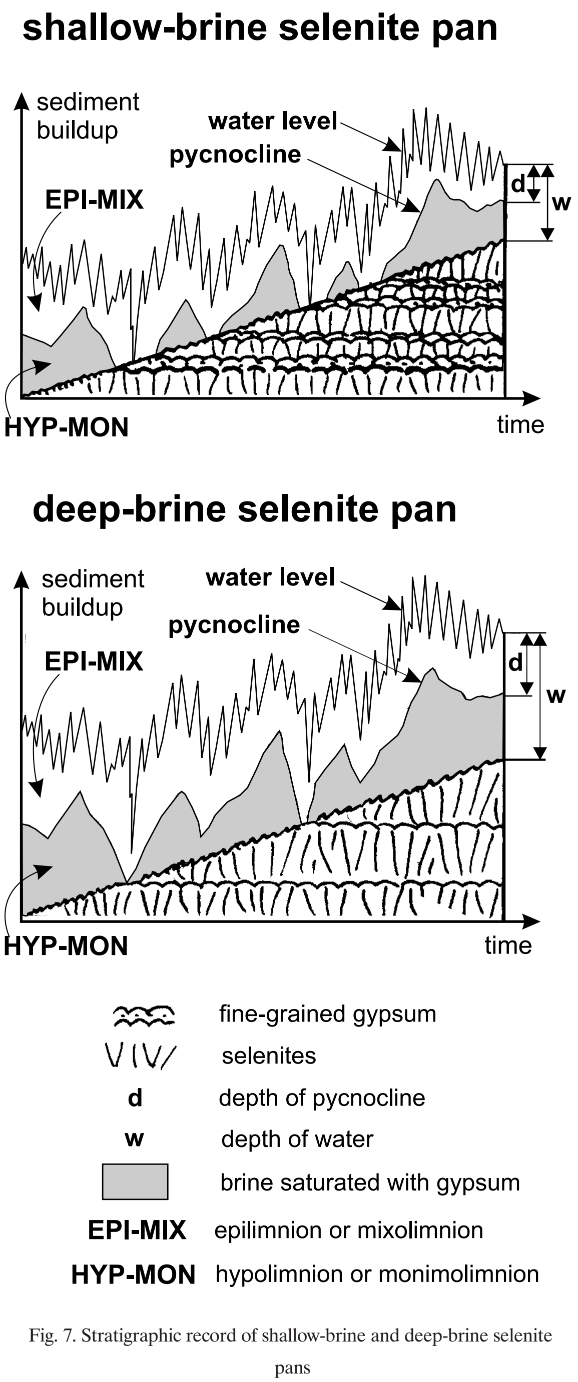

Fig. 7. Stratigraphic record of shallow-brine and deep-brine selenite pans

characteristic for epilimnion or mixolimnion. The bottom below the pycnocline remains within highly saline hypolimnetic or monimolimnetic brine and is not subjected to any drastic salinity fluctuations. The 'lowering' of a pycnocline means that the selenite deposits are exposed from the shelter of the brine and are in contact with the brackish or low-salinity upper waters. Such conditions are reflected by the dissolution surfaces and/or by fine-grained (microbialite) gypsum deposits. Total temporary emersions and increased action of water currents and waves in the fresh or low-salinity waters can produce a cover of pedogenic and clastic sediments. The most important difference in the sedimentary record of shallow and deep pans is that the deep brine selenites do not record small amplitude water-level changes although the growth zonation of crystals is more complete and devoid of significant time gaps (Text-fig. 7). The shallow pans are very sensitive to small-scale water-level changes but the continuous record is interrupted by dissolution surfaces and erosion.

