Precambrian Research, 37 (1987) 305-321
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

PROTEROZOIC COASTAL SABKHA HALITE PANS: AN EXAMPLE FROM THE PRANHITA-GODAVARI VALLEY, SOUTH INDIA

ASRU K. CHAUDHURI and SOUMEN SARKAR

Geological Studies Unit, Indian Statistical Institute, 203 Barrackpore Trunk Road, Calcutta - 700 035 (India)

S.K. CHANDA

Department of Geological Sciences, Jadavpur University, Calcutta - 700 032 (India)

(Received November 18, 1986; revision accepted June 30, 1987)

Abstract

Chaudhuri, A.K., Sarkar, S. and Chanda, S.K., 1987. Proterozoic coastal sabkha halite pans: an example from the Pranhita-Godavari valley, South India. Precambrian Res., 37: 305-321.

Extensive occurrences of pseudomorphs and casts of halite in association with wave-formed shallow water structures and evidence of emergence in quartzarenites at the base of the middle Proterozoic Pakhal Group (c. 1276 ± 20 Ma) in South India point to the development of sabkha environments in arid to semi-arid elimatic conditions. Periodic inundation of the sabkha during storm and subsequent desiccation led to displacive growth of the halite and its dissolution within the sediment just below the surface. The brine pools within the sabkha seem to have developed in fault controlled topographic depressions formed at the embryonic stage of an intra-continental rift ocean or graben system.

Introduction

There are few examples of Proterozoic evaporites in the rock record, and most of the occurrences have been interpreted either as shallow water, coastal sabkha deposits (Badham and Stanworth, 1977; Walker et al., 1977) or as shallow barred basin deposits (Stewart, 1979; Rowlands et al., 1980). Recognition of the depositional environments of most of these occurrences has been generally based on the remarkable resemblance of the evaporite sequences to Recent sediments, particularly those of the Trucial coast, rather than on the detailed facies analysis of the deposits themselves. Integrated analysis of facies together with comparison of the evaporite morphology and the sequence of evaporites with those from different Recent evaporitic settings are, however, essential to understand the origin of the evaporites and their depositional framework. This is perhaps more true for the Proterozoic evaporites, where a palaeontological control is missing.

Our recent field work led to the discovery of a widespread occurrence of halite pseudomorphs and casts at the base of a thick, middle Proterozoic sedimentary prism in South India, the Pakhal Group (c. 1276 ± 20 Ma, N.J. Snelling, personal communication, 1969) of the Pranhita-Godavari Valley. This occurrence is the oldest known evaporite-bearing sequence in the Indian craton that abounds with extensive Proterozoic sedimentary rocks. The present study aims at analysing the occurrence with the following objectives: (1) evaluation of the origin of the halite pseudomorphs; (2) interpretation of the depositional framework of the pseudomorphs bearing sequence; (3) construction of a generalised model for such Proterozoic occurrences; and (4) an appraisal of the tectonic implications of the occurrence.

Geologic framework and distribution of halite

Middle to late proterozoic sedimentary deposits of the Pranhita-Godavari Valley consist primarily of unmetamorphed shallow marine and fluvial sediments, and are believed to have accumulated in an embayment opening towards the southeast (Chaudhuri, 1970b). This embayment has been interpreted as an aulacogen within the Indian craton (Sen, 1982). The sequence unconformably overlies the Archaean Basement Complex in two NW–SE trending outcrop belts (Fig. 1) and has been classified into several groups and subgroups, each separated from the adjoining one by regional unconformities (Table I). The lowest of these major divisions is the carbonate-dominated shallow marine Pakhal Group (c. 1276 ± 20 Ma), characterised by widespread development of halite pseudomorphs in its basal unit.

The Jonalarasi Bodu Formation, the lowest unit of the Pakhal Group, consists of interbedded sandstone and limestone. The formation is gradationally followed upward by the stromatolitic Pandikunta Limestone (Table II) which in places overlaps the former and directly overlies the Basement (Fig. 2).

Broadly speaking, these two formations which comprise interbedded limestone and sandstone are more or less similar. Algal laminites occur in the lower few metres of both Pandikunta Limestone and Jonalarasi Bodu Formation. The two formations, however, differ from each other in terms of the composition of their siliciclastic components. Whereas quartzarenite is the dominant siliciclastic constituent in the Jonalarasi Bodu Formation, sandstone interbeds in the Pandikunta Limestone are arkosic in composition. The boundary between these two formations is arbitrarily defined at the top of the highest quartzarenite.

The feldspar in the arkoses of the Pandikunta Limestone have undergone extensive early diagenetic glauconitization. K–Ar dating of these glauconites gives an age of 1276 ± 20 Ma. The sample dated was collected from ~245 m above the top of the Jonalarasi Bodu Formation and as such sedimentation must have begun substantially earlier than the measured age.

Jonalarasi Bodu Formation and occurrence of halite

The Jonalarasi Bodu Formation is typically developed around Ramgundam (18°45′N, 79°26′E) and was studied mainly in the sections at the base of two hills, Jonalarasi Bodu and Damla Gutta, and in a small outlier ~0.5 km north of Damla Gutta (Fig. 2).

The stratigraphy of the formation is highly variable and is characterised by distinctive, localised facies assemblages consisting of a complex mosaic of mass-flow deposits, lagoonal, fluvial, siliciclastic and mixed siliciclastic–carbonate tidal flat facies. Sharp lateral passage of one facies to another accompanied by abrupt thickness variation across the faults (Fig. 3) is the hallmark of these deposits. Most of the faults affect only the basement and the basal part of the sedimentaries and strongly suggest that the facies collage were controlled to a large extent by the morphology of the precursor sub-basins of the rifted continental margins in the embryonic phase of the basin (Chaudhuri and Chanda, in preparation).

