Lipids of extremely halophilic archaeobacteria from saline environments in India: a novel glycolipid in *Natronobacterium* strains

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Several strains of extremely halophilic archaeobacteria, both non-alkaliphilic and alkaliphilic, including *Halobacterium*, *Haloferax* and *Natronobacterium* species, were isolated from salt locales in India. The major phospholipids in these strains were the C_{20}-C_{20}-glycerol diether analogues of phosphatidylglycerolmethylphosphate (PGP-Me), phosphatidylglycerol (PG) and phosphatidic acid (PA). In addition, the *Halobacterium* strains possessed the characteristic glycolipids, sulfated triglycosyl and tetraglycosyl diethers (S-TGD-1 and S-TeGD, respectively) and the unsulfated triglycosyl diether (TGD-1); and the *Haloferax* strains had the characteristic sulfated and unsulfated diglycosyl glycerol diethers (S-DGD-1 and DGD-1, respectively). The PGP-Me, and PG components of the halokaliphiles each occurred as two molecular species with C_{20}-C_{20} and C_{20}-C_{25} (isoprenoid) glycerol diether lipid cores. In contrast to previous reports of the absence of glycolipids in natronobacteria, the *Natronobacterium* strains from India were found to contain small amounts of a novel glycolipid identified as glucopyranosyl-1→6-glucopyranosyl-1→1-glycerol diether (DGD-4). The lipid cores of DGD-4 also contained mainly unhydroxylated or hydroxylated C_{20}-C_{20}, C_{20}-C_{25} and C_{25}-C_{25} molecular species with unsaturated (isoprenoid) chains. Hydroxylated lipid cores have previously been identified only in some methanogenic archaeobacteria.

Keywords: archaeobacteria, lipids, *Natronobacterium*, *Halobacterium*, *Haloferax*

INTRODUCTION

Comparative study of the polar lipid composition of extremely halophilic archaeobacteria, both non-alkaliphilic (*Halobacterium*, *Haloarcula*, *Haloferax* and *Halococcus*) and alkaliphilic (*Natronobacterium* and *Natronococcus*) species, has proved to be a useful chemotaxonomic tool for this group of archaea (Torreblanca et al., 1986; Grant & Larsen, 1989; Kates, 1993a, b). All strains of extreme halophiles examined possess ether-linked lipids based on the lipid core 2,3-di-O-phytanyl-α-glycerol (C_{20}-C_{20}-diether) (Kates, 1978, 1990; 1993a, b). Extreme haloalkaliphiles also possess 2-O-sesterterpanyl-3-O-phytanyl-α-glycerol (C_{25}-C_{25}-diether) and 2,3-di-O-sesterterpanyl-α-glycerol (C_{25}-C_{25}-diether) lipid cores (De Rosa et al., 1982, 1983), and the former of these two lipids has also been reported in some halococci (Moldoveanu et al., 1990).

The distinctive features of polar lipid composition within the extreme halophiles are: (i) the presence of PGP-Me (Kates et al., 1993) and PG as major phospholipids (Torreblanca et al., 1986; Grant & Larsen, 1989; Kates, 1993b); (ii) the presence of PGS in *Halobacterium* and *Haloarcula* species and its absence in *Haloferax*, *Halococcus*, *Natronobacterium* and *Natronococcus* species (Tindall et al., 1984; Ross et al., 1985; Torreblanca et al., 1986; Grant & Larsen, 1989; Kates, 1993b); (iii) correlation of glycolipid
composition with generic classification of non-alkaliphilic archaea (Torreblanca et al., 1986; Grant & Larsen, 1989; Kates, 1990, 1993a, b); (iv) the absence of glycolipids in halophilic archaea (Tindall et al., 1984; Ross et al., 1983; Grant & Larsen, 1989; Kates, 1990); and (v) the presence of phosphatidyl-1,2-cyclic-glycerophosphate in Natronovococcus, which distinguishes this genus from Natronobacterium (Morth & Tindall, 1985; Lanzotti et al., 1989).

There have been no studies so far to show whether the halophilic archaeobacteria possess hydroxy diether core lipids, which have been reported in methanogens (Ferrante et al., 1988; Sprott, 1992).

