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# CHARACTERIZATION OF MICROBIAL SOURING IN BEREA-SAND POROUS MEDIUM WITH A NORTH SEA OIL FIELD INOCULUM

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Microbial souring ($H_2S$ production) in porous medium was investigated in an anaerobic upflow porous medium reactor at 60°C using produced waters obtained from the North Sea Ninian oilfield as the inoculum. Multiple carbon sources commonly found in oil field waters (formate, acetate, propionate, iso- and *n*-butyrates) with inorganic sulfate as the electron acceptor were used as the substrates. Stoichiometry and the rate of souring in the reactor column were calculated. A large proportion of $H_2S$ was trapped in the column as FeS and possibly as a gas phase. Concentration gradients for the substrates (organic acids and sulfate) and $H_2S$ were generated along the column. At steady state, the highest volumetric substrate consumption and $H_2S$ production were found at the front part (inlet) of the reactor column. The average volumetric sulfate reduction rate after $H_2S$ production had stabilized was calculated to be 203 ± 51 mg sulfate-S$\cdot l^{-1}\cdot d^{-1}$. Comparison of the results with the authors' previous work on the Alaska Kuparuk oilfield waters indicates that the two different microbial inocula (produced waters) exhibited the same experimental trends (rates and location) for souring in the experimental reactor system. This indicates that abiotic factors, as well as microbial parameters, may play an important role for microbial souring in the system.

KEYWORDS: microbial souring, porous medium, mixed culture, multiple substrates, kinetics, oil field

## INTRODUCTION

Souring, the production of hydrogen sulfide ($H_2S$) in oil reservoirs which have been subjected to water flooding (injection), costs oil companies billions of dollars every year (Lee, 1990). The process is believed to be mediated by sulfate-reducing bacteria (SRB) present in oil reservoirs (Cord-Ruwisch *et al.*, 1987; Cochrane *et al.*, 1988; Gevertz *et al.*, 1991; Beeder *et al.*, 1994), which reduce sulfate in the injection water to hydrogen sulfide. Problems associated with $H_2S$ production in oil reservoirs include $H_2S$ toxicity, corrosion, and non-selective reservoir plugging by SRB biomass and precipitated iron sulfide, both of which retard the secondary oil recovery (Cord-Ruwisch *et al.*, 1987). In addition, $H_2S$ production significantly raises the sulfur content of the produced natural gas, where pipeline standards limit the $H_2S$ concentration to several ppm. The problem becomes more serious when sea water, which contains a high concentration of sulfate, is injected into oil reservoirs (Frazer & Bolling, 1991; Rosnes *et al.*, 1991). Sea water is used in many cases because of its proximity and availability.

Major carbon and energy sources used by SRB in oil reservoirs are believed to be short-chain organic acids, which are probably the products of the incomplete bacterial

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oxidation of oil hydrocarbons under aerobic conditions (Carothers & Kharaka, 1978; Barth, 1987; Barth, 1991). However, recent studies have found that petroleum hydrocarbons may also serve as electron donors for sulfate reduction (Jackson & McInerney, 1994; Reuter *et al.*, 1994).

Methods have been investigated for mitigating souring. Several biocides are known to inhibit SRB (Ruseska *et al.*, 1982), but biocide application has several disadvantages. Inhibitory concentrations of biocides determined in laboratory studies may be insufficient in the field where strains other than those detected in the laboratory are present. Chemical components in reservoirs may scavenge biocides through reaction or sorption. Application of biocides in large waterflooding projects is very expensive. In addition, SRB form biofilms which are protective against biocides (Ruseska *et al.*, 1982; Blenkinsopp & Costerton, 1991; Bryers, 1993). Elimination of sulfate (by membrane separation, for example) from the injection water is another possibility for controlling SRB (Bakke *et al.*, 1992). However, this process is also expensive.