In the Jonalarasi Bodu section, the forma-

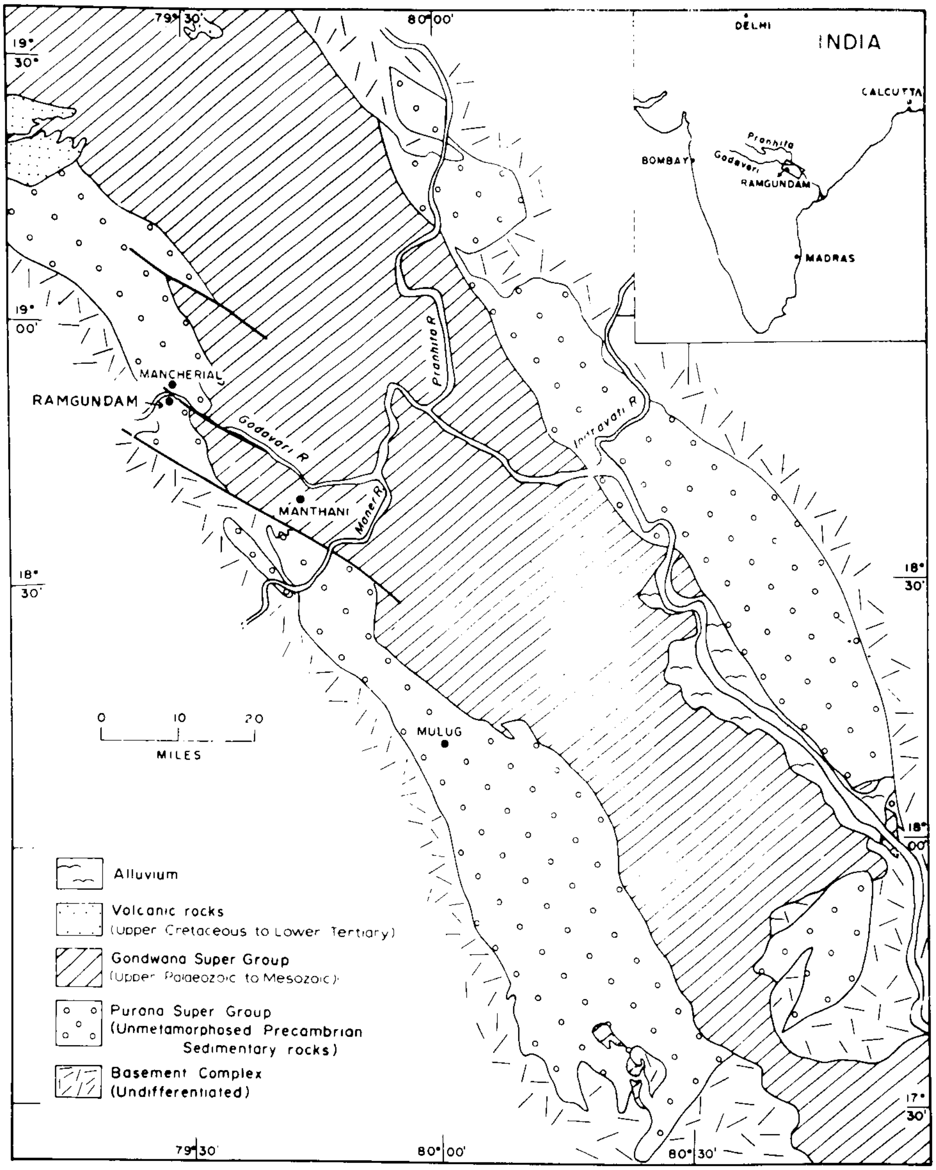

Fig. 1. Geological map of a part of the Pranhita-Godavari Valley. Inset map shows location of Ramgundam.

tion consists of two distinct facies associations: an assemblage of mixed carbonate–siliciclastic sediment gravity flow deposits followed upward by an assemblage of mixed carbonate–siliciclastic tidal facies with an intervening carbonate sediment gravity flow facies (Fig. 3). The tidal facies assemblage consists of a number of superposed shoaling-upward sequences. Each complete shoaling-upward sequence starts with a trough cross-bedded quartzarenite followed upwards by a wave-rippled quartzarenite (Fig. 4) and terminates in an algal laminite interval (Fig. 5). The relative degree of exposure and algal laminites indicate gradual progression of each shoaling-upward sequence from subtidal to supratidal through intertidal depositional regimes. In the Damla Gutta section and in the outlier, cyclic shoaling-upward sequences are absent and the facies association is represented primarily by wave-rippled and/or plane-bedded

TABLE I

Lithostratigraphic succession of the Purana Supergroup around Ramgundam (Chaudhuri, 1985)

Gondwana Supergroup			
Purana Supergroup	Sullavai Group		
	Pakhal Group	Mulug Subgroup	Rajaram Limestone
			Ramgundam Sandstone
			Damla Gutta Conglomerate
		Mallampalli Subgroup	Pandikunta Formation (c. 1276±20 Ma)
			Jonalarasi Bodu Formation
Archaean (?) Basement Complex			

quartzarenite alternating with algal laminites or massive sandy limestone (Fig. 3), directly overlying the basement. Sediment gravity flow deposits are conspicuous by their absence in this section.

The trough cross-bedded facies of shoaling-upward sequences often exhibit well-preserved simple and compound dune bedforms, the dune foresets are commonly wave-rippled near their toes, and the facies is intimately interbedded, in places, with eroded remnants of oolitic limestone. Many beds in wave-rippled facies are just ripple-thick and wavy in nature (Fig. 4), whereas others are thicker and are characterised by planar lower surfaces and rippled upper surfaces. Successive rippled beds are often interleaved with very fine-grained sandstone or muddy siltstone devoid of any wave-generated structure. The ripples are generally symmetrical with smooth rounded crests (Fig. 4). Sharp-crested (Fig. 6), flat-topped and interference ripples, however, are also quite common. Desiccation cracks though not very profuse, are encountered in a number of beds.

Sandstones in the Jonalarasi Bodu Formation, though mostly quartzarenites, are considered to have developed as first cycle air-blown detritus. These sands were derived presumably from extensive unvegetated coastal dune fields and were ultimately mixed with the water-laid sands at the depositional site (Chaudhuri, 1977).

Mode of occurrence of halite

Pseudomorphs of halite are extensively developed in the wave-rippled facies of both the Jonalarasi Bodu and Damla Gutta associations. They also occur, of course less frequently, in the cross-bedded as well as plane-bedded (Fig. 7) facies. The pseudomorphs, however, are conspicuously absent in the calcareous facies, both in the sediment gravity flow deposits and algal laminites, formed in the deepest and the

TABLE II

Regional stratigraphy and distribution of halite in the Pakhal Group. H. halite pseudomorphs

	Formation with maximum thickness (m)	Main lithologies	Halite pseudomorphs
Mulug Subgroup	Rajaram Limestone (735 m)	Thin to medium bedded stromatolitic dolomite and limestone Intraclastic limestone Calcareous shale Calcareous sandstone with lenses of sandy limestone	
	Ramagundam Sandstone (120 m)	Arkosic and subarkosic sandstone with interbedded shale	
	Damla Gutta Conglomerate (90 m)	Conglomerate and pebbly arkose Coarse arkosic sandstone Chert-pebble conglomerate	
	................................Unconformity................................		
Mallampalli Subgroup	Pandikunta Limestone (340 m)	Thin bedded and stromatolitic limestone and dolomite; coarse to medium grained calcareous arkose to arkosic limestone Glauconitic arkose (K-Ar dates)	
	Jonalarasi Bodu Formation (50 m)	Interbedded quartzarenite and limestone/dolomite Medium to coarse grained arkose Matrix (calcareous) supported conglomerate	H

shallowest environments, respectively.

The pseudomorphs and the casts have a characteristic cubic form (Figs. 8 and 9), though a few tend to be rectangular or polygonal in shape. Most of the cubes are internally structureless, but a few show well developed, slightly indented hopper structures (Fig. 9). Some cubes have overgrown faces around a core, with streaks of fine silt intervening between the core and the overgrown faces (Fig. 9). Cubic shapes are best developed where the pseudomorphs float in the host sediments (Figs. 8 and 9). The cubic habit, however, often gets obscured owing to overcrowding of the crystals (Fig. 9). The pseudomorphs may be as large as 15 mm, but 4–8 mm is the most common size range. Besides the well-developed cubes, subhedral to anhedral grains of 1–2 mm size range are quite common.