Discussion of the shallow-brine and deep-brine models

The distinction between the shallow-brine and the deep-brine pan is subtle. The author avoids quantitative estimation of depth because it depends on very local conditions in a given area (climate, salinity). It is assumed that in the shallow-brine pan the inflow of the low-salinity or meteoric waters permits complete refreshment of the brine right to the bottom. This implies that the original brine volume should be small and the brine depth consequently shallow (KENDALL & HARWOOD 1996, p. 288). However, complete dilution also depends on the volume of inflowing waters, the salinity of the bottom brine, and the temperature of the brine and water, factors that make the precise determination of the critical brine depth for such a shallow-brine pan very difficult. It is further assumed that when the thickness of the bottom brine layer (defined as 'w' minus 'd' in Text-figs 6-7) exceeds some critical value, different for various given pans, brine salinity, temperature etc., such dilution will not be complete and a pycnocline remains over the bottom. Such a pan is defined as deep-brine. It is clear that under some circumstances the shallow-brine and deep-brine pans can show the same range of water depths. Nevertheless, the important difference between the two modelled pans is that the bottom of the shallow-brine pan experiences total emersions (water depth equals 0) from time to time, whereas the deepest areas of deep-brine pan are always covered with brine or water (Text-fig. 7), excluding some short-term (hours) exceptional emersions caused e.g. by the highest wind tides, and unrecorded in the selenite crusts.

The shallow-brine pans show thus some critical water depth. The highest limit of water depth for deep-brine selenite pans was not strictly estimated. However, it is believed that the optimum conditions for selenite growth are in monomictic pans several metres deep (commonly less than 5 m; for the reasons discussed earlier). Long-term continuous monomixis appear to be unlikely in very deep (hundred of metres) brine basins and if it occurs it requires some unusual conditions. Recent monomixis in the Dead Sea and Mono Lake is triggered only by rapid drying.

Meromictic selenite pan

Some ancient selenite facies do not fit the described models and are unrecorded from recent environments. One such facies is represented by the Badenian and Messinian selenite debris flow deposits appearing within some clastic gypsum sequences (VAI & RICCI LUCCHI 1977, ROUCHY 1982, ROBERTSON & *al.* 1995, BĄBEL 2004b in press). They require some other depositional models and one of the possibilities is the deep meromictic selenite pan model discussed below.

The model assumes the existence of a deep meromictic pan with relatively steep slopes. In this pan, selenite crystals are able to grow exclusively in the oxygenated mixolimnion zone and are redeposited from there into the deep anoxic meromictic zone by slumps or gravity flows. Such a meromictic selenite pan shows more complex brine stratification than previously analysed pans. The lowest constant pycnocline is acting as a 'virtual bottom' and the mixolimnion zone above is an equivalent of the monomictic to polymictic selenite pans previously described (see HUDEC & SONNENFELD 1980, LEWIS 1983, ANATI 1997). Because of the complicated stratification pattern, with multiple pycnoclines and thermoclines, such a meromictic pan is more difficult to model. More detailed studies of the ancient selenite debris flow facies and further theoretical calculations are required for complete preparation and justification of this model.

The meromictic heliothermal Lago Pueblo in Venezuela is the most suitable modern analogue of the discussed model (Tab. 1). In Lago Pueblo, thin selenite crusts are associated with gypsum microbialites and are accreted exclusively in the 0-1 m shallow mixolimnion zone. They were not found in the anoxic monimolimnion zone from depths below 1.5 m up to 4 m (SONNENFELD & *al*. 1976, 1977; SONNEFELD & HUDEC 1978; SONNENFELD 1984). Gypsum is not precipitating in the monimolimnetic brines, because of the scarcity of SO_4^{2-} anions (HUDEC & SONNENFELD 1980). Seasonal halite precipitation on shoals suggests possible large salinity fluctuations of the hot mixolimnetic brines. These conditions presumably favour the growth of large gypsum crystals (over 2 mm in size) in that shallow zone. Similarly, in the meromictic Dead Sea thin gypsum crusts were recorded only on shores and gypsum precipitation took place only in the 40 m deep surface zone corresponding to the mixolimnion (NEEV & EMERY 1967). These two examples clearly support the reality of the meromictic selenite pan model.

CONCLUSIONS

1. A drawdown basin (a salina) is one of the most suitable environments for subaqueous evaporite deposition, including deposition of the coarse-crystalline gypsum crusts or beds known as selenites.

2. A salina basin is a depression supplied with seawater by seepage and occasional surface inflows. A basin is not directly connected with the sea and technically is a saline lake (or group of interconnected saline pans) and therefore its hydrology and subaqueous environments can be characterised by limnological terminology.

3. Seasonal fluctuations of groundwater tables and brine levels in saline pans, displaying lowstand in the dry seasons and highstand in the wet seasons of the year (within a span of a few tens of decimetres), are one of the most important hydrological features of a salina basin.

