Characterization of attached bacterial populations in deep granitic groundwater from the Stripa research mine by 16S rRNA gene sequencing and scanning electron microscopy

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This paper presents the molecular characterization of attached bacterial populations growing in slowly flowing artesian groundwater from deep crystalline bed-rock of the Stripa mine, south central Sweden. Bacteria grew on glass slides in laminar flow reactors connected to the anoxic groundwater flowing up through tubing from two levels of a borehole, 812–820 m and 970–1240 m. The glass slides were collected, the bacterial DNA was extracted and the 16S rRNA genes were amplified by PCR using primers matching universally conserved positions 519–536 and 1392–1405. The resulting PCR fragments were subsequently cloned and sequenced. The sequences were compared with each other and with 16S rRNA gene sequences in the EMBL database. Three major groups of bacteria were found. Signature bases placed the clones in the appropriate systematic groups. All belonged to the proteobacterial groups beta and gamma. One group was found only at the 812–820 m level, where it constituted 63% of the sequenced clones, whereas the second group existed almost exclusively at the 970–1240 m level, where it constituted 83% of the sequenced clones. The third group was equally distributed between the levels. A few other bacteria were also found. None of the 16S rRNA genes from the dominant bacteria showed more than 88% similarity to any of the others, and none of them resembled anything in the database by more than 96%. Temperature did not seem to have any effect on species composition at the deeper level. SEM images showed rods appearing in microcolonies. The conditions at the levels differ in pH, temperature, redox and flow rate, and in content of sulphate, iron and sulphide. The presence of one dominant species in the laminar-flow reactors at each level indicates that the environments might have offered restrictive physical or physiological conditions difficult to adapt to.

Keywords: deep groundwater, attached bacteria, Stripa, 16S rRNA, scanning electron microscopy

INTRODUCTION

The deep subterranean environment is a relatively new area for microbiological research. The number of papers dealing with the deep groundwaters has increased during the last ten years (Pedersen, 1993a). Groundwaters often offer nutrient-poor conditions, yet bacteria have been found deep down below the ground surface (Pedersen, 1993a; Pedersen & Ekendahl, 1990, 1992a, b). They attract scientific attention for several reasons, such as drinking water contamination problems, toxic waste dumps and the storage of nuclear waste deep underground (Pedersen, 1993b, West et al., 1982, 1985).

Deep granitic rock with groundwater, fractures and
minerals has been suggested as a suitable place for the storage of high-level nuclear waste in Sweden, where this kind of bed-rock is very common. A typical such granite rock formation lies around the former iron ore Stripa research mine in south central Sweden. The iron ore consists of a quartz-banded haematite in a lepatite formation and was mined out in 1976 (Nordström et al., 1985). We have in earlier studies observed that bacteria existed down to 1240 m below ground in a borehole in this mine, that there would be from 4 x 10^9 to 8 x 10^9 more attached than unattached bacteria in a fracture channel and that the attached bacteria were more active than the unattached bacteria (Ekendahl & Pedersen, 1994; Pedersen & Ekendahl, 1992a).

In this study we used the 16S rRNA gene sequencing technique to characterize the Stripa populations attached to glass slides. Results from enrichment cultures of these bacteria and studies of the populations by scanning electron microscopy (SEM) are also reported. Our aim was to identify dominant bacterial species or groups in the populations. The overall distribution of bacteria and the dominant attached groups at each of two levels of the selected borehole are described.

**METHODS**

**Study site and sampling of attached bacteria.** The Stripa mine, the borehole V2, the groundwater and the attachment and growth of bacteria on glass slides in laminar-flow reactors are described in the preceding paper (Ekendahl & Pedersen, 1994). The reactors (Pedersen, 1982; Pedersen et al., 1986) were placed in a mine drift 410 m below ground and connected to the flowing groundwater from the borehole levels 812–820 m (10°C, 2.8 x 10^-3 m s^-1) and 970–1240 m (10°C and 20°C, 0.5 x 10^-3 m s^-1). Slides from these reactors were sampled after 161 and 71 d, respectively, immersed in 0.22 µm filtered groundwater, and transported on dry ice to the laboratory, where the groundwater was decanted from the slides and stored at -80°C until DNA extraction.