Pseudomorphs may occur within sandstone beds but are generally found concentrated along bedding planes. They occur both on the upper and the lower surfaces of the beds, rippled or plane (Figs. 6 and 9), and are best developed

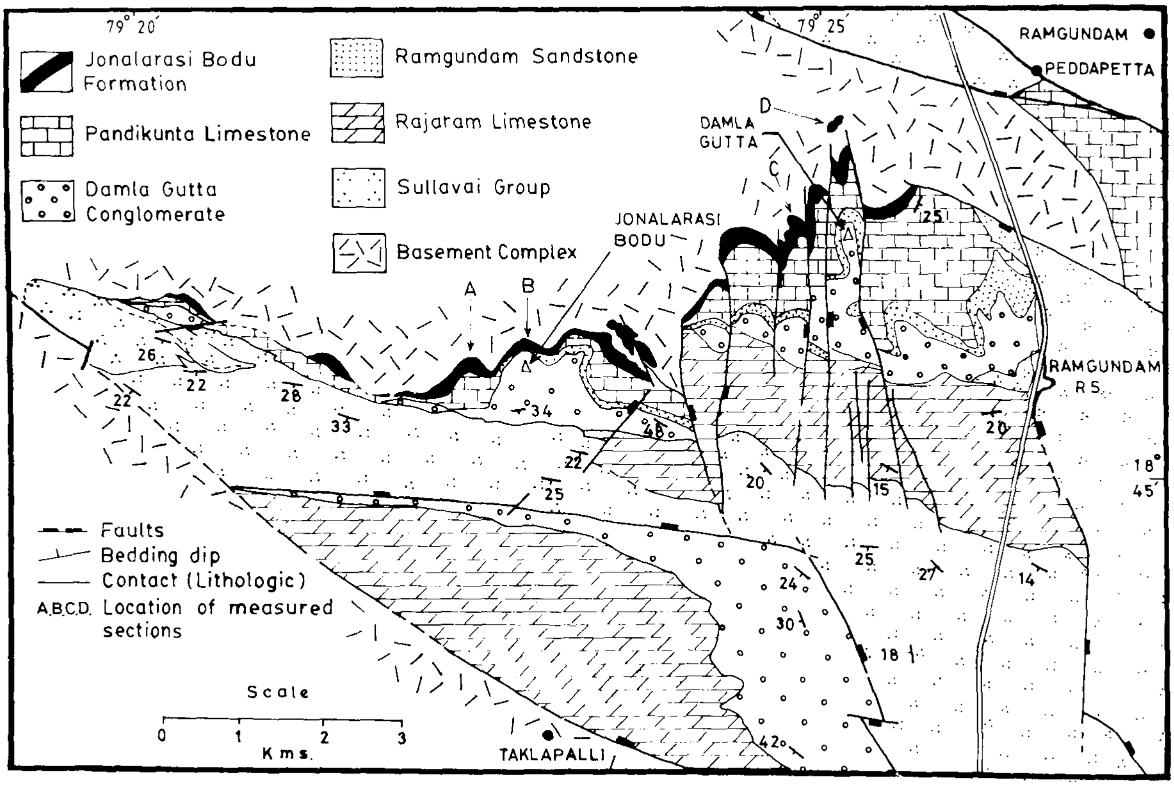

Fig. 2. Geological map around Ramgundam showing locations of Jonalarasi Bodu and Damla Gutta.

where the adjacent sandstone beds are separated by muddy or very fine sandy intercalations. On the rippled surfaces, crystals are more frequent in the troughs than in crests. Swarms of perfectly developed casts also occur on the planed-off rippled crests. In the cross-bedded facies, pseudomorphs occur not only on the upper surfaces of the dune bedforms, but also on the ripples on the dune foresets.

Halites occur in two main modes: (1) either as sparsely-distributed isolated or a few interconnected cubes within abundant matrix (Figs. 8 and 9); and (2) as beds of chaotic mixture of halite and mudstone to very fine-grained sandstone, the latter occurring as isolated polyhedral pockets in the intergranular areas (Fig. 10). The two modes are quite similar to those described from the modern continental sabkha-playa basin at Bristol Dry Lake, California (Handford, 1982). The pseudomorphs form a continuum between two end-members based on texture and fabric. Thickness of such pseudomorph-bearing beds ranges up to 1.5 cm, and such beds either follow or are followed by coarse-grained sandstone beds with abrupt but slightly diffused contact (Fig. 10). The cubes and hoppers do not bear any preferred orientation with respect to the bedding. Cubic faces sometimes lie parallel to the bedding, though pyramidal corners often point in different directions.

Origin of pseudomorphs and other evidence of dissolution

Halite crystals, as a rule, have been pseudomorphed mostly by clay and by silt that contains a few sand grains in places. However, in a few instances, halite has been pseudomorphed by coarser sand grains. Microscopic studies reveal that pseudomorph-forming clay often merges with the clay in the matrix and the clays were evidently transported from the matrix by