4. A salina basin environment can be divided into: (i) seasonally and periodically emerged and semi-emerged areas - represented by ephemeral saline pans and evaporite shoals, and (ii) permanently subaqueous areas - represented by perennial saline pans.

5. Perennial saline pans can show three basic hydrological states crucial for subaqueous evaporite deposition: (i) meromixis – with a permanent pycnocline, (ii) monomixis to polymixis – with a seasonal or periodic pycnocline, and (iii) polymixis - without a constant pycnocline. The shallowest pans (less than ca. 1-3 m deep) are always polymictic because they are easily mixed right to the bottom by atmospheric forces.

6. Monomictic saline pans (exemplified by the recent Solar Lake salina, Egypt), showing stratification in the wet period (during seasonal highstand) and mixis in the dry period of the year (during seasonal lowstand), are the most significant for subaqueous evaporite and selenite deposition. Evaporite deposition takes place mainly during mixis periods coinciding with dry seasons and increased evaporation.

7. Gypsum microbialites constitute an important facies associated with selenites and are useful in the sedimentary analysis of selenite depositional environments. The distribution of selenites and gypsum microbialites is dependent on many complicated interrelated factors, but

commonly is controlled by salinity gradients (lower salinity is typical of gypsum microbialites) and depth (coarse-crystalline selenites are found in brine a few decimetres to several m deep; fine-crystalline selenite crusts and gypsum microbialites are common in very shallow brine).

8. Deposition of large selenite crystals (attaining decimetre-metre size) can take place below a pycnocline in the hypolimnion zone of shallow monomictic (and polymictic) pans. This zone is permanently filled with brine both during stratification and mixis and therefore selenite crystals are sheltered from dissolution and erosion by currents of less saline epilimnetic waters and can continue syntaxial growth during successive periods of mixis. The mm-scale growth zonation in such selenite crystals can reflect successive periods of mixis, most probably annual mixis periods typical of monomictic pans. Gypsum microbialite deposition is expected to occur on shoals in the epilimnion zone.

9. Shallow-brine and deep-brine selenite monomictic-polymictic pans can be distinguished from each other on the basis of the relationship (an average distance) of the seasonally fluctuating pycnocline to the bottom of the pan. In the shallow-brine pans, the bottom often experiences salinity drops and is sometimes emerged, while the bottom of the deep-brine pans is always covered with brine or water and is never emerged. Both types of selenite pans show slightly different gypsum facies. The most important difference is the presence of numerous dissolution surfaces and horizontal intercalations of clastic and microbialite gypsum in selenite crusts in the shallow-brine pans. Giant-crystalline selenite deposits lacking dissolution surfaces are typical of deep-brine pans.

10. Selenite deposition can take place in some deep meromictic pans but only in the shallow mixolimnion zone; evaporite precipitation within the monimolimnion is difficult or not possible because it is permanently separated from the atmosphere and anoxic. The mixolimnion of such pans can be considered as equivalent of the monomictic-polymictic pans (formerly described) resting on the 'virtual bottom' formed by a stable permanent pycnocline over the monimolimnion.

FINAL REMARKS

The evaporite and selenite depositional models introduced in this paper can be used for the interpretation of ancient evaporite and selenite basins. These models have already been applied to the Badenian evaporites, enabling an explanation of the architecture and stratigraphy of gypsum deposits in the Carpathian Foredeep (BĄBEL 2004 in press, 2004a in press, 2004b in press). The similarity of the Badenian gypsum deposits to the many well preserved and diagenetically unaltered Neogene evaporites (e.g. ROUCHY 1982, YOUSSEF 1988) clearly indicates that these models can also be applied to them. For example, the shallow-brine perennial selenite pan model can be used for the grass-like and thin-layered varieties of selenite facies present in many basins. The deep-brine pan model can be applied to thick- or non-layered selenite facies (HARDIE & EUGSTER 1971, ORTÍ & SHEARMAN 1977, VAI & RICCI LUCCHI 1977, SCHREIBER 1978, DRONKERT 1985, ROBERTSON & *al*. 1995, ROSELL & *al*. 1998, AREF 2003b). The depositional models are prepared for a salina type basin but to some extent they can be also applied to the other type of evaporite basins like saline lagoons and continental salt lakes.

The presented models are simple and only qualitative; however, they should enable a better understanding of the complex processes operating in evaporite basins and consequently provide a basis for quantitative models of selenite deposition.

