Ether Polar Lipids of Methanogenic Bacteria: Structures, Comparative Aspects, and Biosyntheses

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INTRODUCTION

Lipids of methanogenic bacteria were first analyzed in 1978 by Tornabene et al. (100) and Makula and Singer (70). They found that the lipids of methanogenic bacteria consisted of di- and tetraethers of glycerol and isoprenoid alcohols. These types of ether lipids had been previously identified in the extreme halophiles (Halobacterium species [50] and thermoacidophiles (Sulfolobus and Thermoplasma species [17, 64]) in the 1960s and the 1970s, respectively. Since then, the characteristic glycerol ether lipids became one of the most remarkable features that distinguish members of the domain Archaea (archaeabacteria) from those of the domains Bacteria (eubacteria) and Eucarya (eukaryotes) (105). The complete structural determination of ether polar lipids of a methanogen (Methanospirillum hungatei) was first described by Kushwaha et al. in 1981 (63). In the mid-1980s collaborations between lipid biochemists and methanogen bacteriologists were formed in a few laboratories. The outcome was a significant advance in methanogen lipid biochemistry by Ferrante et al. (28-33), Morii et al. (74-76), and Nishihara et al. (81-89), who identified nearly 40 novel lipids from seven species of methanogenic bacteria. These were as unique as other compounds from methanogens (coenzymes of methanogenesis [25] or pseudomurein [59]).

Many specific characteristics have been discovered for methanogen lipids, in contrast to the structures of ether lipids of the extreme halophiles and the sulfur-dependent thermophiles. The studies of methanogen lipids in the past several years have been stimulated by the isolation, description, and taxonomic classification of new and unique methanogens. In most recent examples, analyses of lipids from a new methanogen species have led to the discovery of new
lipids. Methanogenic bacteria are relatively diverse in phylogeny, morphology, and cell surface structure despite having a single energy-acquiring metabolism, i.e., methanogenesis. The structures of methanogen lipids not only are more diverse than the above-mentioned phenotypes but also parallel the taxonomy of methanogens. It is therefore necessary to briefly outline the taxonomy before reviewing methanogen lipids.

During the last 10 years, a wide variety of methanogenic members of the Archaea have been isolated and characterized. Of 62 species of methanogenic bacteria validated in the International Journal of Systematic Bacteriology (as of January 1993), 49 were isolated after 1980. Methanogens are mesophilic or thermophilic strict anaerobes that are found together with anaerobic (eu) bacteria or anaerobic protozoa. All methanogenic bacteria form methane, which is produced from a rather restricted list of substrates (H₂ + CO₂, formate, acetate, methanol, methylamines, secondary alcohols + CO₂, primary alcohols + CO₂, and methyl sulfides). However, they show a great diversity in their cell morphology and the chemical nature of their cell surface components.

All methanogen genera that have been validated to date are shown in Table 1. Methanogens are classified into three orders (3, 7): Methanobacteriales, Methanomicrobiales, and Methanococcales. Cells of members of the Methanobacteriales are long or short rods with rigid pseudomurein cell walls, and most of them show a positive reaction to Gram staining (8). They utilize H₂ + CO₂ as methanogenic substrates, with the one exception of Methanospirillum stadtmanae (72), which uses only methanol + H₂. Members of the order Methanococcales and the family Methanococcaceae produce methane from H₂ + CO₂ and have a proteinaceous cell surface structure (9, 104). Most species of the former family have been isolated from marine environments. Some of the methanogens of the families Methanobacteriaceae, Methanococcaceae, and Methanomicrobiaceae can also produce methane from formate. Methanopyrus kandleri (optimum temperature, 98°C; a member of an undefined order [62]), Methanothermus spp. (optimum temperature, 83°C [97]), and Methanococcus jannaschii (45) are the most extremely thermophilic methanogens. Members of the order Methanomicrobiales show various morphologies: irregular cocci, spirilla, filaments, irregular flattened plates, and packets (9, 10, 96, 109). The family Methanosarcinaceae contains all the acetoclastic and methylotrophic methanogens. Some of them can also utilize H₂ + CO₂ but not formate as methanogenic substrates. The cell surface matrix of Methanosarcina is composed of methanochondroitin (61), a nonsulfated acidic heteropolysaccharide. Methanotrix (Methanoseta) cells are filamentous and produce methane only from acetate, an important intermediate in anaerobic digestion. Three genera of halophilic methanogens (Methanohalophilus, Methanohalobium, and Halomethanococcus, with six species) belong to the family Methanosarcinaceae.

Two kingdoms (Crenarchaeota and Euryarchaeota [105]) of the domain Archaea (in which there are three major phenotypes: extreme thermophiles, methanogens, and extreme halophiles) are phylogenetically distinctly related and show a closer relatedness to each other than to members of the domains Bacteria and Eucarya (105). All members of the Archaea contain common glycerol ether lipids. There are four fundamental and common differences between the ester lipids from the Bacteria and Eucarya and the ether lipids from the Archaea. The first is the nature of the linkage between the glycerol and hydrocarbon chains (ester and ether). The second is the nature of hydrocarbon chains themselves (straight fatty acyl chains of the Bacteria and Eucarya in contrast to highly methyl-branched saturated isoprenyl chains of the Archaea). The third is the stereochemical structure of the di-O-radyl glycerol moiety (sn-1,2-di-O-radyl glycerol for the Bacteria and Eucarya and sn-2,3-di-O-radyl glycerol for the Archaea). The final difference is the presence of the tetraether type of lipid in members of the Archaea. Recent phylogenetic studies have revealed a closer relatedness of Archaea to Eucarya than to Bacteria (44, 105), although there are some examples of specific relations of Bacteria and Eucarya at the molecular level (41, 113).
This fact raises the question of the origin of the archaean ether lipids, that is, when and how ester lipids replaced ether lipids or vice versa as cell membrane constituents. This question assumes that the domains Archaea, Eucarya, and Bacteria have a common ancestor and that organisms with ester lipids evolved from organisms with ether lipids or vice versa. It is also possible that the primeval membrane was made of protein (111). A prerequisite for discussing the question of the origin of ether lipids is to have a perspective of the overall structures of archaean lipids and to consider them in a comparative way. Because methanogen lipids are structurally diverse, it is important to have an overview of the range of structural diversity of all lipids. This paper focuses on recent advances in the studies on methanogen lipids. Several excellent reviews concerning archaean lipids have been published (19, 50, 65, 66). The first aim of this review is to summarize the more recent findings of novel and unique structures of lipids from methanogens. The second is to present comparative aspects of lipids among methanogens and among archaean groups. Lastly, we briefly discuss the biosynthesis of methanogen lipids.

NOMENCLATURE OF ARCHAEOAL ETHER LIPIDS

Archaean ether lipids lacked systematic names and had only lengthy names as analogs of ester lipids (for example, an ether analog of phosphatidylserine) or confusing laboratory designations (for example, DGT, DGD, and PL1). Furthermore, it is more confusing to use the word "diether" as the name of the compound representing 2,3-di-O-phytanyl glycerol diether since it is properly used to refer to only the presence of two ether linkages in a compound and does not specify the structure of groups on both sides of the ether linkages. Therefore, Nishihara et al. (87) proposed a new nomenclature for archaean lipids in 1987. The nomenclature is briefly explained in the following paragraph and will be used throughout this paper.

The 2,3-di-O-isopropyl sn-glycerol diether and dieterater-penediy1 glycerol tetraether (ether bonds are located at the sn-2 and sn-3 positions of glycerols) are defined as archaeol and caldarchaol, respectively. Archaetidic acid and caldarchaetidic acid are monophosphate esters of archaeol and caldarchaol, respectively. By condensing archaetidic acid or caldarchaetidic acid with an alcohol (serine, ethanolamine, inositol, etc.), a phosphodiester is formed. These lipids are named as derivatives of archaetidic acid or caldarchaetidic acid, for instance, archaetidylerine. Glycoside derivatives of archaeol, caldarchaol, and the tetraether type of phospholipids are called glycosyl archaeol, glycosyl caldarchaol, and glycosyl caldarchaetidyl-X (X is serine, etc.), respectively. Polar lipids with archaeol or caldarchaol as the core lipid are sometimes called the diether type of polar lipids or the tetraether type of polar lipids, which is abbreviated as diether or tetraether polar lipids.

STRUCTURES OF POLAR LIPIDS FROM VARIOUS METHANOGENS

Polar lipids of methanogens consist of a nonpolar part made up of archaeol or caldarchaol (core lipids) and polar head groups such as an organic phosphate ester or sugar residue. The core lipid structures are archaeol and caldarchaol in most cases. In addition, three derivatives of archaeol have been discovered (Fig. 1). Macroyclic archaeol (Fig. 1c) was found in Methanococcus jannaschii, and two isomers of hydroxyarchaeols (Fig. 1d and e) were detected in many members of the families Methanococaceae and Methanosarcinaceae (see below). Polar lipids that were found in methanogens and whose structures have been determined are discussed in this section.

Methanobacteriaceae

Methanobacterium thermoautotrophicum. Methanobacterium thermoautotrophicum is one of the most thoroughly studied methanogens in terms of both methanogenesis and other biochemical aspects. It was selected as the organism of choice for mass culturing of a methanogen for lipid studies, since the appearance of contaminants in a large fermentor was not a problem when an inorganic medium and high temperature were used.

The caldarchaol core was predominant in the total lipid of Methanobacterium thermoautotrophicum ΔH (75 to 83 mol%). The polar lipids of this organism were separated into 23 or more spots by two-dimensional thin-layer chromatography (TLC) (Fig. 2) (82). On TLC there are at least five pairs of spots with slightly different mobilities. These spots were identified as di-(lower Rf values) and tetaether types of polar lipids with the same polar head group (Table 2). The spots that make up a pair are designated by the same spot designations with the suffix a or b (for example, PNL1a and PNL1b). The structures of 15 lipids from Methanobacterium thermoautotrophicum ΔH have been determined; these lipids account for 91 mol% of the total polar lipids in this species (82, 84, 87, 88). Thirteen of the 15 lipids are bare archaeol, bare caldarchaol, two glycolipids [gentiobiosyl (β-Glc(1-6)-β-Glc) archaeol and gentiobiosyl caldarchaol], six phospholipids, and three phosphoglycolipids (Fig. 3). The two other phospholipids are archaetidic and caldarchaetidic acids (84). The polar head groups of 11 lipids are simply inositol, serine, ethanolamine, or gentiobiosyl groups. These phospholipids and phosphoglycolipids are easily classified into three groups on the basis of phosphoric
TABLE 2. Previous designations and proposed names of ether lipids identified in Methanobacterium thermoautotrophicum*  

| Previous designation | Proposed name |
|----------------------|---------------|
| PNL1a                | Caldarchaetidylethanolamine |
| PNL1b                | Archaetidylethanolamine |
| PNL2a                | Caldarchaetidylserine |
| PNL2b                | Archaetidylethanolamine |
| PL2a                 | Caldarchaetidyl-myco-inositol |
| PL2b                 | Archaetidyl-myco-inositol |
| PL4                  | Archaetidyl-acid |
| PL5                  | Caldarchaetidyl acid |
| PNLGl1               | Gentiobiosyl caldarchaetidylethanolamine |
| PNLGl2               | Gentiobiosyl caldarchaetidylethanolamine |
| PGL1                 | Gentiobiosyl caldarchaetidylserine |
| PGL2                 | Gentiobiosyl caldarchaetidylserine |
| GL1a                 | Gentiobiosyl caldarchaetidylethanolamine |
| GL1b                 | Gentiobiosyl caldarchaetidylserine |

* Data from references 82, 84, 87, and 88. See Figure 2 for the previous designations.