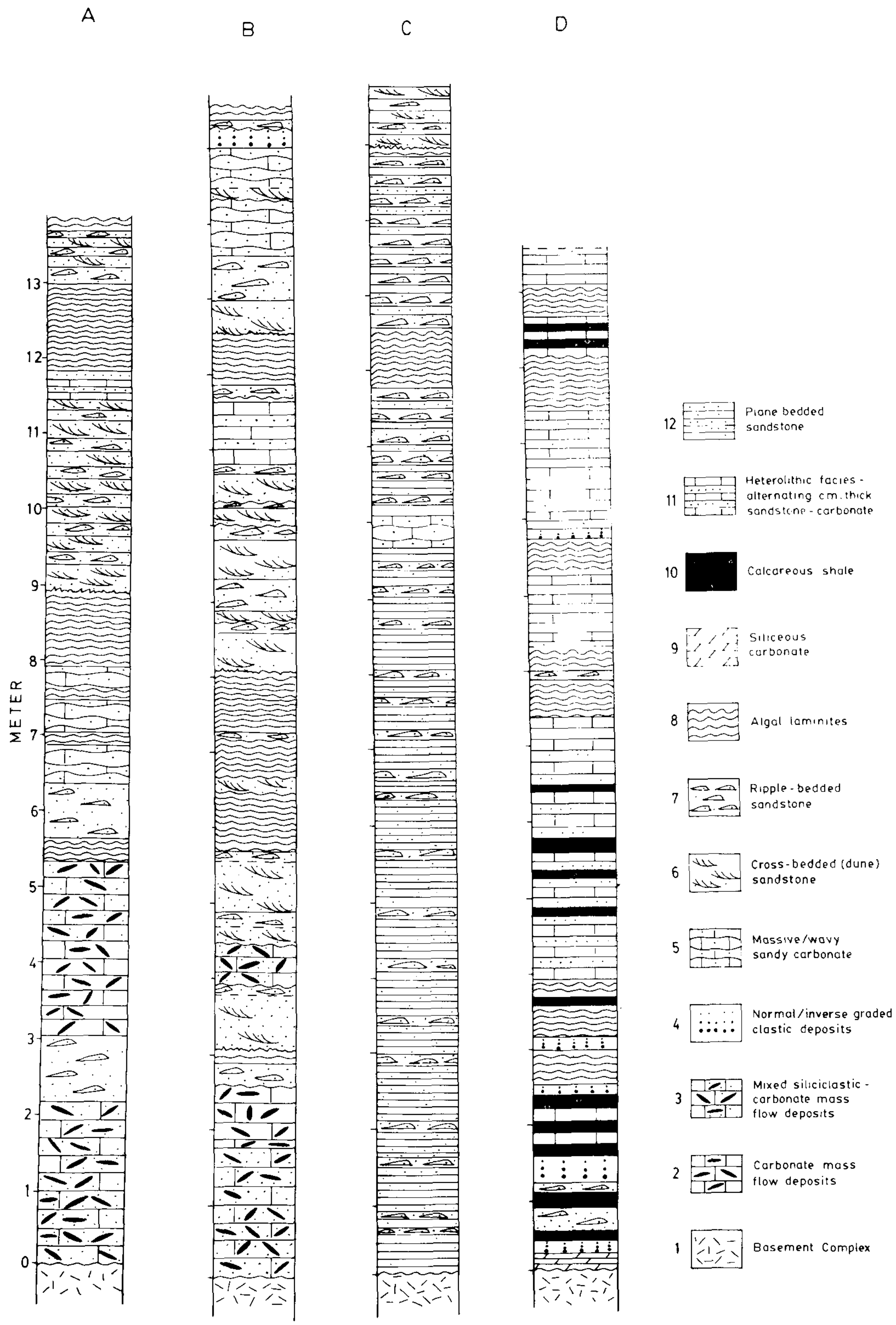

Fig. 3. Stratigraphic columns showing details of halite bearing sequence in the Jonalarasi Bodu Formation. Locations of sections indicated by arrows (A,B,C,D) in Fig. 2.

Fig. 4. Ripple laminated facies with centimetre thick rippled layers.

pore fluid percolating through the porous sands to the halite moulds. Preservation of the details of hopper structures and the overgrowth rims clearly indicate that dissolution of halite and deposition of mechanically transported fine detritus must have been a slow but simultaneous process that occurred in the closed system within the sediments before significant compaction. Evidence for compaction of host sand grains against the void-filling clay also supports the notion that pseudomorphs formed in the pre-compactional stage, presumably in the penecontemporaneous sedimentary environment. In the clay-free beds loose uncompacted sand grains filled up the dissolution moulds to form the pseudomorphs.

Evidence of dissolution can also be found in the form of irregular cavities on the bedding surfaces of coarse grained, plane-bedded arenite facies (Fig. 11). The cavities are up to 1 cm deep; locally polygonal outlines of these large cavities betray a pattern reminiscent of interlocking cubes. Dissolution of clumps of halite crystals apparently led to the formation of such cavities. The existence of halite was initially suspected from these irregular cavities. More subtle dissolution features are extremely irregular bedding surfaces, mimetic after the 'puffy surfaces' (Neal, 1965; Hardie et al., 1978; Handford, 1982) or the 'ploughed grounds' (Bobek, 1959). Such features are believed to have developed through growth of displacive evaporites from interstitial brines (Arthurton, 1980).

Origin of halite

The assemblage of structures in the Jonalarasi Bodu Formation indicates deposition in a shallow coastal environment subjected to alter-

Fig. 5. Algal laminated facies. Algal laminites (bottom) overlain by a penecontemporaneously deformed zone.

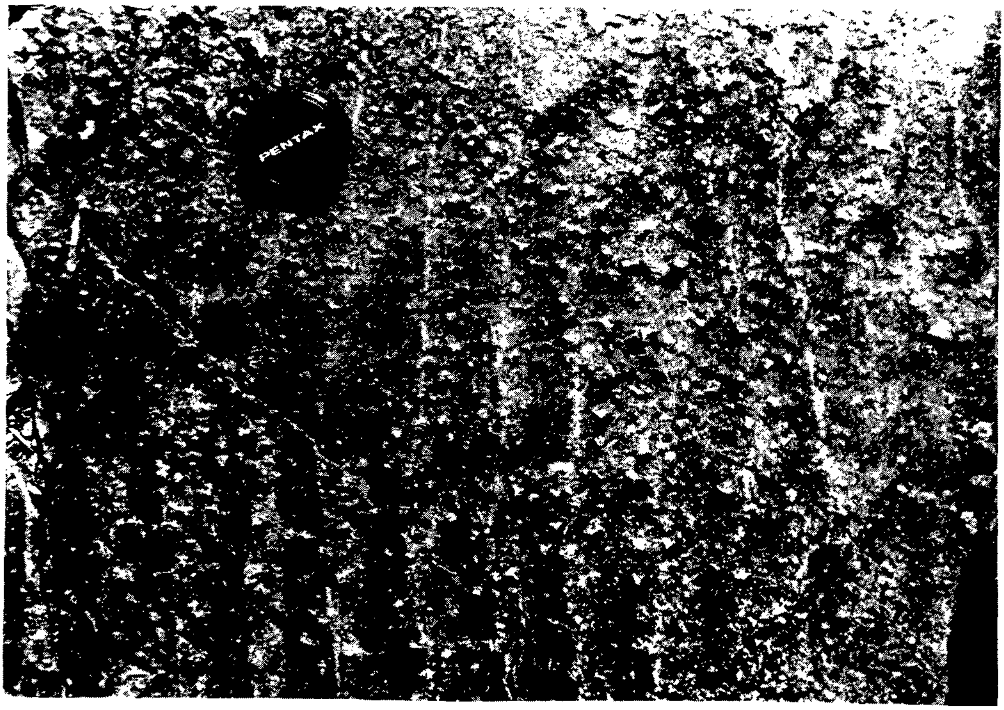

Fig. 6. Halite pseudomorphs on the upper surface of a sharp, straight crested rippled bed.

Fig. 7. Plane-bedded sandstone facies overlying massive, sandy limestone with a sharp contact (marked by arrow). Note concentration of granules in limestone.

nating wave-agitated and calmer phases, accompanied by periodic emergence. The plane-bedded arenite facies (Fig. 7) with local development of parting lineation in the Damla Gutta section, on the other hand, represents deposition in shallow, high energy conditions, apparently in the upper flow regime.

Millimetre thick sand laminae parallel to the algal laminations, bedding-parallel thin layers of rip-up clasts and disturbed zones (Fig. 5) strongly suggest deposition in supratidal flats, periodically inundated by storm surges (see Hardie and Garrett, 1977). Juxtaposition of the wave-rippled facies with the supratidal facies suggests deposition on an extensive peritidal flat with periodic submergence by storm surge.

The presence of structureless, muddy, very fine-grained sandstone or siltstone intervening the rippled beds within the wave-rippled facies clearly points to periodic submergence of the flat into a shallow, wave-dominated lake or lagoon. Although the siliciclastics are dominated by wind-borne sands (Chaudhuri, 1977), they were reworked into the wave-rippled beds during periodic inundations. Very fine sandy or silty layers, on the other hand, are either suspension deposits of the calmer periods or are entirely eolian, deposited seasonally on exposed deflation surfaces of the supratidal flats. In either case, the nature of sand emplacement is suggestive of ephemeral regimes.

The contention of intermittent subaerial exposure is bolstered by the repeated episodes of penecontemporaneous dissolution of halite alternating with periods of precipitation. Alternating periods of inundation, sediment movement with concomitant dissolution of halite and periods of 'non-deposition', evaporative concentration of the brine leading to the growth of halite cyrstals are features typical of saline pans in arid sabkha settings. In arid sabkha settings, the pan and its surrounding flat remain dry except when storm flooding turns it into a temporary lake (Lowenstein and Hardie, 1985).