Successful mitigation of souring depends on understanding the kinetics of $H_2S$ production (sulfate reduction) and the growth characteristics of SRB in porous medium. In a previous study (Chen *et al.*, 1994b), an inoculum (produced water sample) from ARCO's Kuparuk oil fields in Alaska was used and the rate of microbial souring in an anaerobic upflow porous medium reactor was calculated. Multiple carbon sources (formate, acetate, propionate, iso- and *n*-butyrates) commonly found in oil field waters were added with inorganic sulfate as the electron acceptor. In this article, the study was extended to explore souring using an inoculum obtained from the Chevron UK Ltd, North Sea Ninian oilfield. Substrate utilization and product formation in porous medium were investigated using the same reactor system. The stoichiometry of souring, which was not included in the previous study, was calculated. The experimental trends of souring in the reactor system were compared with the Kuparuk field inoculum to identify parameters affecting souring and to determine whether generic trends of souring in porous medium can be obtained with inocula from different oil fields.

## MATERIALS AND METHODS

### *Reactor System*

The anaerobic upflow porous medium reactor system has been described previously (Chen *et al.*, 1994a). The reactor was a packed-bed tubular reactor (50 × 5.5-cm) made of polycarbonate and equipped with six sampling ports. Sampling ports were at column distance z = 5, 10, 15, 20, 30, and 40 cm from the inlet. The porous media were contained in the reactor by brass gauge mesh over each end of the column. The flow was dispersed by a funnel at each end of the reactor column. Anaerobic conditions were maintained by purging the feed medium, which contained small amounts of reducing agents ($Na_2S_2O_4$ and $Na_2S$), with purified $N_2$ gas (Chen *et al.*, 1994a).

Crushed Berea sandstone was used as the porous medium. Berea sand is a standard material used by oil companies for investigating *in situ* oil recovery (Shaw *et al.*, 1989). The porous medium contained sand particles ranging from 35 to 300 µm in diameter with over 50% of particles being in the 220 µm regime. The high column-diameter-to-grain-diameter ratio indicates that wall effects on flow are negligible (Schwartz & Smith, 1953). The porosity of the sand column was 0.42 and the permeability was approximately 4 darcys. The sand pretreatment procedure, reactor sterilization, column packing, and porosity determination have been described previously (Chen *et al.*, 1994a).

*Inoculation*

Produced waters are often used for souring studies as they contain SRB present in the reservoir and nutrients, sulfate and sulfide (Cochrane *et al.*, 1988; Rosnes *et al.*, 1991; Beeder *et al.*, 1994). Produced waters were taken from the Southern Production Platform of Chevron's North Sea Ninian oilfield (northeast of Scotland). Water samples were taken from one operating free water knockout (FWKO #0205) which separates the formation mixture of oil and water. The water samples had a salinity of 2% (w/v) and contained a high amount of sulfate at 1050 mg $S \cdot l^{-1}$. The produced water samples were concentrated (50:1, by a Pellicon filter device) on-site, flash-frozen, and stored at –70°C. The concentrated water samples contained approximately $4 \times 10^4$ bacterial $cells \cdot ml^{-1}$ as determined by the acridine orange direct count (Hobbie *et al.*, 1977). Three batch cultures (30 ml medium in each 50-ml vial) prepared from the concentrated water samples were used to inoculate the reactor at the inlet (Chen *et al.*, 1994b). They were pregrown under SRB enrichment conditions; the $H_2S$ level and the total cell density in these cultures were ~100 mg $S \cdot l^{-1}$ and ~$5 \times 10^6$ $cells \cdot ml^{-1}$, respectively.

The composition of the high-salinity feed medium has been described previously (Chen *et al.*, 1994b). It contained formic acid, acetic acid, propionic acid, iso- and *n*-butyric acids as the carbon and energy sources. These five short-chain organic acids are commonly found in produced waters (Carothers & Kharaka, 1978; Barth, 1987; Barth, 1991). The concentration of each organic acid in the medium was 200 $mg \cdot l^{-1}$ (± 20%) and the sulfate concentration was 300 mg $S \cdot l^{-1}$. The pH of the medium was adjusted to 7.0 (± 0.2) with HCl and NaOH. The pH of the produced water from the knockout was 7.2.