FIG. 2. Two-dimensional TLC of the total lipid of Methanobacterium thermoautotrophicum. TLC was developed first in the vertical direction with a solvent of chloroform–methanol–7 M aqueous ammonia (60:35:8) and next in the horizontal direction with a solvent of chloroform–methanol-acetic acid-water (60:30:15:5). The identities of major polar lipids designated in this figure are shown in Table 2. NL, neutral (nonpolar) lipids. Symbols: III, acid molybdate positive; II, a-naphthol positive; *, ninhydrin positive. Other spots have not been identified. Reproduced from reference 82 with permission of the Japanese Biochemical Society.

Polar lipids. For example, the serine heptad contains archaeol, caldarchaetidylserine, caldarchaetidylethanolamine, gentiobiosyl archaeol, gentiobiosyl caldarchaetidylserine, and caldarchaetidylserine. The major lipids of Methanobacterium thermoautotrophicum ΔH were therefore grouped into three heptads. This regularity is the most remarkable characteristic of the lipid structures. The regularity is summarized as follows: (i) the same kind of polar head group found in diether lipids is also present in tetrather lipids and vice versa; (ii) one polar head group found in tetrather lipid has the same stereochemical structure as that of the corresponding diether lipid; (iii) two polar head groups on each of two glycerol residues of tetrather lipids are not the same, but one is a glycosyl residue and the other is a phosphoric ester. Gentiobiosyl caldarchaetidylserine is consistently the most abundant lipid.

Methanobrevibacter arboriphilicus. A complete inositol heptad was also found in Methanobrevibacter arboriphilicus A2 (75). Gentiobiosyl caldarchaetidylserine was found to be the predominant polar lipid in several members of the Methanobacteriaceae and was designated the signature lipid of this family (75). Archaetidylserine was found in the above two organisms and other members of the Methanobacteriaceae as the first-identified primary amino group-containing (ninhydrin-positive) ether phospholipid in the domain Archaea (58, 74, 76).

Methanococcaceae

Methanococcus voltae. The lipids of Methanococcus voltae were the first analyzed in the family Methanococcaceae (Fig. 4) (31). Methanococcus voltae contains an unusually high proportion (63% of total polar lipids) of a glycolipid (gentiobiosyl archaeol [Fig. 4b]). The other glycolipid identified was monoglycerol archaeol. A novel phospholipid, archaetidyl-N-acetylgalactosamine (Fig. 4a), was also found. The most distinctive feature of this lipid is the phosphoglycosidic group, which is linked directly to archaeol. This kind of linkage has not been found in other organisms. The caldarchaetidyl core was not detected. The presence of ninhydrin-positive lipids (one of which is presumably nonacetylated archaetidylglycerol) was suggested by Ferrante et al. (31).

Methanococcus jannaschii. Methanococcus jannaschii is one of the extremely thermophilic methanogens, which grows at temperatures up to 86°C (45); it was isolated from the deep-sea hydrothermal vent in the East Pacific Rise (depth, 2,600 m). The lipids of this bacterium are very interesting from the point of view of its extreme thermophility. Besides the usual archaeol and caldarchaetidyl, a unique glycerol ether core lipid was identified in this organism. It was identified as macrocyclic archaeol, in which a 40-carbon bifunctional 1,32-biphytanediyl (3,7,11,15,18,22, 26,30-octamethyldirotacamethylene) group was etherified at the sn-2 and sn-3 positions of glycerol, forming a 36-member macrocyclic diether compound (Fig. 1c) (14). The composition of core lipids varies with the growth temperature. At 45°C (close to the lowest temperature for growth of this bacterium), archaeol accounts for 80% of the total core. Caldarchaetidyl and macrocyclic archaeol increase up to 40% each at 75°C (near-optimal temperature [95]). The structures of four polar lipids with the macrocyclic archaeol as the core lipid have been determined (33) and are presented in Fig. 5. These polar groups are 6-(aminoethylphospho)-β-d-glucopyranose, β-d-glucopyranose, gentiobiosyl, and phosphoethanolamine. The first three lipids (glycolipids)
contain macrocyclic archaeol linked through glycosidic linkages, and the fourth is a phospholipid containing a phosphodiester linkage. 6-(Aminoethylphospho)glucosyl archaeol (Fig. 5a) has a glucosyl archaeol structure typical of archaeal glycolipids; however, it is unique because the glucose residue is phosphorylated. The more common archaeolylethanolamine is also present. The five lipids make up 82% of the total lipids, and of these, 6-(aminoethylphospho)-β-p-glucopyranosyl macrocyclic archaeol accounts for 38% of the total. In this bacterium, 68% of the polar lipids contained carbohydrate, as in *Methanococcus voltae*.

**Methanomicrobiaceae**

The structures of the lipids of three members of the *Methanomicrobiales* (Methanospirillum hungatei GP1, Methanothrix soehngenii [Methanoseta concilii] GP6, and Methanosarcina barkeri MS) have been elucidated.

**Methanospirillum hungatei.** Kushwaha et al. (63) reported the structures of polar lipids from *M. hungatei* GP1 in 1981 as the first methanogen polar lipids. These lipids consist of two phosphoglycolipids (both tetraether type) and four glycolipids (two tetraether and two diether types). The glycosyl residues of the six lipids comprise only two species: β-glucopyranosyl(1-2)β-galactofuranosyl and β-galactofuranosyl(1-6)β-galactofuranosyl. The occurrence of galactofuranose residues in glycolipids is uncommon. The phosphate ester group of the phosphoglycolipids is sn-glycerol 3-phosphate (Fig. 6). In 1987 Ferrante et al. (32) identified two novel aminopolyol residues in phospholipids as N,N-dimethylaminopentanetetrol and N,N,N-trimethylaminopentanetetrol by nuclear magnetic resonance (NMR) and mass-spectral analyses. These groups were bound to archaeol through phosphodiester linkages to make archaetidyl(N,N-dimethylamino)pentanetetrol and archaetidyl(N,N,N-trimethylamino)pentanetetrol, respectively (Fig. 7a and b). The presence of archaetidyl-1′-sn-glycerol reported in 1981 (63) was not confirmed (32). Archaetidyl(N,N,N-trimethylamino)pentanetetrol is the only Dragendorff reagent (reactive to quaternary ammonium group)-positive lipid found in members of the *Archaeae*. Archaetidyl(N,N-dimethylamino)pentanetetrol is partially positive to the Dragendorff reagent. Polar head groups found in other families of methanogens (inositol, ethanolamine, and serine) were not detected in *Methanospirillum hungatei*. Two-dimensional TLC of the total lipid of *Methanospirillum hungatei* revealed 15 or more spots, several of which were Dragendorff positive and almost as polar as the tetraether type of phosphoglycolipids (57). Considering the occurrence of two kinds of glycosyI groups and two kinds of aminopentanetetrol residues in the bacterium, it is not unlikely that a few more aminopentanetetrol lipids with a caldarcahol core are present, which suggests a possibility of aminopentanetetrol heptads. Moreover, Kushwaha et al. (63) detected a trace amount of archaetidyl-3′-sn-glycerol which had the same stereochemical structure as the glycerophosphate moiety of the two phosphoglycolipids.

**Methanosarcinaceae**

*Methanothrix soehngenii*. A new acid-labile glycerol ether core lipid (Fig. 1d) (30) was identified in *M. soehngenii* GP6
(also known as *Methanothrix concili* and *Methanosaeta concili*) (for a discussion of the nomenclature of this organism, see references 6 and 91). Usually, strong-acid methanolyis (2.5% HCl-methanol at 65°C for 5 h) or 5% HCl-methanol at 100°C for 3 h (82)) is used to prepare glycerol ether core lipids by splitting off the polar head groups; however, the acid-labile core lipid of this bacterium was degraded to various compounds including monoalkylglycerol under these strong methanolytic conditions. The cause of the lability of the lipid is the presence of a hydroxyl group bound at the 3′ position of the phytanyl chain linked to the sn-3 position of the core glycerol moiety. Archaeol containing 3′-hydroxyphytanyl chain is easily hydrolyzed in the presence of H^+ to yield monoalkylglycerol. Therefore, Ferrante et al. (30) developed mild-acid methanolysis (0.18% HCl-methanol at 50°C for 24 h) for the preparation of intact hydroxyarchaeol. Because these conditions are not sufficient to break all the phosphodiester bonds of phospholipids, a significant amount of polar lipids remained unhydrolyzed. The hydroxyarchaeol core made up 30% of the total.

The structures of eight polar lipids of *Methanothrix soehn- genii* were determined (Fig. 8 and 9) (28, 29). The major lipids were two diglycosylated lipids (Fig. 8d and 9d), which made up 59% of the polar lipids, and archaeidylglycerol (which made up 24%). Glycolipids of this organism contain three kinds of hexose residues: glucose, galactose, and mannose.

The stereochemical structure of phospho-myoinositol of archaeidylglycerol from *Methanothrix soehn- genii* was concluded to be myo-1-inositol 1-phosphate (see Fig. 4 of reference 29) on the basis of the value of [α]_D = -10.0° (pH 2.0), which was compared with that of phosphoinositol prepared from soybean phosphatidylinositol (92). Although the structural formula shown by Pizer and Ballou (92) shows 1L-myoinositol 1-phosphate (named according to the IUPAC-IUB Recommendations of Nomenclature of Cyclitol [43]), these authors presented only the value of [α]_D, and did not determine the absolute configuration of soybean phospho-myoinositol. The 1L configuration depicted in their paper (92) therefore had no experimental basis at that time. The correct structure was established by the same laboratory in 1960 to be 1D-myoinositol 1-phosphate (4). Thus levorotatory phospho-myoinositol is 1D-myoinositol 1-phosphate, which is identical to that from *Methanobacterium thermautotrophicum* (Fig. 3). It should be noted that 1D-myoinositol 1-phosphate, named according to the IUPAC-IUB nomenclature (43), is designated 1-myoinositol 1-phosphate in the Fletcher-Anderson-Lardy nomenclature system (34).