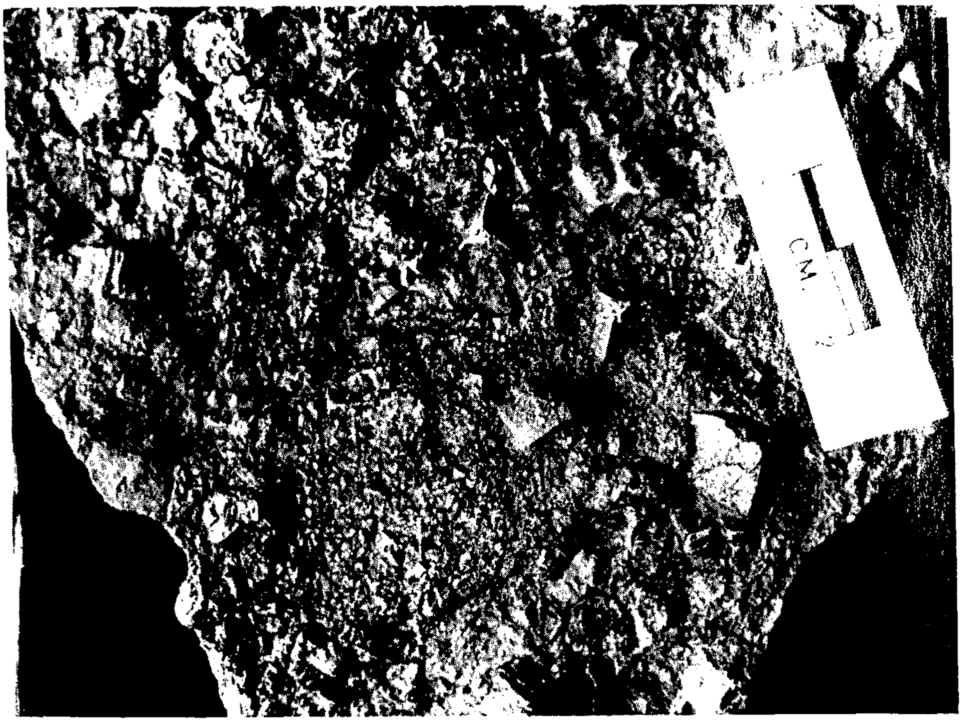

Fig. 8. Halite pseudomorphs with corners pointing in different directions.

Salt pan deposition is known to take place either in coastal sabkha or in continental playas (Handford, 1981, 1982; Lowenstein and Hardie, 1985). The occurrence of halite pseudomorphs in sediments of tidal affiliation in the present case, however, weighs in favour of a coastal rather than an inland playa. Over and above, gradual passage of the Jonalarasi Bodu Formation into the tidal flat carbonate of the Pandikunta Limestone with associated glauconitic arkose (Chaudhuri, 1970a, b) strengthens this contention.

The distinctive morphology and nature of occurrence of the halite pseudomorphs in the Jonalarasi Bodu Formation strongly indicate displacive intrasedimentary growth from supersaturated brines in the desiccation stage of a thin saline pan cycle. The hopper-shaped crystals are nearly identical to the displacive hoppers from the Dead Sea (Neev and Emery, 1967; Gornitz and Schreiber, 1981) and Bristol Dry Lake (Handford, 1982) that most likely developed from evaporating supersaturated brines in the capillary fringe or phreatic zone just beneath the sediment surface. The absence of any upward growing chevron or cornet structure suggests that the crystals did not develop as primary precipitates at the sediment–water interface (cf. Shearman, 1970, 1978; Arthurton, 1973; Southgate, 1982). Although all the crystals have been pseudomorphed, the pseudomorphs preserve the minute details of the internal structures as seen in the hopper structure of the present study (also Southgate, 1982). It may, thus, be suggested that the absence of a chevron structure in the pseudomorphs is a reflection of the primary depositional processes, and is in no way linked with any secondary process related to replacement. The notion of displacive, intrasedimentary growth is also strongly supported by random orientation of the cubes with respect to the bedding, development of isolated subhedral to euhedral cyrstals enclosed within the matrix and clear overgrowth separated by thin films of mud (cf. Smith, 1971; Handford, 1982; Lowenstein and Hardie, 1985).

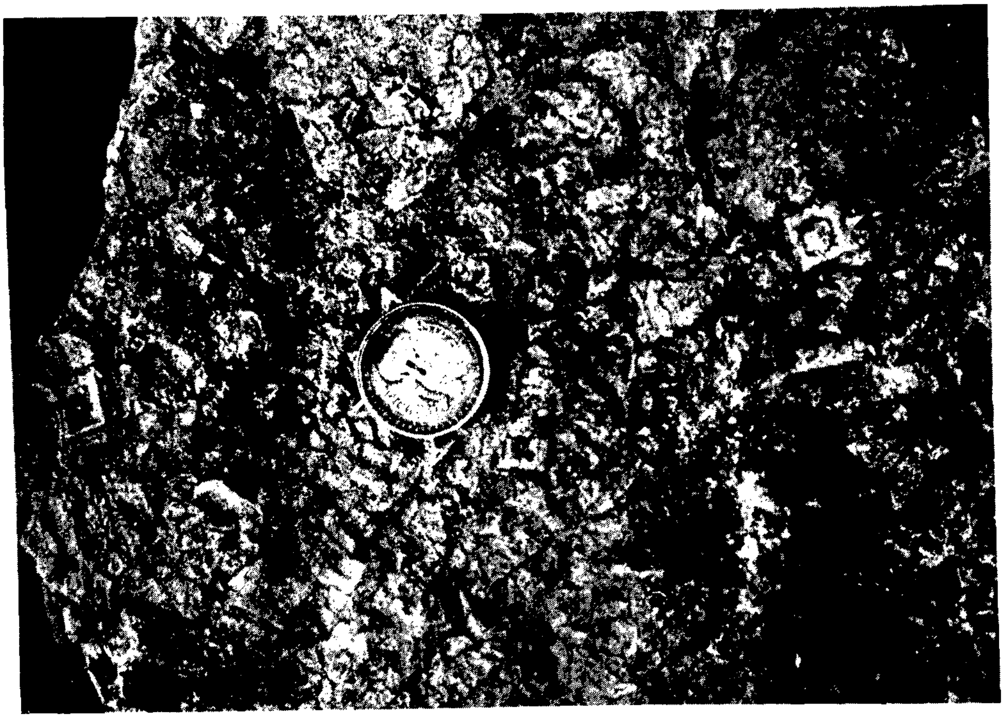

Fig. 9. Densely crowded pseudomorphs with cubic faces parallel to the bedding surface. Note hopper structure in pseudomorph (marked by arrow on the left side) and overgrown cube faces separated from the core by fine silt (marked by arrow on the right side). Diameter of the coin is 1.9 cm.

Fig. 10. A halite bed followed upward by a coarse-grained rippled bed. No sharp demarcation line is present between the two (in section). Note two well-developed crystals marked by arrow. Length of the specimen is 12.5 cm.