Previous studies on the lipids of extreme halophiles from various locales have contributed to the taxonomic assignment of new genera: Natronobacterium and Natronococcus (De Rosa et al., 1982, 1983, 1988; Tindall et al., 1984), Halofex and Haloarcula (Torreblanca et al., 1986; Kates, 1993a, b). We now report on the polar and non-polar lipids of Natronobacterium and other halobacterial strains isolated from salt locales in India (Upasani, 1988; Upasani & Desai, 1990). A novel unsulfated glycolipid (DG4-4) has been isolated and identified in the Natronobacterium strain SSL1 and detected also in other strains of Natronobacterium. The lipid core of this novel glycolipid had mainly C20-C22, C20-C22, and C24-C25 glycerol diethers with unhydroxylated or hydroxylated unsaturated (isoprenoid) chains: hydroxylated lipid cores have previously been found only in some methanogens (Sprott, 1992).

METHODS

Cultures and growth conditions. Halobacterium MSW5 (NCMB 2288) and Halofex MSW1 (NCMB 2287, deposited as Halobacterium) were isolated from marine salterns at Mithapur, India; Natronobacterium SSL1 (ATCC 43988) and SSL6 (ATCC 43987) strains were isolated from Sambhar Salt Lake, India (Upasani, 1988; Upasani & Desai, 1990). Halofex halophilum (NRC 34001) and Halofex volcanii (NRC 2287, deposited by Roger Latta, NRC, Ottawa, and India) was provided by Roger Latta, NRC, Ottawa, and Natronobacterium gregoryi (NCMB 2189) was a gift from W. D. Grant, University of Leicester, UK.

Halobacterium and Halofex strains were grown in the media of Larsen (1981) and Mulikahanhhi & Larsen (1975), respectively. The Natronobacterium cultures were grown in the medium of Brown (1963) as described by Tindall et al. (1980), but using lower magnesium sulfate and sodium chloride concentrations; its composition was (g l\(^{-1}\)): bacteriological peptone (Oxoid) 10.0; trisodium citrate 3.0; MgSO\(_4\) (anhydrous) 2.5; Na\(_2\)CO\(_3\) (anhydrous) 16.0; NaCl 225; pH 9.5. Inorganic and organic salts solution of the respective medium, and total lipids were separated by Kates (1986). Polar lipids were separated from non-polar components by acetone precipitation (Kates, 1986).

Chromatography. Thin-layer chromatography (TLC) of polar lipids was performed on analytical precoated plates (Whatman K\(_6\) silica gel 60A, 0.25 mm thick; preparative, 0.75 mm thick) using single or double development in the following solvent systems: A, CHCl\(_3\)/methanol/conc. ammonium hydroxide (65:35:5, by vol.); B, CHCl\(_3\)/methanol/acetic acid/H\(_2\)O (85:22:5:10;4, by vol.); and C, CHCl\(_3\)/MeOH/CH\(_2\)COOH/H\(_2\)O (85:22:5:8:3, by vol.). The non-polar lipids were separated on analytical precoated plates (Merck silica gel 60H, 0.25 mm thick) using the following solvent systems: D, CHCl\(_3\)/methanol (93:7, v/v) for bacterioruberin and mono- and dihydro-bacterio-ruberin isomers; E, petroleum ether (b.p. 60–80 °C)/diethyl ether (99:1, v/v) for vitamin MK-8, lycopene and \(\beta\)-carotene; F, petroleum ether (b.p. 60–80 °C)/diethyl ether (99:5:0.5, v/v) for squalenes, \(\beta\)-carotene and lycopene; and G, petroleum ether/ethyl ether (70:30, v/v) for diphyanyl-glycerol. Lipids were detected with the following spray reagents (Kates, 1986): 0.5% \(\alpha\)-naphthol/H\(_2\)SO\(_4\) for glycolipids, (NH\(_4\))MoO\(_4\)/H\(_2\)SO\(_4\) for phospholipids; H\(_2\)SO\(_4\)/C\(_6\)H\(_5\)OH (1:1, by vol.) followed by charring at 150 °C, or staining with aqueous rhodamine 6G followed by visualization under ultraviolet light 266 nm) for detection of all lipids. Water-soluble products of methanolysis were chromatographed on TLC cellulose plates (Merck DC cellulose, 0.1 mm thick) in solvent H [pyridine/ethyl acetate/H\(_2\)O (2:5:5, by vol., upper phase)] for sugars, and in solvent I [1-butanol/acetate acid/H\(_2\)O (5:3:1, by vol.)] for phosphate esters. Sugars were detected with the silver nitrate spray reagent and phosphate esters with the phosphate spray reagent (Kates, 1986); they were identified by comparison of their TLC mobilities with those of the corresponding authentic compounds.