*Methanosarcina barkeri*. De Rosa et al. (20) reported that the lipid core of *Methanosarcina barkeri* DSM800 (MS) consists of diphytanyltetritol, caldarchaeol with various numbers of cyclopentane rings, glycer-archaeol with hydrocarbon chains with 20 and 25 carbons, and typical archaeol. This description has been corrected independently by Sprott et al. (94) and by Nishihara and Koga (85), who detected only the usual archaeol and hydroxyarchaeol as the core lipids of the organism. The hydroxyarchaeol of *Metha- nosarcina barkeri* resembles hydroxyarchaeol from *Methano- thrix soehn- genii* but differs in the position of glycerol on which the hydroxyphytanyl group is linked. The 3′-hydroxy-phytanyl chain is etherified at the sn-2 position of glycerol in *Methanosarcina barkeri* (Fig. 1e) and at the sn-3 position in *Methanothrix soehn- genii* (Fig. 1d). This hydroxyarchaeol is also acid labile. The main product of acid methanolyis is 3-monophytanyl sn-glycerol, which shows a positive response to the periodate-Schiff reagent as a result of the presence of the vicinal hydroxyl groups (85), in contrast to *Methanothrix* hydroxyarchaeol. The lower mobility and the staining response of the degradation products on TLC resemble the behavior of diphytanyltetritol, archaeol with C_20 and C_25 chains, or caldarchaeol. The identification of these
FIG. 6. Lipids of *Methanospirillum hungatei*. PGL-I, glucopyranosylgalactofuranosyl caldarchaeidylglycerol; PGL-II, digalactofuranosyl caldarchaeidylglycerol; DGT-I, glucopyranosylgalactofuranosyl caldarchaeol; DGT-II, digalactofuranosyl caldarchaeol; DGD-I, glucopyranosylgalactofuranosyl archaeol; DGD-II, digalactofuranosyl archaeol. Reproduced from reference 63 with permission of Elsevier Science Publishers and M. Kates.

compounds based solely on TLC mobilities may lead to misidentification, as pointed out by Ferrante et al. (30). Nishihara et al. (85) reported that hydrocarbon chains other than the 20-carbon chain were less than 1/600 (the lowest limit of detection), if any, of the phytanyl chain. The reason for the discrepancy between the results of De Rosa et al. (20) and Nishihara et al. (85) or Sprott et al. (94) in the occurrence of caldarchaeol cores with cyclopentane rings is not known. The molecular ratio of archaeol to hydroxyarchaeol in *Methanosarcina barkeri* is 2:3 (85).

Recently, five polar lipids of *Methanosarcina barkeri* MS have been identified by Nishihara and Koga (85). The hydroxyarchaeol-containing phospholipids hydroxyarchaeidylserine and hydroxyarchaeidylinositol (Fig. 10) were identified, as were the usual archaeol-containing phospholipids with the same polar head groups, archaeidylserine and archaeidylinositol. Because the hydroxyarchaeol-containing lipid and the usual archaeol-containing lipid with the same polar group showed similar but slightly different mobilities on TLC, they looked like paired lipids on TLC. The fifth lipid identified in this organism was the most abundant and unusual. The lipid contained archaeol as the core lipid.
and phospho-myoinositol and unacetylated glucosamine as polar groups. The detailed stereostructure of the glucosaminylinositol was 6-(2'-amino-2'-deoxy-a-glucopyranosyl)-1-phosphate (Fig. 11) (189). It is interesting that this structure is the same as the common part of the glycosylated phosphatidylinositol anchor of eukaryotic membrane-bound proteins. It may be assumed that this lipid is the first "hybrid lipid" based on the fact that the glucosaminylinositol moiety has been found only in eucaryal membrane anchor and the glycerol ether core portion is specific to the domain Archaea. Archaetidylethanolamine and hydroxyarchaetidylethanolamine were also found in Methanosarcina barkeri (86).

**Polar Lipids as a Chemotaxonomic Marker**

**Thin-Layer Chromatography Patterns**

As described above, the structures and compositions of the polar lipids of methanogens are divergent and complex. When the total lipid of a methanogenic bacterial species was analyzed on two-dimensional TLC, 5 to 25 spots, depending on the methanogen species, were detected. This number is much larger than that in members of the domain Bacteria; for example, usually only four or five spots are detected on
TLC of Escherichia coli lipids (2). The complexity of the lipid composition of methanogens is caused not only by the diversity of polar head groups but also by the occurrence of two or more kinds of core lipids such as the combination of archaeol, caldarchaeol, hydroxyarchaeol, and macrocyclic archaeol as well as the occurrence of the tetraether type of phosphoglycolipids that have two kinds of polar groups on one molecule. Grant et al. (39) first reported the TLC patterns of various methanogens with taxonomic implications. Nevertheless, because none of the spots was structurally identified and no mobility marker was cochromatographed in their experiments, it was hard for other workers to compare patterns from other methanogens with theirs. Because of the variability of mobility on TLC, depending on the kinds and activation conditions of TLC plates and even the humidity of the laboratory, spots with slightly different mobilities were difficult to distinguish on separate TLC plates. Koga et al. (58) tried a method of overcoming the inherent ambiguity of TLC mobility by using $^{32}$P-labeled archaeidylserine and $^{32}$P-labeled archaeidylethanolamine isolated from Methanobacterium thermoautotrophicum as internal standards in two-dimensional TLC. Complete superimposition of a radioactive spot and a chemically visualized spot confirmed the identity of the respective spots.

Koga et al. (58) reported the following distribution of polar lipids among methanogens as determined by TLC of total lipids with radioactive internal standards. The ninhydrin-positive amino-group-containing polar lipids were found in all the methanogens analyzed so far. Archaeidylserine was detected in members of the Methanobacteriaceae and Methanococcales and Methanosarcina species. Among the members of the Methanobacteriaceae, Methanobacterium species contained archaeidylethanolamine but Methanobrevibacter species did not. A characteristic tetraether phosphoglycolipid, gentiobiosyl caldarchaeidylinositol, was specifically found in members of the Methanobacteriaceae (58, 75). Another characteristic phospholipid, designated PX, was specific to members of the Methanomicrobiales (58). Recently, PX was tentatively identified as unmethylated archaeidylaminopentanetetrol (Fig. 7c) (57). The comparison of TLC patterns of total lipids had been carried out before a number of unique polar lipids were identified. However, the TLC patterns suggested the significance of polar lipids in methanogen taxonomy and have therefore been recommended when describing new taxa of methanogenic bacteria (11).

**FIG. 11. Structure of glucosaminy]archaeidyl-myo-inositol.**

Although radioactive internal standards of known lipids were useful for surveys of the distribution of lipids among methanogens, a TLC pattern of the total lipid is less informative about lipid structure. Only the relative locations of lipid spots on a TLC plate could be compared with another chromatogram of total lipid from another methanogen or a chromatogram reported by other workers. Although the best way to show the relationship between lipids is to compare their complete structures, the determination of the complete structure of a lipid is a laborious and time-consuming effort that is not suitable for routine taxonomic work.

A method that gives more information about lipid structure than TLC and is less time-consuming than complete structure determination is the analysis of the component parts of polar lipids (analyses of polar lipid-constituting moieties) in the total lipid such as the presence or absence of polar head groups, monosaccharide units, core portions, and hydrocarbon chains. This approach provides important information concerning the lipid chemistry of a specific methanogen, although it disregards the arrangement of the moieties. To examine this approach, we have been analyzing lipid component parts from approximately 18 species of methanogens from 12 genera belonging to 5 families (56).

The result is shown in Table 3. Archaeol was present in all species of methanogens examined, so this core lipid cannot be used for taxonomic purposes. Caldarchaeol core lipid was found in the families Methanobacteriaceae, thermophilic Methanococcales, and Methanomicrobiales but not in Methanosarcinae and mesophilic Methanococcus species. Hydroxyarchaeol core lipids were present in Methanosarcina, Methanothrix, and mesophilic Methanococcus species.

Inositol was a constituent of all the polar head groups of the phospholipids from the families Methanobacteriaceae and Methanosarcinaceae but was not detected in Methanococcus species or the family Methanomicrobiales. Phosphoethanolamine was the marker of the genus Methanobacterium in the family Methanobacteriaceae; that is, ethanolamine is present in Methanobacterium sp. but not in Methanobrevibacter arborphilicus. This is confirmed by TLC profiles of total lipids of other Methanobrevibacter species (58). Di- and trimethylaminopentanetetrols were recognized only in species of the family Methanomicrobiaceae. As mentioned above, unmethylated aminopentanetetrol was also found as a unique lipid, PX, in a few methanogens of the family Methanomicrobiaceae, including Methanospirillum hungatei, Methanolancina paynteri, and Methanogenium cariic (58). Therefore aminopentanetetrols, irrespective of methylation, seem to be a specific marker of the family Methanomicrobiaceae.

Glucose was found as a sugar moiety of glycolipids in all the methanogenic species studied so far and was the sole sugar component of glycolipids in many methanogens. Galactose occurs in the glycolipid of members of the Methanomicrobiaceae in addition to glucose. Mannose is a constituent of glycolipids in only Methanotrichs soehngenii. Therefore, the glycolipid-sugar composition may be a discriminating marker of the family Methanomicrobiaceae and the genus Methanothrix. N-Acetylgalactosamine or nonacetylated glucosamine was found in some species, but its chemo-taxonomic implication is not clear. We are in the process of analyzing lipid components of several additional methanogens. The results of this study will extend the information

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**Distribution of Component Parts of Polar Lipids among Methanogens**

Although radioactive internal standards of known lipids were useful for surveys of the distribution of lipids among methanogens, a TLC pattern of the total lipid is less informative about lipid structure. Only the relative locations of lipid spots on a TLC plate could be compared with another chromatogram of total lipid from another methanogen or a chromatogram reported by other workers. Although the best way to show the relationship between lipids is to compare their complete structures, the determination of the complete structure of a lipid is a laborious and time-consuming effort that is not suitable for routine taxonomic work.

A method that gives more information about lipid structure than TLC and is less time-consuming than complete structure determination is the analysis of the component parts of polar lipids (analyses of polar lipid-constituting moieties) in the total lipid such as the presence or absence of polar head groups, monosaccharide units, core portions, and hydrocarbon chains. This approach provides important information concerning the lipid chemistry of a specific methanogen, although it disregards the arrangement of the moieties. To examine this approach, we have been analyzing lipid component parts from approximately 18 species of methanogens from 12 genera belonging to 5 families (56).