The halite beds in the Jonalarasi Bodu Formation do not exhibit any unquestionable primary depositional fabrics. Megascopic examination of polished surfaces show that the beds are comprised of densely crowded, coarsely crystalline, generally equant grains that could only record either displacive intrasedimentary precipitation or primary subaqueous growth of the halite in shallow salt pans followed by dissolution and reprecipitation as a secondary product. Massive, displacive growth, however, is favoured because of the presence of crystals separated by pockets of host sediments and gradational contact with overlying and underlying pseudomorph-bearing beds (Fig. 10). Sharp contacts, formed through planar dissolution in

Fig. 11. Dissolution pits on the upper surface of a plane bedded sandstone.

the flooding stage, with the mechanically transported detrital layers would have been expected if the bedded halite layers formed as primary, subaqueous precipitates (cf. Wardlaw and Schwerdtner, 1966; Lowenstein and Hardie, 1985).

Evidence of alternating periods of precipitation and dissolution induced by surface run-off, infiltration and evaporation, indicates that in the present case the vadose zone was the favoured site for crystal growth. Relatively unstable and fluctuating conditions in the vadose zone arising from alternating periods of flooding and desiccation possibly led to the crystal growth as well as contemporaneous dissolution and development of the pseudomorphs. The conditions, however, could have been attained in the uppermost part of the phreatic zone in response to the fluctuations of the ground-water level. Both downward-percolating brine and upward-evolving brine perhaps played equally important roles in depositing the crystals. The fine-grained mudstone layer with low permeability and intervening coarser sandstone layers with higher permeability probably served as a barrier for both downward and upward migrating brines. These permeability barriers resulted in the localised concentration of crystals both at the upper and the lower surfaces of a number of beds. In extreme cases, continuous beds developed through crystal nucleation in thoroughly brine-soaked fine grained layers.

Depositional model, palaeogeography and recent analogue

Besides the occurrence of halite, the preponderance of 'blown sands' and perhaps also the evidence of extensive penecontemporaneous dolomitization in the Jonalarasi Bodu Formation (Chaudhuri, 1970b, 1977) indicate establishment and long term maintenance of an arid climate. Much of the sand entering the basin was transported by wind from the extensive coastal dune fields (Chaudhuri, 1977) formed in arid desert conditions and were redistributed together with water-borne detritus by currents during the flooding stage. The fine sandy and silty layers, on the other hand, could be wholly eolian. The prevailing situation appears to be similar to that interpreted for the Triassic Keuper Marl of Cheshire (Taylor et al., 1963; Arthurton, 1980), and observed in the present day Ranns of Kutch (Glennie and Evans, 1976) and in the Laguna Ojo de Liebre area of Baja California (Kinsman, 1969). The Jonalarasi Bodu sabkha differs from the typical salt pan scenario in respect of dominance of coarse sands in the pan. Dominance of sand clearly stems from eolian supply from the sand seas formed in desert environments. Large expanses of shallow, ephemeral brackish to hypersaline water bodies receiving detritus from dune fields is characteristic of the coastal areas, under the present-day climatic regime, in South and Western Australia (Arakel, 1980; Warren, 1982). In South Australia, the surface waters of coastal sabkhas completely evaporate during summer, leaving most of the saline surface dry leading to near surface precipitation of evaporites which, however, are redissolved by the winter rain when the salinas get filled with brackish surface water (Warren, 1982).

Arakel (1980) described progressive restriction of Hutt and Leeman Lagoons of Western Australia by growth of barrier beach and dune complexes resulting in the development of dry salt pans with displacive muddy halite. However, apart from such peripheral, restricted lagoons, differential sedimentation may also isolate shallow depressions on the exposed supratidal surfaces which may carry ephemeral pools of brine. Algal bioherms and biostromes and low amplitude sand shoals in the Pandikunta Limestone could have served as natural barriers to marine circulation. Further, depositional morphologies formed by the subaqueous dune fields, preserved as the cross-bedded facies and the oolite shoals could also have created the conditions favourable for restriction (Fig. 12). The preferred concentration of pseudomorphs in the troughs seems compatible with this idea.

The Ranns of Kutch that cover an area of $\sim 30\,000$ km^2 in the flooding stage may be cited as a realistic present-day analogue for the extensive sabkhas of the Jonalarasi Bodu Formation (see Singh, 1980). The Ranns remain dry for the greater part of the year when low-lying bars in their seaward side act as barriers to circulation (P.K. Bose, personal communication, 1985) and are annually flooded by marine and land-derived waters during the southwest monsoon to a distance of 300 km inland (Glennie, 1970; Glennie and Evans, 1976). Halite, which forms widespread crust during emergent periods, is dissolved by subsequent flooding (Glennie and Evans, 1976).

Tectonic implications

Although algal bioherms or the low lying subaqueous sand shoals could have locally provided barriers for the Jonalarasi Bodu pans, the backdrop was in reality set by the topographic depressions imposed through the development of fault-controlled sub-basins in the marginal areas during the embryonic stage of the Pakhal basin (Fig. 12). The scenario is analogous to the occurrence of evaporites in the fault-controlled partially connected, discrete basins in the late Proterozoic Adelaidean System of South Australia (Rowlands et al., 1980). Penecontemporaneous tectonism during early Pakhal sedimentation is indicated not only by the presence of mass-flow deposits immediately below the pseudomorph-bearing beds but also by the abrupt facies variation accompanied with sharp changes in thickness of coeval sections. The role of such penecontemporaneous tectonism in localising evaporites, particularly halite, in tectonically controlled depressions has been documented from both ancient and Recent times (Shearman, 1970; Dacima and Wezel, 1973; Glennie and Evans, 1976; Rowlands et al., 1980; Kendal, 1984).

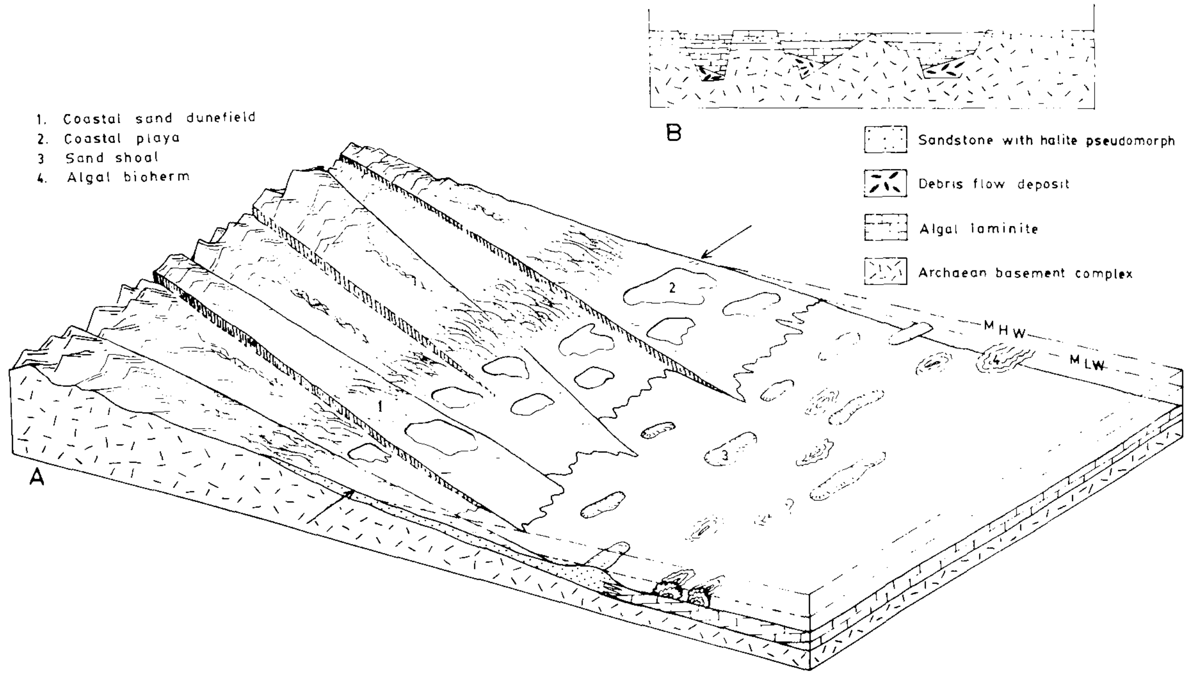

Fig. 12. (A) Palaeogeographic reconstruction of the embryonic mid-Proterozoic basin along its southern margin around Ramgundam. (B) A section along the line marked by arrows in Fig. A.