**SEM studies of attached bacteria.** Microscope slides with attached bacteria were sampled and immersed in groundwater as above, fixed in glutaraldehyde, dehydrated with alcohol/acetone, critical-point dried, sputtered with gold/palladium and observed in a Zeiss DSM 940 scanning electron microscope.

**Enrichment cultures.** Sterile 100 ml serum bottles were provided with a medium of 0.5 ml 3.5 M sodium lactate, 10 ml 350 mM sodium sulphate and 5 mg sodium dithionite, and with solutions of 60 µl trace elements, 60 µl selenite and tungstate, 30 µl mixed vitamins and 60 µl vitamin B12 described elsewhere (Pedersen & Ekendahl, 1990). Ten bottles for each level and temperature were supplied with 50 ml sterile filtered alkaline groundwater under N2. Sterile wooden sticks were used to rub attached bacteria off slides from the reactors and immediately put into the bottles, which were closed with butyl rubber stoppers and stored at room temperature. Sterile glass beads (diameter 5 mm) were added to some of the bottles to increase the surface area for attached growth.

On a subsequent occasion, the same type of enrichment cultures were made, but this time 10 ml of either a borax/NaOH buffer (pH 10) or a carbonate buffer (pH 10) was added to each bottle to keep pH constant. Also, 0.1–0.2 ml Na2S (0.37 M) was added to keep redox low and stable.

In another set of enrichments, a medium consisting of 300 ml deionized water, 9 ml sodium lactate, 60 ml sodium sulphate, solutions of 0.9 ml trace elements and 0.9 ml selenite and tungstate was adjusted to pH 10 and autoclaved. Concentrations were the same as above. The medium was added in 5 ml portions to each of 30 sterile nitrogen-filled Hungate tubes, to which 0.15 g agar (highcell) was added and mixed at +60°C. The tubes were closed with butyl rubber stoppers and cooled. In the mine, the agar medium was melted and the tubes then heated in a +40°C water bath. Ten ml flowing groundwater from 812–820 m was added to some tubes for culturing bacteria from the water phase. The groundwater was Dynagard-filtered into other tubes under N2. Pieces of 20 mm glass slides from a 812–820 m reactor were put into the agar of these tubes to culture attached bacteria. The tubes were cooled and stored at room temperature in the dark.

**DNA extraction.** Our protocol for DNA extraction was based on procedures described by Margulis (1961) and Wallace (1987), but was slightly modified. Glass slides, 40 x 24 mm, from the freezer were thawed and crushed into smaller pieces by putting pressure on the edge of each slide with sterile glass stirrers. The pieces were put in 760 µl 20 mM Tris/HCl, pH 8.0, 20 mM EDTA, 0.35 M sucrose and incubated with lysozyme (2 mg ml^-1; Sigma) at 37°C for 1 h to destroy cell walls. Then, the attached cells were lysed by adding 40 µl 20% (w/v) SDS and the proteins digested with proteinase K (250 µg ml^-1; Sigma) during an additional incubation at 60°C for 1 h. The DNA was extracted from 400 µl of the cell lysate solution with an equal volume of phenol/chloroform/isoamyl alcohol (25:24:1, by vol.), followed by one extraction with chloroform/isoamyl alcohol ('chisam', 24:1) so that no cell debris was visible. Finally the 'chisam' was washed with TE buffer (10 mM Tris/HCl, 1 mM EDTA, pH 8.0). The DNA was precipitated with 1/3 vol. of 10 M ammonium acetate (final concn 2.5 M) and 2.5 vols 99% (v/v) ethanol. To ensure complete recovery, 50 µg tRNA was added as a carrier. The precipitate was washed with 100 µl 70% ethanol and dried in vacuum for 30 s, dissolved in TE buffer and stored at -20°C.

This procedure was repeated once for each borehole level and temperature.

To obtain a representative material, all cells on the glass slides must be disrupted in the initial lysis step. The degree of this cell disruption was measured by staining the slides with acridine orange after lysis as described for total direct counts (Pedersen & Ekendahl, 1990). They were inspected for potential unlysed cells under blue light (390–490 nm) in an epifluorescence microscope (Zeiss, filter 515 nm) at 1250 x enlargement. No cells were detected, indicating complete cell lysis. Additional control experiments with lysis of cell suspensions of Escherichia coli, Desulfovibrio baculatum and Bacillus megaterium showed that 90–95% of the cells were lysed with this method.