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TABLE 3. Distribution of component parts of polar lipids in methanogens

| Species                                | Core lipid | Sugar | Polar head group | Reference(s) |
|----------------------------------------|------------|-------|-----------------|--------------|
|                                        | ArOH      | CAOH  | c-Ar            |              |
| Methanobacterium formicicum            | +         | -     | -               |              |
| Methanobacterium thermosolitotrophicum| +         | -     | -               |              |
| Methanobacterium wolfei                | +         | -     | -               |              |
| Methanolacinia                         | +         | -     | -               |              |
| Methanosphaera                         | +         | -     | -               |              |
| Methanobrevibacter                      | -         | -     | -               |              |
| Methanococcus                          | -         | -     | -               |              |
| Methanococcus volutae                  | +         | -     | -               |              |
| Methanococcus                          | +         | -     | -               |              |
| Methanolobus tindarius                 | -         | +     | -               |              |
| Methanohalophilus mahii                | +         | -     | -               |              |
| Methanothrix soehngenii                | +         | -     | -               |              |
| Methanothrix thermophila               | -         | -     | -               |              |

* Table columns: ArOH, CAOH, c-Ar, hy-Ar, Glc, Gal, Man, EtN, Ser, Ino, APT.
* Abbreviations: ArOH, archaeol; CAOH, caldarchaeol; c-Ar, macroyclic archaeol; hy-Ar, hydroxyarchaeol; Glc, glucose; Gal, galactose; Man, mannose; EtN, ethanolamine; Ser, serine; Ino, inositol; APT, aminopentanetetrol.
* Symbols: +, present; -, absent. Symbols in parentheses indicate the results from TLC profiles.

base for lipid component analysis and help determine its significance as a chemotaxonomic marker.

**COMPARISON OF COMPONENTS OF POLAR LIPIDS OF METHANOGENS WITH THOSE OF OTHER GROUPS OF ARCHAEAE**

The structural features of the lipids of three groups of the domain *Archaea* are presented in Table 4. When compared with methanogen lipids, the polar lipids from extremely halophilic and from sulfur-dependent members of the *Archaea* have features characteristic of each group. Extreme halophiles contain archaeol as the sole core lipid. Most sulfur-dependent members of the *Archaea* have caldarchaeol with a trace amount of archaeol, except *Thermococcus celer*, which has only an archaeol core (24). The core lipids of a number of groups of methanogens are usually both archaeol and caldarchaeol. Variations of core lipids of the three groups are also characteristic. A C_{25}-sesterterpanyl chain-containing archaeol (23) is characteristic of alkaliphilic extreme halophiles. Caldarchaeols of *Sulfolobus solfataricus* contain various numbers of cyclopentane rings in their hydrocarbon chains (22). In this bacterium, one of the two glycerol moieties of some caldarchaeol molecules is replaced by a nine-carbon polyol, nonitol (16). The variation of core lipids in methanogens is restricted to the archaeols as described above (Fig. 1). The caldarchaeol cores of the methanogens identified so far all have the standard structure.

In contrast to methanogens, all the phosphate-containing polar head groups of extreme halophiles contain a glycerol moiety (archaeidiglycerol, archaeacidiglycerophosphate, and archaeacidiglycerosulfate [50]). The only phosphodiester group of lipids identified thus far in sulfur-dependent members of the *Archaea* is phospho-myoinositol (21, 24, 67, 68, 99, 102). *myo*-Inositol and glycerol are found in some but not all groups of methanogens, whereas inositol is not found in extreme halophiles. The presence of a glycerol moiety as a polar head group also has not been reported in sulfur-dependent thermophiles. *Methanospirillum hungatei* is the only methanogen that has a nonalkylated glycerol moiety in its polar lipids. It was shown, on the basis of the sequence analyses of 16S rRNA (107) and 23S rRNA (12), that *Methanospirillum hungatei* has a closer relationship than the other methanogens to the extreme halophiles. These facts suggest that the occurrence of glycerol in the polar lipids in *Methanospirillum hungatei* is not an accidental phenomenon.

**TABLE 4. Comparison of lipid structure among three major groups of the domain *Archaea***

| Component | Methanogens | Sulfur-dependent thermophiles | Extreme halophiles |
|-----------|-------------|-------------------------------|--------------------|
| Core lipid |             |                               |                    |
| Archaeol  | +           | +                             | +                  |
| Hydroxyarchaeol | +       | -                             | -                  |
| Macrocyclic archaeol | +     | -                             | -                  |
| C_{25} chain | -         | -                             | +                  |
| Caldarchaeol | +         | +                             | -                  |
| Cyclopentane ring | -       | +                             | -                  |
| Polar head group |            |                               |                    |
| Inositol  | +           | +                             | -                  |
| Glycerol  | +           | -                             | +                  |
| Amino compound | +       | -                             | -                  |
| Major sugar | Glc        | Glc, Gal                       | Glc, Gal, Man, sulfated sugar |

* Symbols: +, present; -, absent.
but implies a phylogenetic relatedness. One of the most characteristic features of polar lipids of methanogenic bacteria is the occurrence of a variety of phosphatase-linked head groups (see above). The simplicity of phosphate-containing polar groups in halobacteria and sulfur-dependent thermophiles may be compensated by the complexity of their sugar groups. As to the sugar moieties of glycolipids, extreme halophiles have mono-, di-, tri-, and tetrasaccharide residues composed of glucose, mannose, galactose, and sulfated galactose (52). At least seven kinds of sugar residues composed of glucose, galactose, sulfated glucose, and phosphoglucose have been identified in sulfur-dependent thermophiles (19, 67, 68, 99). Most methanogens contain mono- or diglucose residues as glycosyl groups of glycolipids. At present, a few species of methanogenic bacteria are known to contain sugars other than glucose in their glycolipids. In conclusion, membrane lipid variation in methanogenic bacteria seems to occur among phosphodiester-bonded, watersoluble phospholipids and alkyl-phospholipids. On the other hand, halophilic and sulfur-dependent thermophilic members of the Archaea it occurs in the sugar residues of glycolipids.

APPLICATION OF LIPID ANALYSIS TO THE ECOLOGICAL STUDY OF METHANGENS

Estimation of Methanogen Groups Present in an Ecosystem

Methanogens in natural ecosystems cohabit with many kinds of organisms of the domain Bacteria and sometimes with protozoa through interspecies hydrogen transfer. Quantitative and qualitative analysis of methanogen species and biomass are an important aspect of microbial ecology. In pure culture, for example, Methanosarcina and Methanothrix species can be readily differentiated by microscopic observation. For samples from consortia collected from natural environments, immunological methods (69) and gene amplification methods such as the polymerase chain reaction (37) are two main strategies for the identification of methanogen species. Another method entails the direct analyses of total lipid extracted from a natural sample to estimate methanogen biomass (15) and the composition of families of methanogenic bacteria that constitute the ecosystem (56, 81).

Analysis of component parts of ether lipids could also be a tool for estimating the groups of methanogens in a sample taken from the natural environment. After the total lipid extracted directly from such a sample is treated with mild acid and alkali to degrade acyl esters and alkenyl ether (plasmalogenic) lipids, respectively, the resultant lipid is analyzed for its components as described above. For example, Nishihara et al. (81) concluded that a sludge sample from an anaerobic digester contained Methanothrix species on the basis of the total lipid analysis of the sample, in which they found mannose and galactose as lipid-sugar moieties and hydroxyarchaeol as a core lipid. In another sludge, they detected glucose as the major lipid-sugar moiety; ethanolamine, serine, and inositol as polar head groups; and hydroxyarchaeol as a core lipid. These data indicated the predominance of Methanosarcina species in the sludge (81). If inositol and caldarchaeol are not detected in the lipid fraction of a sample, it is highly likely that members of the Methanobacteriaeae are absent.

Quantification of Methanogenic Cells by Lipid Core Analysis

Either core lipids are specific to the domain Archaea and are highly stable to chemical reactions that degrade diacetyl and plasmalogen lipids. In most methanogens, which do not have the outer membranes or special wall lipids, the cytoplasmic membrane is the sole membrane structure made of lipids in the cells, and the cell size and surface area per dry-cell weight are almost constant. On this basis, a high-pressure liquid chromatography (HPLC) method was developed to determine methanogen biomass in natural environments (15). Total lipid was subjected to acetylation and acid methanolysis to convert polar lipids completely into core lipids. During this treatment, diacetyl and plasmalogen lipids were degraded to glycerol, fatty acids, and fatty aldehydes, which could be easily separated from ether core lipids. A UV-absorbing group, dinitrobenzoyl, was introduced into the hydroxyl groups of the resultant core lipids for sensitive detection on HPLC. Dinitrobenzoyl-archaeol and dinitrobenzoyl-caldarchaeol were well resolved and measured in a short time with HPLC equipped with a UV detector. The total amount of core lipids (archaeol plus caldarchaeol) detected by UV absorption on HPLC was proportional to the dry-cell weight of methanogens independent of species. For Methanobacterium thermoautotrophicum or Methanospirillum hungatetii. The lowest limit of detection was 2.5 μg of cells (approximately 3 × 10^10 cells). A similar method was proposed by White and coworkers (71, 80) and was based on HPLC detection of the refractive index of core lipids prepared from the phospholipid fraction rather than from total lipid after treatment by acid methanolysis alone. Demizu et al. (15) pointed out that the phospholipid content in total lipid varied from species to species of methanogens and that a significant amount of phospholipids could not be methanolyzed. The method of Demizu et al. therefore improved the accuracy of the above-mentioned estimation of methanogenic cells. However, this new method, as well as the method of White et al., does not detect hydroxyarchaeols, because the strong-acid treatment used to prepare core lipids causes their degradation. Since hydroxyarchaeols are not only the predominant constituents of Methanosarcina and Methanothrix species but are also found in several Methanococcus species (56, 94), a further improved method in which hydroxyarchaeols as well as archaeol and caldarchaeol can be measured during one assay should be developed.

Applications of lipid analysis to ecological studies of methanogens still remain in the developmental stage.

SPECIAL METHODS OF METHANOGEN LIPID ANALYSIS

Various methods for analysis of archaeal ether lipids have been established by Kates. Each polar lipid from the extreme halophiles and thermoacidophilic members of the Archaea contains polyols (glycerol or inositol) or sugars as polar head groups. On the other hand, several novel structures are present in methanogens, for example, acid-labile hydroxyarchaeol cores, serine, or ethanolamine that is poorly released from the ether lipids by the usual acid methanolysis. Some new analytical methods were therefore required not only for the elucidation of ether lipid structure but also for chemotaxonomic and ecological purposes. Considering the special significance of new analytical methods that were developed for the unique methanogen lipids, the new methods are briefly reviewed here. Important but conventional or routine analytical methods are not included here.