Restriction of the pseudomorph-bearing rocks at the base of the Pakhal Group and their facies-specific distribution indicate that either climatic or the tectonic conditions evolved through time, so that halite precipitation ceased in later stages of basin development and sedimentation. Significantly, there is no evidence as yet to suggest any major change in relative humidity during sedimentation of the upper formations where 'blown' sand and dolomite are as abundant as in the Jonalarasi Bodu Formation. Apparently, physical restriction inhibiting normal marine circulation in the near-shore areas diminished through time, leading to a gradual return to open-circulation marine conditions. Secondly, the occurrence of halite pseudomorphs in the sandy facies in preference to algal laminite suggests that salinity could reach the level of halite precipitation only within the porous sands through concentration by repeated dissolution, evaporation in the capillary zone and reprecipitation. The situation is similar to that described by Kinsman (1975) and Burke (1975) for the young rift-oceans or grabens formed in the early stages of continental rupture within a climatic belt of net evaporation. Deposits of evaporatic mode in proto-oceans normally form in brackish conditions during the initial few million years of post-rifting development and are overlain by thick marine sequences of non-evaporatic mode. Patterns of evaporite deposition in and along the margins of the proto-oceans may be very complex and evaporites may show the characteristics of shallow water or even subaerial sabkha facies (Kinsman, 1975) and this is exactly the situation observed in the Jonalarasi Bodu Formation. The rift basin model is also consistent with the geophysical data from the Pranhita-Godavari Valley (Qureshy et al., 1968), which is considered to have been a tectonically active zone since Archaean times (Naqvi et al., 1974).

Conclusions

(1) The earliest Proterozoic sediments in the southern flank of the Pranhita-Godavari Valley were deposited in semi-arid coastal sabkha–salt pan environments.

(2) Profuse development of halite casts and pseudomorphs in the interfaces of sandstone and mudstone arises from penecontemporaneous, displacive crystallisation of precursor halite.

(3) Displacive halite crystals developed in the vadose zone and in the capillary fringe of the phreatic zone through concentration of downward-and upward-percolating hypersaline pore water along sand-mud interfaces.

(4) Precipitation of halite took place during the drying stage of the salt pans, and the crystals were dissolved and pseudomorphed during the flooding stage.

(5) Restriction requires that the development of brine pools in the sabkha flats was probably provided by fault-controlled depressions in the marginal areas during the incipient stage of basin development. Normal marine circulation was further impeded by sand shoals and algal reefs.

Acknowledgements

The programme was supported and financed by the Indian Statistical Institute, Calcutta. We are grateful to N.J. Snelling for dating the glauconite and to D. Briggs for the preparation of the dated sample. Appreciation is extended to Sankar Das for valuable assistance in the field and to Ajoy K. Das for drafting the diagrams.

References

Arakel, A.V., 1980. Genesis and diagenesis of Holocene evaporitic sediments in Hutt and Leeman Lagoons, Western Australia. J. Sediment. Petrol., 50: 1305-1326.

Arthurton, R.S., 1973. Experimentally produced halite compared with Triassic layered halite rock from Chesire, England. Sedimentology, 20: 145-160.

Arthurton, R.S., 1980. Rythmic sedimentary sequences in the Triassic Keuper Marl (Mercia Mudstone Group) of Chesire, Northwest England. Geol. J., 15: 43-58.

Badham, J.P.N. and Stanworth, C.W., 1977. Evaporites from the Lower Proterozoic of the East Arm., Great Slave Lake. Nature, 268: 516-518.

Bobek, H., 1959. Features and formation of the Great Kavir and Masileh. Univ. of Tehran, Arid Zone Research Centre 2, Tehran.

Burke, K., 1975. Atlantic evaporites formed by evaporation of water spilled from Pacific, Tethyan and Southern Oceans. Geology, 3: 613-616.

Chaudhuri, A., 1970a. Precambrian Stromatolites in the Pranhita-Godavari Valley (South India). Palaeogeogr. Palaeoclimatol. Palaeoecol., 7: 309-340.

Chaudhuri, A., 1970b. Precambrian stratigraphy and sedimentation around Ramgundam, Andhra Pradesh. Ph.D. Thesis, Calcutta University, 236 pp. (unpublished).

Chaudhuri, A., 1977. Influence of eolian processes on Precambrian sandstones of the Godavari Valley, South India. Precambrian Res., 4: 339-360.

Chaudhuri, A., 1985. Stratigraphy of the Purana Supergroup around Ramgundam, Andhra Pradesh. J. Geol. Soc. India, 26: 301-314.

Dacima, A. and Wezel, F., 1973. Late Miocene evaporites of the Central Sicilian Basin. In: W.B.F. Ryan and K.J. Hsu et al. (Editors), Initial Reports of the Deep Sea Drilling Project, Vol. XIII, U.S. Govt. Printing Office, Washington, DC, pp. 1234-1240.

Glennie, K.W., 1970. Desert Sedimentary Environments. Developments in Sedimentology, 14. Elsevier, Amsterdam, 222 pp.

Glennie, K.W. and Evans, G., 1976. A reconnaissance of the Recent sediment of the Ranns of Kutch, India. Sedimentology, 23: 625-647.

Gornitz, V.M. and Schreiber, B.C., 1981. Displacive halite hoppers from the Dead Sea: implication for ancient evaporative deposits. J. Sediment. Petrol., 51: 787-794.

Handford, C.R., 1981. Coastal sabkha and salt-pan deposition of the Lower Creek Formation (Permian), Texas. J. Sediment. Petrol., 51: 761-778.

Handford, C.R., 1982. Sedimentology and evaporite genesis in a Holocene continental-sabkha playa basin - Bristol Dry Lake, California. Sedimentology, 29: 239-253.

Hardie, L.A. and Garrett, P., 1977. Some miscellaneous implications and speculations. In: L.A. Hardie (Editor), Sedimentation on the Modern Carbonate Tidal Flats of Northwest Andros Island, Bahamas. The John Hopkins University. (Studies in Geol. No. 22), University Press, Baltimore, pp. 184-187.

Hardie, L.A., Smoot, J.P. and Eugster, H.P., 1978. Saline lakes and their deposits: a sedimentological approach. In: A. Matter and M. Tucker (Editors), Modern and Ancient Lake Deposits. Int. Assoc. Sedimentol., Spec. Publ. No. 2, pp. 7-41.