**PCR amplification and purification of the product.** One microlitre of the extracted DNA solution was sufficient to amplify the 16S rRNA region by PCR (Saiki et al., 1988). The DNA was added to a mixture of 10 µl of 10× PCR buffer (Stratagene), 0.2 mM of each nucleotide triphosphate, 0.25 µM of each primer and double-distilled water to a final volume of 100 µl. The samples were first treated with RNase A (10 mg ml^-1; Sigma) for 15 min at 37°C and then incubated at 95°C for 5 min, before addition of 1 µl Pfu DNA polymerase.
agarose extraction kit (Qiagen), following the specification of distilled water and stored at -20 °C.

From each culture 0.5 ml was suspended in 0.5 ml conc. glycerol and stored at -20 °C. Every third clone (12 of every 30 clones), was picked out for subsequent sequencing. The attempts to cultivate the Stripa bacteria in serum bottles and agar-shakes were all unsuccessful. Two morphological types of cells could be seen when sub-samples from 970–1240 m, 20 °C, were stained with acridine orange (Pedersen & Ekendahl, 1990) and studied with epifluorescence microscopy. Some AODC images from this depth showed a few bacteria with an outer morphology resembling Planctomycetes (not shown). Occasionally, stalked bacteria resembling Caulobacter could be observed (Fig. 1g). Figs 1(c) and 1(d) show bacteria from 970–1240 m, 10 °C, after 71 d exposure. These rods had a mean length of 2.4 μm but were sometimes filamentous (more than 5 μm long). They appeared in colonies, and thin (100 nm) threads were present together with the bacteria.

Characterization of deep groundwater bacteria

Control for quantitative PCR. Pure cultures of typical groundwater bacteria were harvested in the lag phase. Mixtures of 4 parts D. baculatum and 1 part Gallionella ferruginea at 5 × 10⁴ and 1 × 10⁵ cells ml⁻¹ and of 1 part each of B. megaterium, D. baculatum and G. ferruginea at 1 × 10⁴ and 1 × 10⁵ cells ml⁻¹ were extracted, PCR-treated, cloned and sequenced as above.

Sequence analysis. Multiple alignments and comparison with 16S rRNA genes of other organisms were made using the Genetic Computer Group (GCG) sequencing analysis and the EMBL database. The sequences were also compared with signature bases in Woese (1987) to place them into systematic groups.

RESULTS

SEM studies

Figs 1(a) and 1(b) show microscope slides which had been exposed to flowing groundwater from 812–820 m depth (2.8 × 10⁻³ m s⁻¹) for 161 d. A thin film that dried during SEM preparations (Fig. 1h) covered colonies of short rods, 1–2.5 μm, mean 2.0 μm. Some AODC images from this depth showed a few bacteria with an outer morphology resembling Planctomycetes (not shown). Occasionally, stalked bacteria resembling Caulobacter could be observed (Fig. 1g). Figs 1(c) and 1(d) show bacteria from 970–1240 m, 10 °C, after 71 d exposure. These rods had a mean length of 2.4 μm but were sometimes filamentous (more than 5 μm long). They appeared in colonies, and thin (100 nm) threads were present together with the bacteria.

Enrichment cultures

The attempts to cultivate the Stripa bacteria in serum bottles and agar-shakes were all unsuccessful. Two morphological types of cells could be seen when sub-samples from 970–1240 m, 20 °C, were stained with acridine orange (Pedersen & Ekendahl, 1990) and studied with epifluorescence microscopy. Some were long thin rods and others were oval in shape. The bacteria in one bottle grew to five times their original numbers during 9 d, but did not grow any further after that. Heat shock may explain the lack of growth in the agar-shakes.

Control for quantitative PCR

Applying this technique to equal-sized bacteria (mixture 1), the sequences were obtained in the same proportions as in the start mixture (Table 1). When the 24 times larger B. megaterium was included, its DNA dominated the result.