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### Acid Extraction

Extraction of *Methanobacterium thermoautotrophicum* by standard neutral Bligh-and-Dyer solvent mixture (5) resulted in a low level of lipid (for example, 1.6% on a dry-cell weight basis) (40, 60, 70, 100). Acidification of the solvent with trichloroacetic acid was found to be effective for maximum yield of lipid (5.6% of dry-cell weight) from this bacterium (82). Cell disruption was also effective for high-yield lipid extraction in *Methanobacterium thermoautotrophicum* and *Methanobrevibacter arboriphilicus* (70, 75, 82). It should be noted that the acidic solvent increased not only the total lipid yield but also the recovery of tetraether lipids. Therefore, neutral extraction resulted in incomplete extraction of tetraether polar lipids, which remained in the residual fraction containing macromolecular materials. The extraction yields reported by various authors are summarized in Table 5. The results of Makula et al. (70) and Nishihara et al. (82) are almost consistent. Hedrick et al. (40) reexamined the effectiveness of the acid-extraction method of Nishihara et al. (82) by using *Methanobacterium formicicum*. They also obtained twice as much tetraether lipid by acid extraction as by neutral extraction, although their reported amount of lipid per gram (dry-cell weight) was extremely small (1/40 to 1/100, if there is no error in their calculation) compared with values obtained under similar conditions by other authors. They used the usual Bligh-and-Dyer method for the analysis of bacterial and archaeal lipids in one extract to avoid any destructive effect of the acidic conditions on cyclopropane fatty acids. After Bligh-and-Dyer extraction, they recovered caldarchaeol, which accounted for 75% of total core lipids, in the residual fraction by acid methanolysis. This implied that the neutral Bligh-and-Dyer extraction could extract only 25% of the total lipids from this methanogen. Kramer and Sauer (60) reported the core lipid composition of *Methanobacterium thermoautotrophicum* cells collected at various growth phases. They found that the archaeol-to-caldarchaeol ratio increased remarkably from the 2-day culture to the 6-day culture (Table 5). It is, however, important to reexamine whether the growth phase affects the extraction efficiency of tetraether lipids when the lipid is extracted from intact cells with a neutral solvent, because the extraction yield of total lipid reported by Kramer and Sauer was considerably lower (1.6%) than that reported by Nishihara et al. (82). In general, attention should be given to extraction yield and especially to fractional extraction during examinations of the core lipid composition of cells under various growth conditions or in different growth phases.

### Acetolysis and Acid Methanolysis for Complete Removal of Polar Head Groups

Makula and Singer (70) suggested the presence of phosphonolipids (lipids containing a P–C bond) in *Methanobacterium* species because the acid methanolysis-resistant phosphorus-containing lipids were retained at the origin in TLC. The difficulty in achieving complete hydrolysis of archaetidylserine was also described by Morii et al. (76), who found that archaetidylserine did not contain the phosphonate (P–C) group. The reason for the acid stability of some types of ether phospholipids has been discussed by Nishihara et al. (87). They concluded that the polar head group lacking free hydroxyl groups (serine or ethanolamine) in ether phospholipid could not be split off from the core residues, because ether bonds are not readily methanolyzed. Because the polar lipids containing these types of polar residues accounted for a significant part of the total lipids, the presence of unmethanolyzable lipids caused significant error in the quantitative preparation of ether core lipids. Morii et al. (76) used acetolysis for the complete removal of phosphoserine from archaetidylserine. The acetyl group(s) added to archaeol or caldarchaeol during acetolysis and the glycoside groups of glycolipids were hydrolyzed by subsequent acid methanolysis. This procedure permitted a quantitative preparation of ether core lipids from all kinds of polar lipids when used in conjunction with the acidic-extraction method, and it gave more correct values for the core lipid composition. In the tetraether type of phosphoglycolipid, phosphoric ester and glycosyl groups are attached to

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**Table 5. Lipid extraction from cells of the family Methanobacteriaceae**

| Reference | Cells* | Growth phase | Extraction solvent | Total lipid/ cell (%) | ArOH/CAOHb (molar ratio) |
|-----------|--------|--------------|--------------------|----------------------|--------------------------|
| 70        | Intact | Late log     | Neutral            | 2.0*                 | 41:59                    |
| 82        | Disrupted | Late log    | Neutral            | 3.9*                 |                          |
| 75        | Intact | 5 days       | Neutral            | 0.98                 | 35:36                    |
| 75        | Disrupted | 5 days | Acidic | 5.6          | 10:83                    |
| 40        | Intact | Late log     | Neutral            | 3.0                  | 52:48                    |
| 40        | Intact | Late log     | Acidic             | 5.8                  | 19:81                    |
| 60        | Intact | 2 days       | Neutral            | 1.6                  | 41:59                    |
| 60        | Intact | 4 days       | Neutral            |                      | 80:20                    |
| 60        | Intact | 6 days       | Neutral            |                      | 89:11                    |

* Methanobacterium thermoautotrophicum except when otherwise noted.
* ArOH, archaeol; CAOH, caldarchaeol.
* Phospholipid dry-cell calculated from data in reference 70 for lipid-phosphorus, assuming that the average molecular weight is 1,300.
* Methanobrevibacter arboriphilicus.
* Methanobacterium formicicum.
* Calculated from data in reference 40, assuming that the molecular weights of diether and tetraether polar lipids are 850 and 1,700, respectively.

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the different glycerol moieties. In the structural determination of a phosphoglycerolipid, the selective liberation of either group has particular significance because acetylation does not cleave a glycosidic bond. HCl methanolysis (removal of the glycosyl bond) or acetylation and subsequent mild-alkali methanolysis (removal of the phosphate ester) permit the selective liberation of either polar group (87). These procedures constitute the most powerful tools for the determination of the structure of tetratera phosphoglycerolipids.

**Mild-Acid Methanolysis for Preparation of Hydroxyarchaeols**

Because of the acid lability of hydroxyarchaeol-containing lipids, they were converted to monoalkylglycerol by using the usual (strong) methanolytic conditions under which the polar head groups of the polyol-containing ether lipids are split off to produce the archaeol or caldarchaeol core. Ferrante et al. (30) found that mild-acid methanolysis (0.18% HCl-methanol at 50°C for 24 h) was sufficient to split off phosphodiester head groups while keeping the hydroxyarchaeal core intact. This mild-acid methanolysis was readily used for the preparation of *Methanohalix* *sn*-3-hydroxyarchaeol and *Methanosarcina* *sn*-2-hydroxyarchaeol (85). Because hydroxyarchaeols are not restricted to these two genera (56, 94), this method has potential significance for methanogen lipid biochemistry. HF is also used to prepare unmodified hydroxyarchaeols (94). A very characteristic signal of the 1H-NMR spectrum at 1.24 ppm, attributed to the C-17' methyl group (bound at C-3' of the phytanyl chain) in the aliphatic region, was found to be specific to hydroxyarchaeols and could be used as a marker of this kind of core lipid (94).

**Boron Trichloride Cleavage of the Ether Bond for Preparation of Glycerophosphoesters**

BCl₃ treatment was first introduced by Gerrard and Lappert (36) to cleave ether bonds and applied to the ether bonds between glycerol and phytanyl groups of archaeol prepared from *Halobacterium* phospholipids (54). Because the phosphodiester groups had been removed by acid methanolysis in this case, the effect of BCl₃ on the phosphodiester bond was not known. Nishihara and Koga (83) found that BCl₃ cleaved ether bonds while keeping phosphodiester bonds intact. BCl₃ cleavage converted the ether phospholipids into the corresponding glycerophosphoesters with a nearly 100% yield. Glycerophosphoesters were identified by cellulose-TLC, which provided information on the polar head groups of ether lipids. This method is as significant as mild-alkali methanolysis as a tool for the structural analysis of diacylster lipids. Although HI can also cleave ether bonds, it is not adequate to prepare glycerophosphoesters because HI treatment also degrades phosphodiester bonds. Unfortunately, the BCl₃ method did not yield glyceryl glycosides from the ether glycolipids since BCl₃ degrades glycosidic bonds.

**Hydrogen Fluoride Cleavage of Phosphodiester Bonds**

When glycerophosphoesters prepared by BCl₃ treatment were hydrolyzed with HCl at 100°C, the stereoisomers such as L-serine were racemized. To identify the stereochemical configuration of a polar group, HF cleavage (0°C for 24 h) of the intact lipid is useful. Although the yield of serine from arachietylserine by HF cleavage was 60 to 70% and a variable amount of NH₃ was produced, the liberated serine was not racemized (74). HF cleavage is also used to prepare intact hydroxyarchaeols from ethanalamine or serine-containing phospholipids which are not methanolized by mild-acid methanolysis.

**BIOSYNTHESIS OF ETHER POLAR LIPIDS**

The interesting points of biosynthesis of ether lipids are (i) the synthesis of the phytanyl chain, (ii) the formation of ether bonds, (iii) the formation of the unusual 2,3-di-O-radyl sn-glycerol structure, and (iv) the head-to-head condensation for the formation of tetratera ether lipids. These points correspond to the uniqueness of archaeal ether lipid structure. Studies of lipid biosynthesis that focus on methanogens are very fragmentary at present. The following therefore includes results obtained from experiments on other kinds of organisms of the Archaea. Recently, in vivo studies of the incorporation of radioactive or stable isotopes into archaeal lipids followed by chemical or NMR analyses were carried out, and two in vitro experiments have been reported. The major results of these studies are summarized as follows.

(i) *Methanospirillum hungatei* (26) and *Methanotherrix soehngenii* (27) cells incorporated [1,3-3H]acetate or [2-13C]acetate into the isoprenoid hydrocarbon chains of their lipids in a position-specific manner. That is, every second carbon along the chain and branch methyl groups is labeled by the methyl group of acetate ([2-13C]acetate) and the remaining carbons are labeled by the carboxyl carbon of acetate ([1-13C]acetate). This labeling pattern is consistent with the typical condensation of three acetate molecules to form one mevalonate molecule. However, Ekiel et al. (26) pointed out that caution should be exercised in reaching conclusions about mevalonate biosynthesis because of the presence of a nonstandard pathway to this compound in halobacteria. Tachibana et al. (98) detected premethyl transferase activity in the cell extract of *Methanobacterium thermoformicicum* (recently reclassified as *Methanobacterium thermoautotrophicum* [101]).