Kendal, A.C., 1984. Evaporites, In: R.G. Walker (Editor), Facies Models. Geoscience, Canada, pp. 259-296.

Kinsman, D.J.J., 1969. Modes of formation, sedimentary associations and diagnostic features of shallow water supratidal evaporites. Bull. Am. Assoc. Petrol. Geol., 53: 830-840.

Kinsman, D.J.J., 1975. Salt floors to geosynclines. Nature, 255: 375-378.

Lowenstein, T.K. and Hardie, L.A., 1985. Criteria for the recognition of salt pan evaporites. Sedimentology, 32: 627-644.

Naqvi, S.M., Divakara Rao, V. and Narain, H., 1974. The protocontinental growth of the Indian Shield and the antiquity of its rift valleys. Precambrian Res., 1: 345-398.

Neal, J.T., 1965. Geology, Mineralogy and Hydrology of U.S. Playas. U.S. Air Force Cambridge Research Lab., Environ. Res. Pep., 96: 104 pp.

Neev, D. and Emery, K.O., 1967. The Dead Sea, depositional processes and environments of evaporites. Bull. Israel Geol. Surv., 31: 147 pp.

Qureshy, M.N., Brahmam, N.K., Garde, S.C. and Mathur, B.K., 1968. Gravity anomalies and the Godavari Rift, India. Bull. Geol. Soc. Am., 79: 1221-1230.

Rowlands, N.J., Blight, P.G., Jarvis, D.M. and von der Borch, C.C., 1980. Sabkha and playa environments in Late Proterozoic grabens, Willorean Ranges, South Australia. J. Geol. Soc. Aust., 27: 55-68.

Sen, S., 1982. Epeirogenic disturbances in the Indian Shield area from the Proterozoic to the Neogene times. Q. J. Geol. Min. Met. Soc., India. 54: 101-113.

Shearman, D.J., 1970. Recent halite rock, Baja California, Mexico. Trans. Inst. Min. Metal. B, 79: 155-162.

Shearman, D.J., 1978. Halite in sabkha environments. In: W.E. Dean and B.C. Schreiber (Editors), Marine Evaporites. Soc. Econ. Palaeont. Mineral, Tulsa, Short Course No. 4, pp. 30-42.

Singh, I.B., 1980. Precambrian sedimentary sequences of India: their peculiarities and comparison with modern sediments. Precambrian Res., 12: 411-436.

Smith, D.B., 1971. Possible displacive halite in the Permian Upper Evaporite Group of Northeast Yorkshire. Sedimentology, 17: 221-232.

Southgate, P.N., 1982. Cambrian skeletal halite crystals and experimental analogues. Sedimentology, 29: 391-407.

Stewart, A.J., 1979. A barred-basin marine evaporite in the Upper Proterozoic of the Amadeus basin, Central Australia. Sedimentology, 26: 33-62.

Taylor, B.J., Price, R.H. and Trotter, F.M., 1963. Geology of the County around Stockport and Kuntsford. Mem. Geol. Surv. U.K., 183 pp.

Walker, R.N., Muir, M.D., Diver, W.L., Williams, N. and Wilkins, N., 1977. Evidence of major sulphate evaporite deposits in the Proterozoic McArthur Group, Northern Territory, Australia. Nature, 265: 526-529.

Wardlaw, N.C. and Schwerdtner, W.M., 1966. Halite-anhydrite seasonal layers in the Middle Devonian Prairie Evaporite Formation, Saskatchewan, Canada. Bull. Geol. Soc. Am., 77: 331-342.

Warren, J.K., 1982. The hydrological setting and significance of gypsum in Late Quaternary Salt Lakes in South Australia. Sedimentology, 29: 609-637.

Kinsman, D.J.J., 1969. Modes of formation, sedimentary associations and diagnostic features of shallow water supratidal evaporites. Bull. Am. Assoc. Petrol. Geol., 53: 830-840.

Kinsman, D.J.J., 1975. Salt floors to geosynclines. Nature, 255: 375-378.

Lowenstein, T.K. and Hardie, L.A., 1985. Criteria for the recognition of salt pan evaporites. Sedimentology, 32: 627-644.

Naqvi, S.M., Divakara Rao, V. and Narain, H., 1974. The protocontinental growth of the Indian Shield and the antiquity of its rift valleys. Precambrian Res., 1: 345-398.

Neal, J.T., 1965. Geology, Mineralogy and Hydrology of U.S. Playas. U.S. Air Force Cambridge Research Lab., Environ. Res. Pep., 96: 104 pp.

Neev, D. and Emery, K.O., 1967. The Dead Sea, depositional processes and environments of evaporites. Bull. Israel Geol. Surv., 31: 147 pp.

Qureshy, M.N., Brahmam, N.K., Garde, S.C. and Mathur, B.K., 1968. Gravity anomalies and the Godavari Rift, India. Bull. Geol. Soc. Am., 79: 1221-1230.

Rowlands, N.J., Blight, P.G., Jarvis, D.M. and von der Borch, C.C., 1980. Sabkha and playa environments in Late Proterozoic grabens, Willorean Ranges, South Australia. J. Geol. Soc. Aust., 27: 55-68.

Sen, S., 1982. Epeirogenic disturbances in the Indian Shield area from the Proterozoic to the Neogene times. Q. J. Geol. Min. Met. Soc., India. 54: 101-113.

Shearman, D.J., 1970. Recent halite rock, Baja California, Mexico. Trans. Inst. Min. Metal. B, 79: 155-162.

Shearman, D.J., 1978. Halite in sabkha environments. In: W.E. Dean and B.C. Schreiber (Editors), Marine Evaporites. Soc. Econ. Palaeont. Mineral, Tulsa, Short Course No. 4, pp. 30-42.

Singh, I.B., 1980. Precambrian sedimentary sequences of India: their peculiarities and comparison with modern sediments. Precambrian Res., 12: 411-436.

Smith, D.B., 1971. Possible displacive halite in the Permian Upper Evaporite Group of Northeast Yorkshire. Sedimentology, 17: 221-232.

Southgate, P.N., 1982. Cambrian skeletal halite crystals and experimental analogues. Sedimentology, 29: 391-407.

Stewart, A.J., 1979. A barred-basin marine evaporite in the Upper Proterozoic of the Amadeus basin, Central Australia. Sedimentology, 26: 33-62.

Taylor, B.J., Price, R.H. and Trotter, F.M., 1963. Geology of the County around Stockport and Kuntsford. Mem. Geol. Surv. U.K., 183 pp.

Walker, R.N., Muir, M.D., Diver, W.L., Williams, N. and Wilkins, N., 1977. Evidence of major sulphate evaporite deposits in the Proterozoic McArthur Group, Northern Territory, Australia. Nature, 265: 526-529.

Wardlaw, N.C. and Schwerdtner, W.M., 1966. Halite-anhydrite seasonal layers in the Middle Devonian Prairie Evaporite Formation, Saskatchewan, Canada. Bull. Geol. Soc. Am., 77: 331-342.

Warren, J.K., 1982. The hydrological setting and significance of gypsum in Late Quaternary Salt Lakes in South Australia. Sedimentology, 29: 609-637.