Clone groups

The clones examined clustered into three major groups called I, II, and III (Table 2). Clones that were identical
Fig. 1. For legend see facing page.
Characterization of deep groundwater bacteria

Figure 1. SEM images of attached bacteria on microscope slides exposed to flowing groundwater from the Stripa borehole V2. (a, b) 812–820 m, 10 °C, 161 d; (c, d) 970–1240 m, 10 °C, 71 d; (e, f) 970–1240 m, 20 °C, 71 d; (g, h) 812–820 m, 10 °C, 161 d. Bars: (a) 20 μm, (b) 2 μm, (c) 5 μm, (d) 2 μm, (e) 20 μm, (f) 2 μm, (g) 1 μm, (h) 2 μm.

Table 1. Species distribution of 12 randomly chosen clones for two different bacterial mixtures and concentrations

<table>
<thead>
<tr>
<th>Bacteria in mixture</th>
<th>Cell volume ratio</th>
<th>Mixture</th>
<th>Species distribution of clones at:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 × 10^4 cells ml^-1</td>
</tr>
<tr>
<td>Mixture 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desulfovibrio baculatum: Gallionella ferruginea</td>
<td>1:1</td>
<td>4:1</td>
<td>10:2</td>
</tr>
<tr>
<td>Mixture 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacillus megaterium: Desulfovibrio baculatum: Gallionella ferruginea</td>
<td>24:1</td>
<td>1:1</td>
<td>11:1:0</td>
</tr>
</tbody>
</table>

were placed in the same group and clones that differed from the major groups, appearing only once, were regarded as single observations. None of the clones among the single observations were identical, but some were closely related to the dominant groups, differing by only a few bases.

(i) Level 812–820 m. Almost two-thirds of the clones from this level belonged to group I (Table 2). Two clones belonged to group II, and the remaining four clones (17%) clustered in group III. Three clones were single observations. The ratio between the two extractions is close to 1:1 and therefore comparable.

(ii) Level 970–1240 m. Group II dominated this level at 10 °C. As much as 83% of the clones were of this type. No clones from group I were found and only one clone belonged to group III.

At 20 °C, 13 clones (54%), belonged to group II, none to group I, and four to group III. Four of the seven clones that were single observations did not show much resemblance to any other sequences. Since these four clones were found only in the first DNA extraction and two of them were related to eukaryotes, one of them showing 100% similarity to human chromosomal DNA, we suspected that this extraction was contaminated in the laboratory. These four clones are therefore not considered further.

The ratio of clones between the two extractions was close to 1:1 at both 10 and 20 °C. The distribution of clones
Table 2. Groups of bacterial clones screened from two levels of the Stripa borehole V2 and their distribution

DNA from bacteria attached to glass surfaces was extracted, and the 16S rRNA genes were amplified by PCR, cloned and sequenced using primer 907–926. Each of the groups I, II and III contains identical clones. Single observations were not identical.

<table>
<thead>
<tr>
<th>Clone group</th>
<th>812–820 m, 10 °C</th>
<th>970–1240 m, 10 °C</th>
<th>970–1240 m, 20 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of clones*</td>
<td>% of total</td>
<td>No. of clones*</td>
</tr>
<tr>
<td>I</td>
<td>15 (6+9)</td>
<td>63</td>
<td>0 (0+0)</td>
</tr>
<tr>
<td>II</td>
<td>2 (2+0)</td>
<td>8</td>
<td>20 (10+10)</td>
</tr>
<tr>
<td>III</td>
<td>4 (2+2)</td>
<td>17</td>
<td>1 (1+0)</td>
</tr>
<tr>
<td>Single observations</td>
<td>3 (2+1)</td>
<td>12</td>
<td>3 (1+2)</td>
</tr>
</tbody>
</table>

* The total number of clones in each clone group is followed, in parentheses, by the numbers achieved in extraction 1 and 2, respectively.
† Four of these clones are probably due to contamination, see text for details.