Isolation and purification of individual polar lipids. Individual polar lipids were isolated and purified by repeated TLC on silica gel in solvent B for phospholipids and solvent C for glycolipids. Solvent C was effective in completely separating the glycolipid (GL-1) in Natronobacterium strain SSL1 from the PGP-Me component. The bands corresponding to individual phospholipids (PGP-Me and PG) were eluted from the silica with CHCl\(_3\)/methanol/H\(_2\)O (1:1:0.1, by vol.) or CHCl\(_3\)/methanol/0.2 M HCl (1:2:0.8, by vol.), and the glycolipid (GL-1) was eluted using CHCl\(_3\)/methanol/H\(_2\)O (1:1:0.1, by vol.), as described elsewhere (Kates, 1986). The acidic phospholipids (free acid form) were neutralized with methanolic 1 M Nh\(_2\)OH and precipitated as the ammonium salt forms (Kates, 1986; Moldoveanu et al., 1990). Lipid components were identified by TLC mobilities relative to those of authentic standards (Moldoveanu et al., 1990).

Analytical methods. Phosphorus and total hexose contents of phospholipids and glycolipids, respectively, were determined as described elsewhere (Kates, 1986). Separated lipid components were determined gravimetrically after elution from the plates.

Physical measurements. The purified lipid components were analysed by negative and positive fast atom bombardment mass spectrometry (FAB-MS) with a Kratos Concept 2H mass spectrometer (caesium gun ion source), and by chemical ionization-mass spectrometry (CI-MS), with a VG 7070E mass spectrometer.
RESULTS

Characterization of strains from saline environments in India

The non-alkaliphilic extreme halophiles isolated from marine salterns were separated into two groups on the basis of morphology, salt requirements and biochemical group 11 (MSW4-MSW6), the genus marine salterns were separated into two groups on the follows: group I (MSW1-MSW3), in India non-alkaliphilic extreme halophiles isolated from saline environments were analysed as the partially methylated alditol acetates by GC-MS on a JMW-DB-17 capillary column, as described elsewhere (Moldoveanu et al., 1990). Partially methylated alditol acetates of sugars were analysed by GC-MS on a HMW-DB-17 capillary column (30 m), temperature-programmed from 180 °C (at 2 °C min⁻¹) on a Hewlett Packard HP-5985 GC-MS instrument.

Methanolysis of lipids. Acid methanolysis of phospholipids and glycolipids was performed in 2 M HCl in methanol at 75 °C for 5 h (Kates, 1986). The hydrophobic products (petroleum-ether-soluble, mainly diether lipid cores, also some isoprenyl degradation products) were identified by TLC in solvent G and by CI-MS analysis. The methanol/water-soluble products (phosphate esters, sugars) were identified as described elsewhere (Moldoveanu et al., 1990).

For detection of hydroxylated lipid cores, mild acid methanolysis was carried out with 0.5 M methanolic HCl at 50 °C for 16 h (Sprott, 1992), and the products analysed by TLC and CI-MS (Ferrante et al., 1988; Moldoveanu & Kates, 1988).

Permethylation analysis. Glycolipid (GL-1) was permethylated and the partially methylated sugars obtained after methanolysis were analysed as the partially methylated alditol acetates by GC-MS on a JMW-DB-17 capillary column, as described elsewhere (Moldoveanu et al., 1990; Kates, 1986). The anomeric configuration of the glycosidic linkages was assigned by ¹H-NMR in permethylated DMSO (see Kates, 1990).

Lipid composition

The cellular content of total lipids for the strains examined was in the range 5–8% of dry cells (Table 1). Lipid-P (lipid-associated phosphorus) amounted to 2.4–3.6% of total lipids for all the strains except Natronobacterium SSL1, which had a higher lipid-P content (4.7%), probably due to its lower content of non-polar lipids (Table 1, see below). Total lipid-associated hexose amounted to 3–5% of total lipids for the non-alkaliphilic strains and about 0.2% of total lipids for the Natronobacterium strains. The presence of lipid-hexose in the Natronobacterium strains suggested that these strains do contain small amounts of glycolipids, which have not been found previously in natronobacteria.