(ii) Formation of an unusual 2,3-di-O-radyl sn-glycerol structure seems to proceed through different mechanisms in *Halobacterium* and *Sulfolobus* or *Methanobacterium* species. On the basis of the fact that [1,3-3H]glycerol but not [2-3H]glycerol was incorporated into the glycerol moiety of the *Halobacterium* lipid without loss of radioactivity, dehydrogenation at the 2 position (oxidation of the 2-hydroxy group to a 2-keto group) was postulated to be involved in lipid biosynthesis (53). To investigate the behavior of individual hydrogen atoms of the glycerol molecule and the prochirality of glycerol, Kakimura et al. (47) fed [sn-1,3-3H]glycerol or [sn-3,3-3H]glycerol separately to a culture of *Halobacterium halobium* and determined the position on the glycerol moiety of archaeol into which 3H was incorporated by using 1H-NMR and 3H-NMR. The results showed that sn-1-3H of glycerol appeared at the sn-3 position of archaeol-glycerol and that sn-3-2H of glycerol appeared at the sn-1 position, indicating that an inversion between the sn-1 and sn-3 positions occurred during the biosynthesis of ether lipids. Their data confirmed the results of Kates et al. (53), however, suggesting that the participation of dihydroxyacetone (a symmetric molecule) was eliminated. Similar types of experiments with *Sulfolobus acidocaldarius* showed no loss of 3H at the sn-2 position of glycerol and no inversion during ether lipid synthesis (46). This is in contrast to the situation with *Halobacterium* species, in which the glycerol moiety was inverted at the sn-2 position after...
phosphorylation at the α position. Zhang et al. (110) showed that the cell extract of Methanobacterium thermautotrophicum catalyzed the synthesis of 3-geranylgeranylsn-glycerol 1-phosphate from sn-glycerol 1-phosphate and geranylgeranylnyl PPγ. This result suggests that inversion at the sn-2 position either is not involved in the synthesis of ether lipids of Methanobacterium thermautotrophicum or takes place only before alkylation. Their experiment, however, has not determined how sn-glycerol 1-phosphate is synthesized (direct phosphorylation of glycerol at sn-1 position, inversion of sn-glycerol 3-phosphate, or other mechanisms) in Methanobacterium species. Because this bacterium incorporated exogenous glycerol into its polar lipids very poorly, experiments similar to those carried out with Halobacterium or Sulfolobus species were difficult.

(iii) [1-32P]Olglycerol was incorporated into ether lipid (48), indicating that the nucleophilic attack by the glycerol-phosphate moiety of the C-1 carbon atom of the alkyl donor led to ether bond formation.

(iv) It was suggested that the hydrocarbon chain had not been saturated at the time when the ether bond formed (73). This suggestion was based on results obtained by Moldoveanu and Kates (73) that ether lipids extracted from a culture of Halobacterium cutirubrum pulse-labeled with a radioactive precursor were readily degraded by acid methanolysis and that compounds derived from the phytanyl group or the geranylgeranyl group were produced.

(v) Geranylgeraniol was incorporated in vivo into Methanospirillum hungatei polar lipids with higher efficiency than phytol was (93). Therefore, the former is a more likely precursor than the latter is.

On the basis of the above observations, an outline of ether lipid biosynthesis was derived. The hydrocarbon chain is supplied as diterpenyl alcohol (probably geranylgeraniol, in its PPγ ester form) synthesized by the mevalonate pathway. The ether bond is formed through nucleophilic attack by sn-glycerol 1-phosphate (in Methanobacterium or Sulfolobus species) or dihydroxyacetonephosphate or sn-glycerol 3-phosphate (in Halobacterium species) on a putative unsaturated hydrocarbon precursor, geranylgeranyl PPγ. The hydroxyl group at the sn-2 position of the glycerol-phosphate moiety had to be inverted either before or after ether bond formation at the α-hydroxyl group in Halobacterium species. Glycerol kinase and glycerophosphate dehydrogenase of Halobacterium species were stereospecific for sn-3-phosphate (103). Figure 12 illustrates a tentative biosynthetic pathway for ether polar lipids that is based mainly on the halobacterial pathway proposed by Kakinuma et al. (48).

The main route is probably adopted only by halobacteria. In Fig. 12, an alternate route to synthesis of pre-archaeidic acid in methanogens is also illustrated. However, the other parts of the biosynthesis of methanogen lipids is not known at all. Moldoveanu et al. (73) showed that a polar lipid-ide, phosphate-free precursor that was the common precursor of various polar lipids formed before archaeidic acid formed.

The results obtained by Kakinuma et al. (46-48) do not indicate any precursors with or without a phosphate group. Their pathway contains no phosphate-free lipiddes precursor. It remains to be seen whether one can construct a plausible pathway that is consistent with both the data of Moldoveanu et al. (73) and those of Kakinuma et al. (46-48).

Little is known about the biosynthetic pathway of various polar lipids from archaeol, archaeoidic acid, or its derivatives. Only in vivo incorporation kinetic studies have suggested metabolic pathways of polar lipids. Ferrante et al. (52) monitored the incorporation of [14C]mevalonic acid into polar lipids in Methanospirillum hungatei and showed that there was a distinct possibility that a back-reaction or the synthesis of methanobacterium thermautotrophicum pentanetetrol was a biosynthetic precursor of archaeidyl (trimethylamino)pentanetetrol. An unpublished pulse-chase experiment with [32P]P and Methanobacterium thermautotrophicum suggested that archaeidylethanolamine was derived from archaeidyletheramine (57). This pathway is similar to phosphaethanolamine synthesis in E. coli (49). On the basis of structural relationships (lipids shown in Fig. 8b to d and those shown in Fig. 9c and d), Ferrante et al. hypothesized two possible biosynthetic schemes of glycolipids (28).

The primary problem in tetraether lipid biosynthesis is whether the head-to-head condensation of the alkyl groups occurs between two molecules of free archaeols or between diether lipids that have already been substituted by polar head groups. On the basis of the examination of the structural regularities in the tetraether core lipids, Langworthy (65) and De Rosa and Gambacorta (18) inferred that two molecules of archaeol were condensed before polar head groups became attached to the archaeol, although Langworthy (65) circumspectly did not exclude the possibility that condensation occurred between diether lipids already substituted with polar head groups. On the other hand, Kushwaha et al. (63) considered, on the basis of the structures of polar diether and tetraether lipids of Methanospirillum hungatei, that biosynthesis of tetraether polar lipids might occur by head-to-head condensation of diether polar lipids. Three heptads of polar lipids of Methanobacterium thermautotrophicum (88) and one heptad of inositol lipids of Methanobrevibacter arborophilicus (75) provided another line of evidence for the latter speculation. Incorporation kinetics and pulse-chase experiments (88) also supported the mechanism of condensation of diether polar lipids. When growing cells of M. thermautotrophicum were pulse-labeled with [32P]P, there was a significant lag between the rapid incorporation of radioactivity into the diether phospholipids and the incorporation of label into the corresponding tetraether polar lipids. In a pulse-chase experiment with [32P]P, rapid turnover of the diether polar lipids was observed. At the same time, radioactivity was incorporated into the tetraether polar lipids. Poulet et al. (93) reported that archaeol added to the culture medium of Methanospirillum hungatei was incorporated into the nonpolar lipid fraction but not converted to the diether or to the tetraether polar lipids. The exact precursors and the chemical mechanism of tetraether biosynthesis remain to be elucidated.

SPECULATION ABOUT THE SIGNIFICANCE AND EVOLUTIONARY ORIGIN OF ETHER LIPIDS IN ARCHAEOA

The question of the significance, origin, and evolution of archaeal ether lipids as mentioned in the Introduction can be answered only speculatively at present, because “there is a great deal of interplay between many forces in the determination of what lipids shall be present in a given cell at a given time” (79). Here we briefly discuss this problem, considering mainly the biosynthetic mechanisms and the distribution of ether lipids.

Zillig et al. (112) have proposed that the domain Eucarya originated by a fusion event based on the chimeric nature of eucaryal RNA polymerases and some other molecules. In this context, the eucaryal ether lipids are speculated to be acquired from members of the Bacteria. This hypothesis can account for the sharing of ether lipids by the Bacteria and Eucarya, although the origin of ether lipids in the Bacteria
and ether lipids in the Archaea is still in question. Later, Zillig (111) postulated that the primeval membrane was probably neither of isoprenyl ether nor of the fatty acid ester type but was rather, for example, made of protein. If this is the case, the question raised in the Introduction still remains to be answered in a modified form: when and how did the lipid membrane replace the protein membrane after the bifurcation of the Archaea and Bacteria?

Among the four differences in structure between the ether lipids of the Archaea and the glycerol-fatty acid ester lipids of the Bacteria and Eucarya, the most significant points are the nature of the ether and ester linkages and the nature of the hydrocarbon chains (high methyl branching without unsaturation in the Archaea and almost straight chains with unsaturation in the Bacteria and Eucarya). Assuming that the most significant role of polar lipids is to constitute cell membranes, some fractions of straight-chain fatty acids must have cis unsaturation to give membranes their proper physicochemical properties, since membranes composed of only saturated fatty acid chains are too rigid to play a proper role in vital cells at moderate temperatures. On the other hand, highly methyl-branching, saturated isoprenoid hydrocarbon chains are bulky and have a phase transition temperature low enough for cells to function properly (51). Unsaturated fatty acids are synthesized in most aerobic organisms, from bacteria to mammals, by desaturation of saturated fatty acids in the presence of molecular oxygen (38, 77, 78).
It is hypothesized that during the early stages of the origin or evolution of life under an anoxic atmosphere before the generation of atmospheric oxygen on Earth, isoprenoid hydrocarbon chains prevailed as the lipid components of biomembranes. Unsaturated fatty acids synthesized through the nonoxidative mechanism found in many microorganisms such as *E. coli* are also assumed to be hydrophobic components of biomembranes during the anaerobic stage of life on Earth. Isoprenoid carboxylic acids rarely occur but are detected as highly restricted metabolites (78). It is conceivable that under anoxic conditions isoprenoid alcohols were readily reduced to saturated isoprenoid alcohols rather than oxidized to isoprenoid carboxylic acids. As a result, isoprenoid alcohol could produce ether with glycerol during polar-lipid formation. This is the hypothetical reason for the anaerobic origin of ether lipids. Fatty acids might more easily modulate their physicochemical properties by desaturation than isoprenoids would on changes in the environmental growth conditions. Organisms with fatty acids therefore acquired a greater capability to adapt to diverse and changeable environments. After the appearance of a significant amount of molecular oxygen in the atmosphere, such organisms became prevalent on Earth, gaining the adaptability of fatty acid ester lipids.