Table 3. Comparison of similarity between the sequenced Stripa clone groups and 16S rRNA sequences in the EMBL database

<table>
<thead>
<tr>
<th>Clone group</th>
<th>EMBL accession no.</th>
<th>Overlap, no. of bp compared*</th>
<th>Systematic group†</th>
<th>Most related bacteria</th>
<th>% similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I L20810</td>
<td>764</td>
<td>737</td>
<td>Beta Proteobacteria</td>
<td>Pseudomonas solanacearum</td>
<td>91.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Zoogloea ramigera</td>
<td>91.2</td>
</tr>
<tr>
<td>II L20811</td>
<td>877</td>
<td>877</td>
<td>Beta-1 Proteobacteria</td>
<td>Pseudomonas testosteroni</td>
<td>95.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brachymonas denitrificans</td>
<td>94.9</td>
</tr>
<tr>
<td>III L20812</td>
<td>739</td>
<td>737</td>
<td>Gamma Proteobacteria</td>
<td>Acinetobacter calcoaceticus</td>
<td>96.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pseudomonas aeruginosa</td>
<td>87.7</td>
</tr>
</tbody>
</table>

* Between the clone and the most related bacterium.
† According to signature bases in Woese (1987).

between the two temperatures at this level is also comparable if the four contaminants are excluded. Due to their exclusion, the percentage of the group II bacteria at 20 °C rises to 65%, group III to 20% and the single observations decrease to 15% of the total number of clones at 20 °C (compare Table 2).

Phylogenetic relationships

Comparison of the fully sequenced clone from group I with signature bases (Woese, 1987) placed it among the beta group of the Proteobacteria, as shown in Table 3. This group was found only at the 812–820 m level and the highest percentages of similarity were found with the bacteria Pseudomonas solanacearum (91.7%) and Zoogloea ramigera (91.2%).

Except for two clones from the 812–820 m level, group II was found to exist and dominate at the 970–1240 m level, at both temperatures. This group fell into the beta-1 group of the Proteobacteria and the highest percentages of similarity were found with Pseudomonas testosteroni (95.9%) and Brachymonas denitrificans (94.9%).

Group III was found at both levels in comparable frequencies. This group belonged to the gamma group of the Proteobacteria and showed highest similarities with Acinetobacter calcoaceticus (96.1%) and Pseudomonas aeruginosa (87.7%).

Comparing the whole bacterial sequences from the three major groups with each other (Table 4) showed that the highest percentage of similarity (88.4%) was found between groups I and II. Comparisons between the most related bacteria for each group are also included in this table.
DISCUSSION

Knowledge of the bacterial species present in an ecological system is of interest to evaluate the specific properties and functions of the system. Good methods for enumeration and identification of these species or groups are necessary. All attempts to enrich and grow the viable (Pedersen & Ekendahl, 1992a) Stripa bacteria failed. Earlier attempts to culture them on plate count growth media for heterotrophs with and without oxygen resulted in less than 1% of the total population growing (Pedersen, 1988). The negative plate count and enrichment results emphasize the importance of methods in microbial ecology that are independent of laboratory culturing techniques. In this study we have used a molecular method that can reveal both cultivable and uncultivable bacteria in deep groundwater. We regard our results as a fairly accurate reflection of the actual distribution of different bacterial cells in the original samples, based on the following discussion.

We used PCR for amplifying rRNA genes from mixed natural populations, being aware that archaeobacteria are reported to have usually single copies of the rRNA gene, while eubacteria commonly have 5–10 copies per haploid genome (Davies & Nomura, 1972; Pace et al., 1986; Ward et al., 1992). The control experiment for quantitative PCR (Table 1) indicated that the PCR technique used was quantitative for populations with equal-sized non-growing bacteria in addition to its qualitative nature, but biased when bacteria of different sizes were investigated. This result indicates that bacteria may have rRNA gene copies per genome in relation to their size, which seems reasonable. The transcription activity per rRNA gene locus under defined growth conditions will then be approximately constant and independent of large differences in size for bacteria with similar growth kinetics and comparable growth rates. The Stripa populations were very slow-growing (Ekendahl & Pedersen, 1994) and very probably in a one-genome state.

To get the gene abundance for a particular species, one should multiply the number of cells of the studied species with the number of rRNA gene copies per cell (Ward et al., 1992). The specific/total rRNA gene ratios achieved in this study are thus an approximate and not an absolute estimate of cell numbers, but they are more accurate for estimating organism abundance than the rRNA ratios. In our study we did not detect any archaeobacteria, and the size distribution of the investigated bacteria was equal in the different samples (Ekendahl & Pedersen, 1994), which indicates the clone distribution results to be an accurate approximation of the relative species abundance (cf. Table 2 and Fig. 3 in Ekendahl & Pedersen, 1994).