Polar lipids accounted for 79–85% of total lipids except for strains MSW5 and SSL6, which had only 58–60% polar lipids (Table 1). The content of non-polar lipids plus pigments accounted for the remainder of the lipids and was unusually high in the strains MSW5 and SSL6, amounting to about three times the value reported for halobacterial strains previously studied (Kamekura & Kates, 1988).

Non-polar lipids. TLC of the non-polar (acetone-soluble) lipids in solvents D, E and F showed the presence in all strains examined of C30 isoprenoids (squalene, dihydro-squalene and tetrahydro-squalene), C40 carotenoids (carotene and lycopene) and C50 carotenoids (bacterioruberins and anhydrobacterioruberins), as well as retinal and vitamin MK-8. However, the relative proportions of these components varied among these strains. The strains of Indian extreme halophiles and haloalkaliphiles appear to be similar to other known halobacteria with respect to the presence of isoprenoid compounds and carotenoid pigments (Kamekura & Kates, 1988).

Table 1. Lipid content and composition of extremely halophilic archaeobacterial strains from India

<table>
<thead>
<tr>
<th>Strain</th>
<th>Total lipids (%) by wt*</th>
<th>Polar lipids (%) of total lipids</th>
<th>Non-polar lipids (%) of total lipids</th>
<th>Lipid-P (%) of total lipids</th>
<th>Lipid-hexose (%) of total lipids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haloferax MSW1</td>
<td>7.5</td>
<td>79</td>
<td>21</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Halobacterium MSW5</td>
<td>5.2</td>
<td>58</td>
<td>42</td>
<td>2.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Natronobacterium SSL1</td>
<td>4.6</td>
<td>85</td>
<td>15</td>
<td>4.7</td>
<td>0.24</td>
</tr>
<tr>
<td>Natronobacterium SSL6</td>
<td>8.6</td>
<td>60</td>
<td>38</td>
<td>3.4</td>
<td>0.17</td>
</tr>
<tr>
<td>Natronobacterium gregoryi</td>
<td>5.0</td>
<td>83</td>
<td>8</td>
<td>2.6</td>
<td>-</td>
</tr>
</tbody>
</table>

* Based on an estimated dry cell weight being 10% of wet cell weight.
Table 2. TLC mobilities and polar lipid composition in extremely halophilic archaeobacteria from Indian salterns

Single TLC development was in one of two solvent systems: A, CHCl₃/methanol/conc. ammonium hydroxide (65:35:5, by vol.); C, CHCl₃/methanol/acetic acid/H₂O (85:22:8:3, by vol.). TLC plates were stained for phospholipids and glycolipids as described in Methods. tr, trace.

<table>
<thead>
<tr>
<th>Lipid component</th>
<th>Rs value in solvent:</th>
<th>Presence (+) or absence (-) of lipid component in Indian strains:</th>
<th>Presence (+) or absence (-) of lipid component in reference species:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>C</td>
<td>MSW1</td>
</tr>
<tr>
<td>PL-1 (unidentified)</td>
<td>0:02</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S-TeGD</td>
<td>0:038</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>S-TGD-1</td>
<td>0:13</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>TGD-1</td>
<td>0:15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S-DGD-1</td>
<td>0:23</td>
<td>0:32</td>
<td>+</td>
</tr>
<tr>
<td>DGD-1</td>
<td>0:28</td>
<td>0:51</td>
<td>+</td>
</tr>
<tr>
<td>GL-1</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>C20-C20</td>
<td>0:20</td>
<td>0:39</td>
<td>-</td>
</tr>
<tr>
<td>C19-C23</td>
<td>0:20</td>
<td>0:44</td>
<td>-</td>
</tr>
<tr>
<td>PL-2 (unidentified)</td>
<td>0:07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PGP-Me</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>C20-C20</td>
<td>0:20</td>
<td>0:25</td>
<td>+</td>
</tr>
<tr>
<td>C20-C25</td>
<td>0:22</td>
<td>0:28</td>
<td>-</td>
</tr>
<tr>
<td>PGS</td>
<td>0:30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PG</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>C20-C20</td>
<td>0:60</td>
<td>0:77</td>
<td>+</td>
</tr>
<tr>
<td>C20-C25</td>
<td>0:63</td>
<td>0:82</td>
<td>-</td>
</tr>
<tr>
<td>GL-2 (unidentified)</td>
<td>0:80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PA</td>
<td>0:10</td>
<td>0:96</td>
<td>tr</td>
</tr>
</tbody>
</table>