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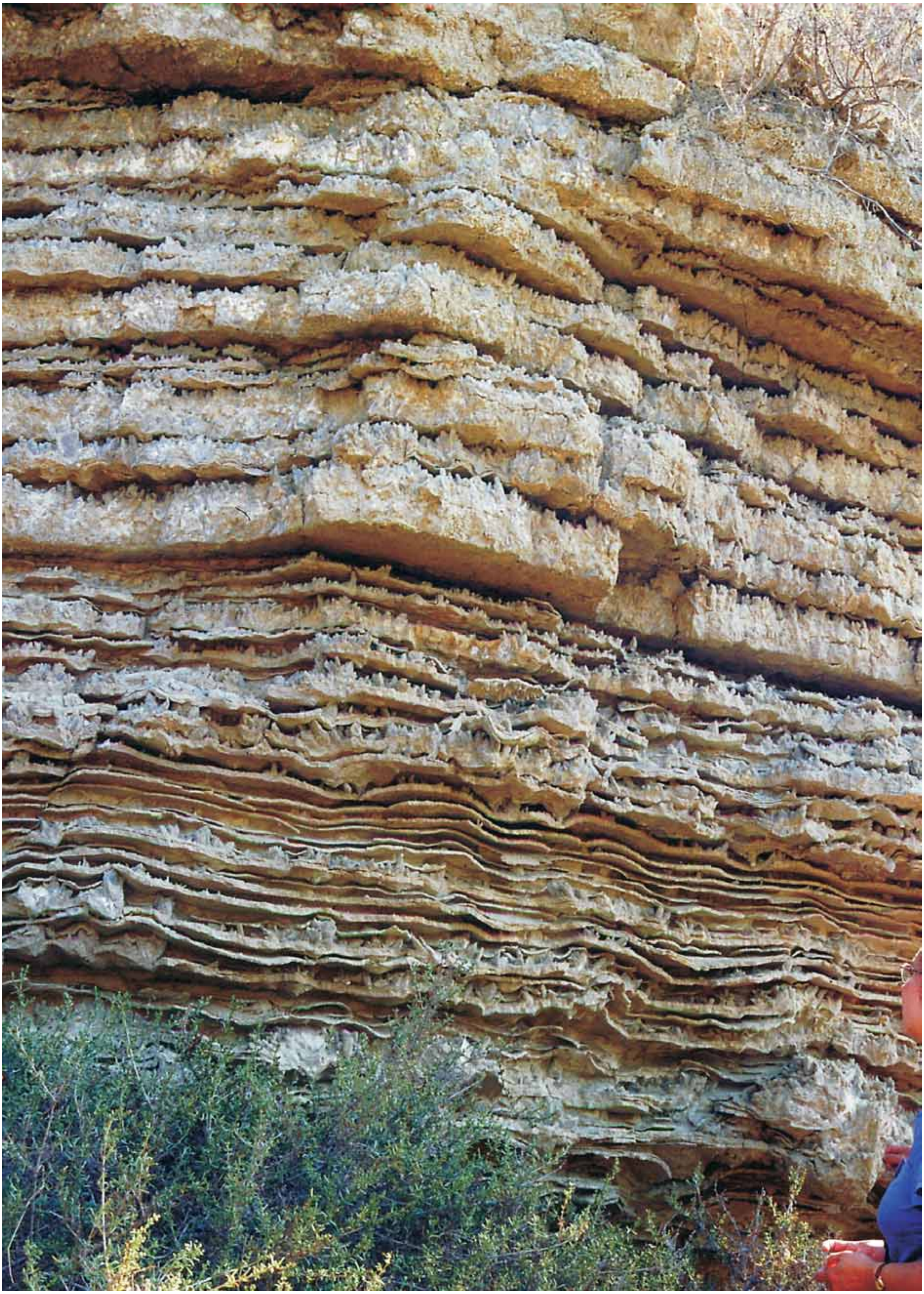
1

Single gypsified (incrusted with gypsum) cyanobacterial mat. Coastal saline lagoon near Ras Gemsa, Egypt, Red Sea

2

Selenite domes in solar saltwork pan. Salinas of Cabo de Gata, Spain



Grass-like selenite crusts. Messinian, Eraclea Minoa, Sicily