All of the bacteria found belonged to the Proteobacteria. Two of the major groups fell into the beta group of Proteobacteria and the third into the gamma group. None of the sequences from the three groups was identical to any of the bacteria in the EMBL database. The similarity values obtained between the clone groups and the bacteria in the database are far too remote to make comparisons of their phenotypic characters reasonable (Tables 2–4). Several of the single observations showed close relation to the dominant groups, differing by only a few bases. Thus the dominant groups may have even greater importance in their ecological impact. The activities of these bacteria are discussed extensively by Ekendahl & Pedersen (1994).

Our SEM images of the glass surfaces indicated that the two levels in the borehole had populations that were different. The bacteria were mostly rods, and differed only slightly in size between the levels (Fig. 1). Within the deeper level, the bacteria at 20 °C had a different

Table 4. Similarity values (%) between 165 rRNA gene sequenced Stripa clones and closely related bacteria from the EMBL database

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>88</td>
<td>82</td>
<td>91</td>
<td>51</td>
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</tr>
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morphology from those at 10 °C. They seemed to have secreted thin threads that might act as holdfasts or for cell-cell interactions (Fig. 1e, f). The threads might be extracellular material that covered the whole colonies but dried during SEM dehydration (Fig. 1h), but this seems less probable if judged from the images.

The 16S gene data (Table 2) support the SEM observations that there were different populations at the two levels. The beta Proteobacteria in group I were found only at the higher level in the borehole, whereas the beta Proteobacteria in group II were found almost exclusively at the deeper level. Two clones from group II were, however, found at the higher level. As shown elsewhere, the conditions at the levels differ in pH, temperature, redox and flow rate, and in content of sulphate, sulphide and total inorganic carbon (Ekendahl & Pedersen, 1994). The numbers of bacteria in the bulk water phase, the CO₂ assimilation and lactate respiration rates on glass slides were higher at the deeper level. The gamma Proteobacteria in group III seem to be equally distributed. The different temperatures at the deeper level had very little effect on species composition, though there was a slight indication that group II bacteria thrive better at 10 than at 20 °C at the 970-1240 m level. An increase in temperature thus affected the morphology (Fig. 1) but not the population composition. The bacterial groups present may thus be selectively adapted to these different environments. For example, it can be speculated that since there was a high redox value and traces of oxygen at 812-820 m, the group I bacteria dominating this level may be more adapted to a facultative anaerobic metabolism, while the group II bacteria are perhaps obligate anaerobes that instead will thrive in the anoxic, sulphide-rich, low-redox groundwater at 970-1240 m. The presence of one dominant species in the laminar-flow reactors at each level suggests that the environment may have offered restrictive physical or physiological conditions, difficult to adapt to. The situation in the rock is probably similar, with only a few dominant bacteria present (cf. Ekendahl & Pedersen, 1994).

To make the description of bacterial populations in natural ecosystems complete and to reliably identify and characterize environmental samples, both genotypic and phenotypic characterization must be used in polyphasic taxonomy. Combining studies on physiology (Ekendahl & Pedersen, 1994), morphology, and the molecular composition of deep groundwater populations, with methods like labelling and scintillation counts, SEM and sequencing, has revealed new information about deep granitic groundwater microbial ecosystems (Ekendahl & Pedersen, 1994; Pedersen & Ekendahl, 1992a, b). The study presented here strongly confirms our theory that there is a pronounced spatial distribution of bacteria between sampling sites as a function of environmental conditions. We have now continued our investigations on bacterial populations in deep granitic bed-rock at the Åspö Hard Rock Laboratory (Gustafsson et al., 1988, 1989, 1991), which is under construction on the southeast coast of Sweden. Preliminary results confirm a pronounced spatial distribution of subterranean bacteria, also reported from other sites (Pedersen, 1993a). The results also suggest that in some cases the distribution of bacterial populations on glass slides is similar to the distribution of unattached bacteria in the groundwater, in other cases it is different. With the use of the techniques discussed above and also other techniques, like fluorescent molecular probes and anaerobic viable counts to quantify bacterial species in situ, we continue to investigate the structure of deep groundwater populations, what governs their existence and activity, and also what effect they may have on the surrounding environment.

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REFERENCES


Pace, N. R., Stahl, D. A., Lane, D. J. & Olsen, G. J. (1986). The


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