Polar lipids. The polar lipids of the Indian strains of extreme halophiles were readily separated by TLC in solvents A, B or C and were identified by comparison of their mobilities to those of the lipids in the reference strains of *Haloferax*, *Halobacterium* and *Natronobacterium* (Table 2), and by NMR and mass spectrometry as described below. The C20-C20 and C19-C23 molecular species of PGP-Me, PG and GL-1 were best-resolved by TLC in solvent C, and were identified by FAB-MS as described below.

The non-alkaliphilic strains of group I (e.g. strain MSW1) showed the presence of S-DGD-1, DGD-1, and C20-C20 species of PGP-Me and PG, and the absence of PGs, characteristic of *Haloferax* strains (Torreblanca et al., 1986; Kates, 1993), whereas those of group II (e.g. strain MSW5) showed the presence of S-TeGD, S-TGD, TGD-1, and C20-C20 species of PGP-Me, PGs and PG, characteristic of *Halobacterium* strains (Torreblanca et al., 1986; Kates et al., 1993; Kates, 1993a, b) (Table 2).

In contrast, the lipids of the haloalkaliphilic strains (e.g. strain SSL1) contained both C20-C20 and C20-C25 species of PGP-Me and PG, and lacked any PGs, as reported previously for *Natronobacterium* strains (Tindall et al., 1984; Morth & Tindall, 1985; De Rosa et al., 1988) (Table 2). Surprisingly, however, an unidentified glycolipid (GL-1) was clearly detected on TLC plates of the polar lipids of alkaliphilic strains SSL1 and SSL6 by staining with the α-naphthol sugar reagent (Table 2). This observation is in contrast to all previously reported analyses of haloalkaliphile lipids, which indicated the absence of glycolipids in known haloalkaliphiles (Tindall et al., 1984; Morth & Tindall, 1985; De Rosa et al., 1988; Upasani & Desai, 1990). GL-1 also occurred as both C20-C20 and C20-C25 molecular species. It is of interest that a glycolipid spot with the same mobility as GL-1 could be detected on TLC plates of the polar lipids of the reference strain *N. gregoryi* when a high lipid load was applied (Table 2).

Quantitative composition (% by wt) of the polar lipid components of *Natronobacterium* strain SSL1 was found to be as follows: PGP-Me was the major lipid (approx. 72%, by wt) followed by PG (22%) and the novel glycolipid (GL-1, 6%). Small amounts (<1%) of PA and two unidentified phospholipids (PL-1 and PL-2), and traces of another unidentified glycolipid (GL-2) were also present. PL-1, PL-2 and GL-2 were not further investigated.

Identification of polar lipids in *Natronobacterium* strain SSL1

Phosphatidylglycerolmethylphosphate (PGP-Me). The PGP-Me component was separated into two molecular species by preparative TLC in solvent system C (Table 2),
and each isolated molecular species was subjected to negative FAB-MS and identified as the C_{20}-C_{20} (slower moving) species: [M−H]^{−}, m/z 897-9; [M+Na−H]^{−}, m/z 921.6 (calculated M = 900); and the C_{20}-C_{25} (faster-moving) species: [M−H]^{−}, m/z 969-7; [M+Na−H]^{−}, m/z 991.7 (calculated M = 970). Identification of these molecular species was confirmed by CI-MS of the corresponding lipid cores (diphytanylglycerol diethers) obtained after acid methanolysis, showing [M+1]^+ ion peaks with m/z 653 and 723, as expected for the C_{20}-C_{20} (M = 652) and C_{20}-C_{25} (M = 722) diethers, respectively. The C_{20}-C_{20} species (slower moving) was present in higher proportion than the C_{20}-C_{25} species (faster moving), in contrast to the lower proportions of the C_{20}-C_{20} species found in other natronobacteria, but similar to the findings for Natronococcus occultus (De Rosa et al., 1988).