The fact that tetraether lipids were found first in the thermoacidophiles *Sulfolobus* and *Thermoplasma* species has led many people to conclude that tetraether lipids evolved in those thermoacidophiles to adapt to the environment of high temperature and low pH. The monolayer structure of membranes made of tetraether lipids was believed to give suitable rigidity to the membrane at high temperature. Woese, however, called attention to the fact that the ether lipids are not simply an adaptation to extreme environments (106). Nes and Nes (79) also pointed out that the absence of an association between the presence of unusual lipids and the nature of the environment presumably reflects a familial rather than an adaptive relationship. Now we have more examples of ether core lipid composition of organisms grown under various conditions. According to a list of core lipid composition, the tetraether lipid structure is not restricted to thermophiles but is also found in some mesophilic methanogens (*Methanobrevibacter arboripholicus* [75] and *Methanospirillum hungatiae* [63]). On the other hand, two extremely thermophilic members of the *Archaea* (Methanopyrus kandleri and *Thermococcus celer*) contain only an archaeol core (24, 62). These facts strongly indicate that the occurrence or the evolution of tetraether lipids is not related to an adaptation to high temperature or low pH and that qualitative but not quantitative core lipid composition might be determined rather by a genetic or phylogenetic relationship. Methanogens that have ether lipids generally share living conditions in their habitat with members of the *Bacteria* that have ester lipids. Furthermore, not all the thermophilic microorganisms have ether type lipids. Thermophilic members of the *Bacteria* such as *Thermus* spp. have ester lipids (79). Recently it has been assumed that the ancestor of recent members of the *Archaea* and *Bacteria* most probably was an extreme thermophile (1) since *Thermotoga maritima* has been isolated and placed on the deepest branch of the bacterial line (1, 42). Although *Thermotoga* spp. and sulfur-dependent thermophilic members of the *Archaea* share the habitat, their lipids are not at all similar; the former bacteria do not contain diether or tetraether lipids but do contain various long-chain dicarboxylic fatty acids. Moreover, the same long-chain dicarboxylic fatty acid (HOOC(CH₂)₆(CH(CH₃)₂)₄CH₂COOH) is not specific to *Thermotoga* spp. but occurs also in a mesophilic rumen bacterium, *Butyryrivibrio* sp. strain S-2 (13, 55). This fact again indicates the unrelatedness of lipid constitution and environmental adaptation. These simple examinations of lipid distribution seem to show that the conditions in the ancestral habitat do not determine whether an organism has ester or ether lipids in its membrane.

The above consideration does not necessarily mean that ether lipids do not have any advantages over ester lipids in survival of the organism at elevated temperatures. Certain physicochemical properties of membranes made of isoprenoid ether lipids might give an advantage to archaeal organisms. For example, a chemically synthesized model lipid with phytanyl chains which mimicked archaeal tetraether lipids shows a greater ability than ester lipids and diether lipids to retain low- and high-molecular-weight compounds inside the vesicles at high temperatures (108). If it is assumed that a low rate of leakage is an important property of biological membranes, it may be concluded that isoprenoid tetraether lipids have a thermophilic or thermostable property that allows thermophilic organisms to grow at elevated temperatures. However, because of a variety of habitat conditions (high-salt, high-temperature, or anoxic conditions) of the *Archaea*, a variety of metabolisms, and many other kinds of presumed properties of ether lipid membranes, it is difficult to attribute a single common physiological function to an ether lipid property.

### CONCLUDING REMARKS

Complete structures of lipids from seven species of methanogens have been elucidated during the past 10 years. Although the 7 species make up a minor fraction of the 62 species of methanogens, they represent four of seven families. Because to date the composition of polar lipids is uniform among all species belonging to a genus, lipids of almost 31 species may be presumed from the identified lipids of 7 species. This does not exclude the possibility that lipids with new and unique structures will not be discovered in the future. Lipids from methanogens that inhabit extreme environments or have unique metabolisms are attracting special interest; these include *Methanosphaera stadtmanae*, *Methanothermus fervidus*, *Methanococcus thermolithotrophicus*, *Methanohalophilus halini*, *Methanococcus igneus*, *Methanopyrus kandleri*, and some members of the order *Methanomicrobiales* for which lipid studies have not been reported or are very limited.

Methanogen lipids were characterized by their diversity in phosphate-containing polar head groups and core lipids and, in turn, could be used in studies of the chemotaxonomy of methanogens. The uniqueness of ether lipids of methanogens was also exploited in a method to determine the methanogenic biomass in natural samples. In no other bacteria are the lipids more useful in chemotaxonomy and ecological surveys than in methanogens.

Biochemical studies of methanogen lipids have revealed significant progress in recent years, but the methods have remained, as a whole, at the in vivo experimental level. We hope to be able to develop cell-free systems of ether lipid biosynthesis and to elucidate enzymatic mechanisms of novel reactions such as ether bond formation and head–head condensation of isoprenoid hydrocarbon chains of diether polar lipids.

The significance and the origin and evolution of ether lipids in the *Archaea* is only speculatively discussed. A clue to resolving this problem may be obtained by metabolic
studies of archaeal ether lipids and gene analysis of enzymes involved in their metabolism.

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REFERENCES

1. Achenbach-Richter, L., R. Gupta, K. O. Stetter, and C. R. Woese. 1986. From the original subcellular thermophiles? Syst. Appl. Microbiol. 9:34–39.

2. Ames, G. F. 1968. Lipids of Salmonella typhimurium and Escherichia coli: structure and metabolism. J. Bacteriol. 95: 833–843.

3. Balch, W. E., G. E. Fox, L. J. Magrum, C. R. Woese, and R. S. Wolfe. 1979. Methanogens: reevaluation of a unique biological group. Microbiol. Rev. 43:260–296.

4. Balou, C. E., and L. I. Pitzer. 1960. The absolute configuration of the myo-inositol 1-phosphates and a confirmation of the stereoisomeric configurations. J. Am. Chem. Soc. 82:3333–3335.

5. Bligh, E. G., and W. J. Dyer. 1959. A rapid method of total lipid extraction and purification. Can. J. Biochem. Physiol. 37:911–917.

6. Boone, D. R., and R. A. Mah. 1989. Group I. Methanogenic archaeabacteria. p. 2173. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

7. Boone, D. R., and R. A. Mah. 1989. Order I. Methanobacteriales Balch and Wolfe 1981, 216VP, p. 2174. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

8. Boone, D. R., and R. A. Mah. 1989. Family I. Methanosarcinae Balch and Wolfe 1981, 216VP, p. 2191–2197. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

9. Boone, D. R., and R. A. Mah. 1989. Family II. Methanospirillaceae Balch and Wolfe 1981, 216VP, p. 2198–2211. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

10. Boone, D. R., and W. B. Whitman. 1988. Proposal of minimal standards for describing new taxa of methanogenic bacteria. Int. J. Syst. Bacteriol. 38:212–219.

11. Burggraf, S., A. Ching, K. O. Stetter, and C. R. Woese. 1991. The sequence of Methanospirillum hungatei 235 rRNA confirms the specific relationship between the extreme halophiles and the Methanomicrobiales. Syst. Appl. Microbiol. 14:358–363.

12. Clark, N. G., G. P. Hazlewood, and R. M. C. Dawson. 1980. Structure of diabolic acid-containing phospholipids isolated from Butyribrio sp. Biochem. J. 191:561–569.

13. Comita, P. B., R. B. Gagosian, H. Pang, and C. E. Costello. 1984. Structural elucidation of a unique macrocyclic membrane lipid from a new, extremely thermophilic, deep-sea hydrothermal vent archaeabacterium, Methanococcus jannaschii. J. Biol. Chem. 259:15234–15241.

14. Denizzi, K., S. Ohshubo, S. Kohno, I. Miura, M. Nishihara, and Y. Koga. 1992. Quantitative determination of methanogenic cells based on analysis of ether-linked glycerolipids by high-performance liquid chromatography. J. Ferment. Bioeng. 72:135–139.

15. De Rosa, M., S. De Rosa, A. Gambacorta, and J. D. Bu’Lock. 1980. Structure of caldytol, a new branched-chain nonitol, and of the derived tetraether lipids in thermococcales carchaeabacteria of the Caldariella group. Phytochemistry 19:249–254.

16. De Rosa, M., S. De Rosa, A. Gambacorta, L. Manale, and J. D. Bu’Lock. 1977. Chemical structure of the ether lipids of thermophilic acidophiliic bacteria of the Caldariella group. Phytochemistry 16:916–1965.

17. De Rosa, M., and A. Gambacorta. 1986. Lipid biosynthesis in archaeabacteria. Syst. Appl. Microbiol. 7:278–285.

18. De Rosa, M., A. Gambacorta, and A. Gliozzi. 1986. Structure, biosynthesis, and physicochemical properties of archaeabacterial lipids. Microbiol. Rev. 50:70–80.

19. De Rosa, M., A. Gambacorta, V. Lanzotti, A. Trincane, J. E. Harris, and W. D. Grant. 1986. A range of ether core lipids from the methanogenic archaeabacterium Methanosaeta barkeri. Biochim. Biophys. Acta 85:487–492.

20. De Rosa, M., A. Gambacorta, B. Nicolaus, and J. D. Bu’Lock. 1980. Complex lipids of Caldariella acidophilica, a thermoacidophilic archaeabacterium. Phytochemistry 19:821–825.

21. De Rosa, M., A. Gambacorta, B. Nicolaus, B. Chappe, and P. Albrecht. 1983. Isoprenoid ethers: backbone of complex lipids of the archaeabacterium Sulfolobus solfataricus. Biochim. Biophys. Acta 785:249–256.

22. De Rosa, M., A. Gambacorta, B. Nicolaus, H. N. M. Ross, W. D. Grant, and J. D. Bu’Lock. 1982. An asymmetric archaeabacterial diether lipid from alkaliphilic bacterial haliohphiles. J. Gen. Microbiol. 128:343–348.

23. De Rosa, M., A. Gambacorta, A. Trincane, A. Basso, W. Zillig, and I. Holz. 1987. Lipids of Thermococcus celer, a sulfur-reducing archaeabacterium: structure and biosynthesis. Syst. Appl. Microbiol. 9:1–14.

24. DiMarco, A. A., T. A. Bobik, and R. S. Wolfe. 1990. Unusual coenzymes of methanogenesis. Annu. Rev. Biochem. 59:355–394.

25. Ekiel, I., I. C. P. Smith, and G. D. Sprott. 1983. Biosynthetic pathway in Methanosporillum hungatei as determined by 13C nuclear magnetic resonance. J. Bacteriol. 156:316–326.

26. Ekiel, I., G. D. Sprott, and G. B. Patel. 1985. Acetate and CO2 assimilation by Methanococcus concilii. J. Bacteriol. 162:905–908.

27. Ferrante, G., J. R. Brison, G. B. Patel, I. Ekiel, and G. D. Sprott. 1989. Structures of minor ether lipids isolated from the aceticlastic methanogen, Methanococcus concilii GP6. J. Lipid Res. 30:1601–1609.

28. Ferrante, G., I. Ekiel, G. B. Patel, and G. D. Sprott. 1988. Structure of the major polar lipids isolated from the aceticlastic methanogen, Methanococcus concilii GP6. Biochim. Biophys. Acta 963:162–172.