The ¹H-NMR spectrum of PG-P-Me(NH₄)₂ (in CDCl₃) showed diagnostic signals that were essentially identical to those reported previously (Moldoveanu et al., 1990; Kates et al., 1993). The ¹³C-NMR spectrum of PG-P-Me was identical to that reported previously and clearly showed the presence of the P-O-CH₃ signal (doublet) at 53 p.p.m. (Kates et al., 1993; Stewart et al., 1988).

The water-soluble products of methanolysis were identified as glycerol diphosphate by TLC on cellulose plates in solvent I (Moldoveanu et al., 1990), as expected for PG-P-Me.

**Phosphatidylglycerol (PG).** As described for PG-P-Me, the PG component was also separated into two molecular species by TLC in solvent C (Table 2), and these were identified by FAB-MS as the C_{20}-C_{20} and C_{20}-C_{25} molecular species of PG: [M−H]^{−}, m/z 805-7 and 875-8, respectively; calculated M = 806 and 876, respectively. The identity of the two molecular species was confirmed by CI-MS analysis of the lipid cores, as described above for PG-P-Me. As was observed for PG-P-Me, the C_{20}-C_{20} molecular species of PG appeared to be present in higher proportion than the C_{20}-C_{25} species, in contrast to the proportions reported for other natronobacteria, but similar to those reported for Natronococcus occultus (De Rosa et al., 1988).

The water-soluble products of acid methanolysis contained glycerophosphate, as expected for PG. The ¹H-NMR spectrum showed the same signals for the phytanyl ether linked chains, for glycerol CH-O and CH₂-O groups, and for CH₂-O-P groups, but not for P-O-CH₃ groups, as in the spectrum of PG-P-Me (Kates et al., 1993); a signal at 3-63 p.p.m. (CH₃-CH=O in glycerol) was present, as expected for PG.

**Phosphatidic acid (PA).** This phosphorus-positive minor component was identified on the basis only of its TLC mobilities in solvents A and C (Table 2), and was not further characterized because of insufficient material.

**Novel diglucosylglycerol diether.** This novel glycolipid (GL-1) could not be completely separated from PG-P-Me by TLC in solvents A or B, but could be isolated in pure form by preparative TLC in solvent C, which was designed specifically for this purpose.

Acid methanolysis of GL-1 yielded only glucose as the water-soluble product and dihytanylglycerol as the hydrophobic product, identified by TLC in solvents H (cellulose plates) and G (silica gel plates), respectively. Quantitative sugar analysis and gravimetric estimation of the diether component gave a molar ratio of glucose:diether of 2:1, showing that GL-1 was a diglycosyl diether (designated DGD-4). Permethylation analysis of GL-1 yielded two partially methylated sugars, shown by GC-MS analysis of their alditol acetates (retentions relative to 1,5-diacyl-2,3,4,6-tetramethyl-β-glucitol: 1:00 and 1:33) to be 2,3,4,6-tetramethylglycol and 2,3,4-trimethylglucose, respectively. The two glucose units are thus linked 1→6.

The anomeric configuration of each glucose unit was studied by ¹H-NMR, which showed signals for the presence of both α- and β-glucosidic linkages at 4.13-4.15 p.p.m. (doublet, J, 7.5 Hz; anomeric H of methyl-β-glucoside, 4.35 p.p.m., J, 7.5) and at 4.613-4.625 p.p.m. (doublet, J, 3.75; anomeric H of methyl-α-glucoside, 4.68 p.p.m., J, 3.5) (see data in Kates, 1990). The fact that the 4.62 p.p.m. signal showed essentially no shift relative to that of α-methylglucolose, whereas the 4.13 p.p.m. signal was shifted downfield from the β-methylglucolose signal suggests that the terminal glucose is β-linked and the internal glucose attached to 2,3-diphanylglycerol is α-linked. Attempts to determine the anomeric configuration by the action of specific glucosidases were unsuccessful since no hydrolysis products were observed after incubation of GL-1 with these enzymes.