29. Ferrante, G., I. Ekiel, G. B. Patel, and G. D. Sprott. 1988. A novel core lipids isolated from the aceticlastic methanogen, Methanococcus concilii GP6. Biochim. Biophys. Acta 963:173–182.

30. Ferrante, G., I. Ekiel, and G. D. Sprott. 1986. Structural characterization of the lipids of Methanococcus voltae, including a novel N-acetylgallosamine 1-phosphate diether. J. Biol. Chem. 261:17062–17066.

31. Ferrante, G., J. C. Richards, and G. D. Sprott. 1990. Structures of polar lipids from the thermophilic, deep-sea archaeabacterium Methanococcus jannaschii. Biochim. Biophys. Acta 682:274–283.

32. Fletcher, H. G., Jr., L. Anderson, and H. A. Lardy. 1951. The nomenclature of the cyclolhexitols and their derivatives. J. Org. Chem. 16:1238–1246.

33. Fulco, A. J. 1974. Metabolic alterations of fatty acids. Annu. Rev. Biochem. 43:215–241.

34. Gerard, W., and M. P. Lappert. 1952. Fission of mixed ethers by boron trichloride. J. Chem. Soc. 1952:1486–1490.

35. Giovannioni, S. J., T. B. Britschgi, C. L. Moyer, and K. G. Field. 1990. Genetic diversity in Sargasso Sea bacterioplankton. Nature (London) 345:60–63.

36. Goldfine, H. 1965. The evolution of oxygen as a biosynthetic reagent. J. Gen. Physiol. 49:253–268.
POLAR LIPIDS OF METHANOCOCCUS JANNASCHII

Kassma, R.A., and E. M. Singer. 1987. Ether-containing lipids of methanogenic bacteria. Biochim. Biophys. Acta 82:716–722.

Morii, H., M. Nishihara, and Y. Koga. 1986. Composition of polar lipids of Methanobrevibacter arboriphilus. Biochim. Biophys. Acta 879:103–105.

Morii, H., and Y. Koga. 1986. Absolute stereochemical configuration of dihydromyristate ether analog of phosphatidylethanolamine of Methanobrevibacter arboriphilus. Biochim. Biophys. Acta 879:103–105.

Nes, W. R., and M. L. McKea. 1977. Biochemistry of steroids and other isoprenoids, p. 147–170. University Park Press, Baltimore.

Nes, W. R., and M. L. McKea. 1977. Biochemistry of steroids and other isoprenoids, p. 171–203. University Park Press, Baltimore.

Nes, W. R., and D. W. Nes. 1980. Lipids in evolution. Plenum Press, New York.

Nichols, P. D., C. A. Mancuso, and D. C. White. 1987.
Measurement of methanotroph and methanogen signature phospholipids for use in assessment of biomass and community structure in model systems. Org. Geochem. 11:451–461.

Nishihara, M., M. Akagawa-Matsubita, Y. Togo, S. Takeo, and Y. Koga. 1991. Analysis of methanogen flora in anaerobic digestor sludges based on the analyses of ether lipids, abstr. 268, p. 72. Abstr. 1991 Annu. Meet. Soc. Ferment. Technol. Jpn. (In Japanese.)

Nishihara, M., and Y. Koga. 1987. Extraction and composition of polar lipids from the archaeabacterium, Methanobacterium thermautotrophicum: effective extraction of tetraether lipids by an acidified solvent. J. Biochem. 101:997–1005.

Nishihara, M., and Y. Koga. 1990. Natural occurrence of archaetic acid and caldarchaetic acid (di- and tetraether analogues of phosphatidic acid) in the archaeabacterium Methanobacterium thermautotrophicum. Biochem. Cell Biol. 68: 91–95.

Nishihara, M., and Y. Koga. 1991. Hydroxymethanocarchaetidylsine and hydroxyarchaeetidyl-myo-inositol in Methanococcus barkeri: polar lipids with a new ether core portion. Biochim. Biophys. Acta 1082:211–217.

Nishihara, M., and Y. Koga. 1992. Structures of two kinds of ethanolamine-containing ether lipids in Methanococcus barkeri, abstr. 2Z:12, p. 145. Abstr. 1992 Annu. Meet. Jpn. Soc. Biosci. Biotechnol. Agrochem. (In Japanese.)

Nishihara, M., H. Morii, and Y. Koga. 1987. Structure determination of a quartet of novel tetraether lipids from Methanococcus barkeri. J. Biochem. 101:1007–1015.

Nishihara, M., H. Morii, and Y. Koga. 1989. Heptapods of polar ether lipids of an archaeabacterium, Methanobacterium thermautotrophicum: structure and biosynthetic relationship. Biochemistry 28:95–102.

Nishihara, M., Y. Koga, H. Akouz, and Y. Koga. 1992. Archaea contain a novel diether phospholipid core with a polar head group identical to the conserved core of eucaryal glycosyl phosphatidylinositol. J. Biol. Chem. 267:12432–12435.

Onitshubu, S., H. Miyahara, K. Denizli, S. Kohno, and M. Miura. 1991. Isolation and characterization of new Methanothrix strains. Int. J. Syst. Bacteriol. 41:358–362.

Patel, G. B. 1992. A contrary view of the proposal to assign a neotype strain for Methanothrix soehngenii. Int. J. Syst. Bacteriol. 42:234–236.

Pizer, F. J., and C. E. Ballon. 1959. Studies on myo-inositol phosphates of natural origin. J. Am. Chem. Soc. 81:915–921.

Poulter, C. D., T. Aoki, and L. Daniels. 1988. Biosynthesis of isoprenoid membranes in the methanogenic archaeabacterium Methanospirillum hungatii. J. Am. Chem. Soc. 110:2620–2624.

Sprott, G. D., I. Ekel, and C. Dicair. 1990. Novel, acid-labile, hydroxydiether lipid cores in methanogenic bacteria. J. Biol. Chem. 265:13735–13740.

Sprott, G. D., M. Meloche, and J. C. Richards. 1991. Proportions of diether, macrocyclic diether, and tetraether lipids in Methanococcus jannaschii grown at different temperatures. J. Bacteriol. 173:3907–3910.

Stetter, K. O. 1989. Family Methanoplanoaceae Widdiguber, Thonnen, and Stetter, 1984, 270VP, p. 2211–2213. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

Stetter, K. O. 1989. Family II. Methanothecaceae Stetter 1982, 266VP, p. 2183–2184. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

Tachibana, A., T. Tanaka, M. Taniguchi, and S. Ot. 1992. On the prenyltransferase from the archaeabacterium Methanobacterium thermostophilicum SF-4, abstr. 4P:42, p. 320. Abstr. 1992 Annu. Meet. Jpn. Soc. Biosci. Biotechnol. Agrochem. (In Japanese.)

Thurl, S., and W. Schäfer. 1988. Lipids from the sulfur-dependent archaeabacterium Thermoproteus tenax. Biochim. Biophys. Acta 961:253–261.

Tornabene, T. G., R. S. Wolfe, W. E. Balch, G. Holzer, G. E. Fox, and J. Oro. 1978. Phytanyl-glycerol ethers and squalenes in the archaeabacterium Methanobacterium thermotrophicum. J. Mol. Evol. 11:259–266.

Touzel, J. P., E. Conway de Macario, J. Nölling, W. M. de Vos, T. Zhihina, and A. M. Lyssenko. 1992. DNA relatedness among some thermophilic members of the genus Methanobacterium: emendation of the species Methanobacterium thermautotrophicum and rejection of Methanobacterium thermostrophium as a synonym of Methanobacterium thermotrophicum. Int. J. Syst. Bacteriol. 42:408–411.

Trincione, A., V. Lanzotti, B. Nicholas, W. Zillig, M. De Rosa, and A. Gambaccorta. 1989. Comparative lipid composition of aerobically and anaerobically grown Desulfurobacter ambivalens, an autotrophic thermophilic archaeabacterium. J. Gen. Microbiol. 135:2751–2757.

Wassef, M. K., J. Sarner, and M. Kates. 1970. Stereospecificity of the glycerol kinase and the glycero phosphate dehydrogenase in Halobacterium cutirubrum. Can. J. Biochem. 48:69–73.

Whitman, W. B. 1989. Order II. Methanococcales Balch and Wolfe 1981, 216VP, p. 2185–2190. In J. T. Staley, M. P. Bryant, N. Pfennig, and J. G. Holt (ed.), Bergey’s manual of systematic bacteriology, vol. 3. The Williams & Wilkins Co., Baltimore.

Woese, C. R., O. Kandler, and M. L. Wheelis. 1990. Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. Proc. Natl. Acad. Sci. USA 87:4576–4579.

Woese, C. R., J. L. Magrum, and G. E. Fox. 1978. Archaeabacteria. J. Mol. Evol. 11:245–252.

Woese, C. R., and G. J. Olsen. 1986. Archaeobacterial phylogeny: perspectives on urkingdoms. Syst. Appl. Microbiol. 7:161–177.

Yamauchi, K., Y. Sakamoto, A. Moriya, K. Yamada, T. Hosokawa, T. Higuchi, and M. Koshita. 1990. Archaeabacterial lipid models. Highly thermostable membranes from 1,13,1,3-dioctadecylmethylen)-bis(2-phytanyl)-glycerol-3-phosphocholine. J. Am. Chem. Soc. 112:3188–3191.

Zellner, G., E. Stackebrandt, P. Messner, B. J. Tindall, E. Conway de Macario, H. Kniefel, and U. B. Sleyr. 1989. Methanocorpusculaceae fam. nov., represented by Methanocorpusculus parvum, Methanocorpusculaceae sinense spec. nov. and Methanocorpusculaceae bavaricum spec. nov. Arch. Microbiol. 151:381–390.

Zhang, D.-L., L. Daniels, and C. D. Poulter. 1990. Biosynthesis of archaeabacterial membrane. Formation of isoprenyl ether by a prenyl transfer reaction. J. Am. Chem. Soc. 112:1264–1265.

Zillig, W. 1991. Comparative biochemistry of Archaea and Bacteria. Curr. Opin. Genet. Dev. 1:544–551.

Zillig, W., H.-P. Klenk, P. Palm, H. Leffers, G. Pühler, F. Gropp, and R. A. Garrett. 1989. Did eukaryotes originate by a fusion event? Endocytobiosis Cell Res. 6:1–25.

Zillig, W., H.-P. Klenk, P. Palm, G. Pühler, F. Gropp, R. A. Garrett, and H. Leffers. 1989. The phylogenetic relations of DNA-dependent RNA polymerases of archaeabacteria, eukaryotes, and eubacteria. Can. J. Microbiol. 35:73–80.