Negative FAB-MS of GL-1 showed the presence of two molecular ion peaks, [M−H]^{−}, with m/z 967-8 and 1037-6, corresponding to the C_{20}-C_{20} and the C_{20}-C_{25} molecular species with four double bonds each (calculated M, 976–8H = 968, and 1046–8H = 1038, respectively). This suggests that one of the lipid core chains may be isoprenoid rather than isoprenoid ion peaks, [M−H]^{−}, were also observed at m/z 989-7, 1057 and 1127, corresponding to hydroxylated and monounsaturated C_{20}-C_{20}-DGD-4 (M = 990), hydroxylated and diunsaturated C_{20}-C_{25}-DGD-4 (M = 1058) and hydroxylated and diunsaturated C_{20}-C_{25}-DGD-4 (M = 1128), respectively (see Ferrante et al., 1988; Sprott, 1992). The presence of these hydroxylated and unsaturated species was corroborated by ion fragment peaks at m/z 669-4, 731-6 and 805-5, corresponding to hydroxylated C_{20}-C_{20} diether (M = 668), hydroxylated and unsaturated (three double bonds) C_{20}-C_{25}-diether (M = 732) and hydroxylated and monounsaturated C_{20}-C_{25}-diether (M = 806), respectively.

The presence of saturated, unsaturated and hydroxylated lipid cores was confirmed by CI-MS of the intact GL-1 and of its hydrophobic products of mild acid methanolysis (Moldoveanu et al., 1990; Ekiel & Sprott, 1992). The following CI-MS ion peaks, [M+1]^+, were observed for the intact GL-1 (m/z): 653 (C_{20}-C_{20}-diether; calculated...
M = 652); 723 (C₂₀-C₂₅-diethe; calculated M = 722); 373, 355 (monophytylglcerol, C₂₀-MPG; calculated M = 372; M - 18 = 354); 443, 425 (C₃₅-MPG; calculated M = 442; M - 18 = 424). The hydrophobic products of acid methanolation showed ion peaks with m/z 311 (methoxyphytol and methxyisophytol, calculated M = 310); 297 (phytol, calculated M = 296); 281 (phytylen, calculated M = 280); 681 (monounsaturated methoxy-C₂₀-C₂₀-diethe; M = 680); 753 (methoxy-C₂₀-C₂₅-diethe; M = 752). All of these peaks are diagnostic of hydroxylated or unhydroxylated isoprenoid chains, which are readily cleaved from the diether lipid cores, and of the hydroxylated lipid cores themselves (Ferrante et al., 1988; Moldoveanu & Kates, 1988; Moldoveanu et al., 1990; Ekiel & Sprott, 1992). Parent ion peaks, [M + H]⁺, of the intact diether lipid cores were also present at m/z 653 (saturated C₂₀-C₂₀-diethe; calculated M = 652); 669 (HO-C₂₀-C₂₀-diethe; calculated M = 668); 717 (unsaturated C₂₀-C₂₅-diethe; calculated for three double bonds; M = 716); 732 (unsaturated OH-C₂₅-C₂₅-diethe; calculated for three double bonds, M = 732); and 789 (diunsaturated C₂₅-C₂₅-diethe; calculated M = 788).

The presence of unsaturated isoprenoid chains in GL-1 was further supported by its ¹H-NMR spectrum which showed signals at 1-62 p.p.m. for allylic methyl groups, at 2-08 p.p.m. for allylic methylene groups, and at 5-0 p.p.m. for olefinic isoprenoid protons (Moldoveanu et al., 1990).

The data thus show that the most probable structure of the new glycolipid DGD-4 is as shown in Fig. 1(a): glucopyranosyl-β1 → 6-glucopyranosyl-α1 → 1-glycerol diethe. The alternative structure, glucopyranosyl-α1 → 6-glucopyranosyl-β1 → 1-glycerol diethe (Fig. 1b), is less likely, but has not yet been eliminated. The diether core of GL-1 contains C₂₀-C₂₀, C₂₀-C₂₅ and C₂₅-C₂₅ saturated, unsaturated and/or hydroxylated molecular species; the C₂₀-C₂₀ and C₂₀-C₂₅ species are present in approximately equal amounts, while the C₂₅-C₂₅ species is present only in low amounts.

**DISCUSSION**

The extreme-alkaliphile phenotype encompasses three different classes of archaeal membranes: the exclusively C₆₀-C₆₀ bilayer type found in non-alkaliphilic halophiles (Ross et al., 1981; Kates, 1978, 1993a, b); a 'zip'-type membrane with about equal proportions of C₂₀-C₂₀ and C₂₀-C₂₅ core lipids in haloalkaliphiles and halococci (De Rosa et al., 1982, 1983; Moldoveanu et al., 1990); and the mixed bilayer/zip-type composed of major proportions of C₂₀-C₂₅ core lipid with lesser amounts of the C₂₀-C₂₀ and C₂₀-C₂₅ species as in *Natronobacterium* strains, or major proportions of the C₂₀-C₂₀ species and lesser amounts of the C₂₀-C₂₅ and C₂₀-C₂₅ species as in *Natrorococcus* strains (De Rosa et al., 1983, 1988). The relative proportions of each of the three molecular species of lipid cores and the resulting bilayer type is dependent largely on genetic and phenotypic factors and on growth conditions of the extreme halophiles (Tindall, 1985; Morth & Tindall, 1985). These factors may account for the fact that the lipids of the Indian strains of *Natronobacterium* examined here are more similar to those of *Natronococcus* strains with respect to their core lipid profile than to those of *Natronobacterium* studied previously (De Rosa et al., 1988).

The results of the present survey of archaeobacteria from saline environments in India show that, on the basis of their polar lipid composition, the non-alkaliphilic halobacteria from marine salterns at Mithapur comprise two groups belonging to the genera *Haloflexus* (group I, strains MSW1–MSW3) and *Halobacterium* (group II, strains MSW4–MSW6), respectively. The haloalkaliphilic strains (SSL1–SSL6) from Sambhar Salt Lake brines clearly belong to the genus *Natronobacterium*, but their lipid composition differs somewhat from that reported previously for *N. gregoryi* and other haloalkaliphiles (Ross et al., 1985; Grant & Larsen, 1989) in that a novel glycolipid (DGD-4) was detected, possessing hydroxylated and unsaturated lipid cores. A glycolipid with the same TLC mobility as DGD-4 was also detected in the type strain *N. gregoryi*. It should be noted that unsaturated (isoprenoid) chains have been identified previously in polar lipids of *Halococcus* species from Spain (Moldoveanu et al., 1990) and in lipid biosynthetic intermediates in *H. cutirubrum* (Moldoveanu & Kates, 1988), but hydroxylated lipid cores have previously only been reported in methanogen species of archaeobacteria (Sprott, 1992). It is possible that hydroxylated diether lipid cores may be generally distributed in extreme halophiles and have been missed because of the relatively harsh hydrolytic procedures used in their isolation (Ekiel & Sprott, 1992; Sprott, 1992). However, it is not clear what function there would be for the presence of a hydroxyl group at the 3' position of the phytanyl group in the lipid core of the glycolipid DGD-4, which would make the lipid core molecule less...
hydrophobic and also less thermostable and more susceptible to hydrolytic breakdown.

Apart from having hydroxylated and unsaturated diether lipid cores, the glycolipid DGD-4 is further unique in having a \( \beta_1 \rightarrow 6 \)-linked diglucosyl sugar moiety rather than the \( \alpha_1 \rightarrow 2 \)-linked mannosyl-glucosyl glycolipid group (with sugar or sulfate substitution at C-3 and/or C-6 of the mannos residue) found in glycolipids diethers of all extreme halophiles examined so far (see Kushnera et al., 1982; Torreblanca et al., 1986; Kates, 1990, 1993a, b), with the following exceptions: (i) the mannosyl-2-sulfate-\( \alpha_1 \rightarrow 4 \)-glucosyl diether in H. sodomense (Trincone et al., 1990); (ii) the mannosyl-2-sulfate-\( \alpha_1 \rightarrow 2 \)-glucosyl diether in H. trapanicum (Trincone et al., 1993); and (iii) the mannosyl-2,6-disulfate-\( \alpha_1 \rightarrow 2 \)-glucosyl diether in an extreme halophile (strain 172) from Japan (Matsubara et al., 1994).

However, the \( \beta_1 \rightarrow 6 \)-diglucosyl structure in DGD-4 is even more unusual, since it bears a striking resemblance to the \( \beta_1 \rightarrow 6 \)-diglucosyl(gentiobiosyl)diether glycolipid (hydroxylated or unhydroxylated) present in several species of methanogens (Sprott, 1992). The presence in haloalkaliphiles of this unusual 'methanogen-like' glycolipid (DGD-4) raises the question whether the Natrobacteria from Indian saline environments, or in general, may have an evolutionary relation to the methanogens (see Kates, 1993a, b). Further surveys of glycolipids in haloalkaliphiles, and perhaps also halophilic methanogens, some species of which have recently been found (Paterek & Smith, 1985), may be of interest in this connection.

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