The porous medium reactor was incubated at 60°C, which represents a common high-temperature condition found in oil reservoirs. However, oil reservoir temperature varies through a formation, as it can be as low as 4–10°C (sea water temperature) near the injection well and rises throughout the formation. The temperature of the produced water from the knockout was 87°C. The flow rate of the medium was 650 (± 100) $ml \cdot d^{-1}$, which equals a superficial flow velocity of 27.4 (± 4.2) $cm \cdot d^{-1}$. A similar flow regime is used by oil companies for water injection (Ligthelm *et al.*, 1991).

*Analytical Methods*

During incubation, aqueous-phase samples were taken periodically from the anaerobic reactor column for assays of the cell density and the concentrations of $H_2S$, sulfate and organic acids. Total bacterial cells in the aqueous phase were counted by the acridine orange direct count (Hobbie *et al.*, 1977). Hydrogen sulfide was analyzed by the methylene blue method (Cline, 1969). Sulfate and organic acids were measured by ion chromatography (Chen *et al.*, 1994b). Aqueous hydrogen sulfide and sulfate concentrations were expressed in terms of sulfur content ($H_2S$-S and sulfate-S).

## RESULTS

*Dynamics of Souring*

Hydrogen sulfide production (sulfate reduction) in the reactor column can be visualized by the formation of black precipitates of ferrous sulfide (FeS; the feed medium contained 7.5 $\mu M$ of $Fe^{2+}$ and the sandstone contained residual $Fe^{2+}$; Chen *et al.*, 1994a, b). The formation of black spots in the column indicates the production of $H_2S$ and growth of SRB at nearby regions (Chen *et al.*, 1994a). Black spots were initially observed at the

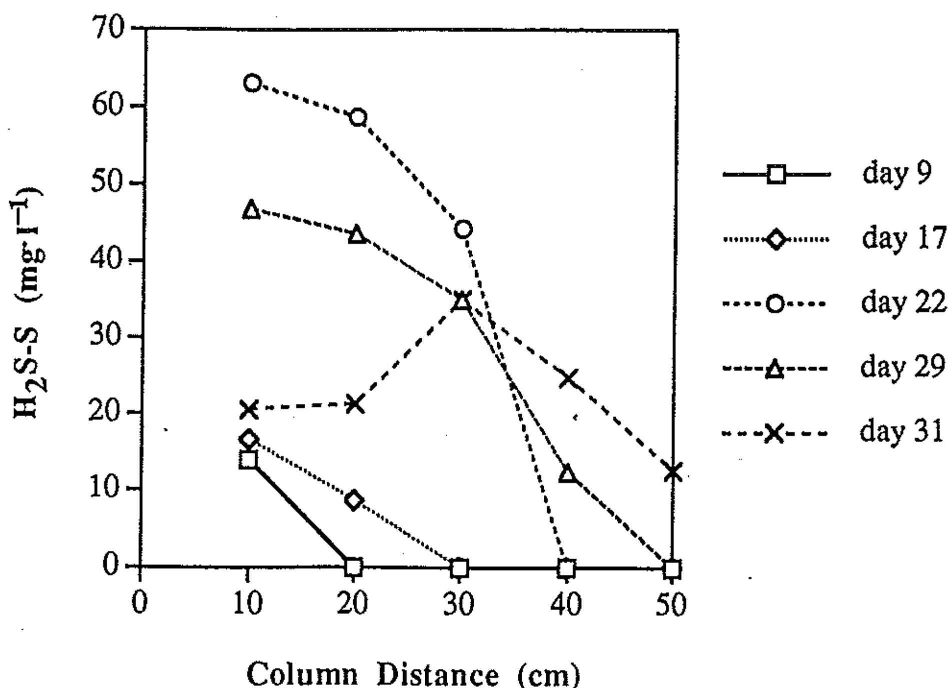


Fig. 1 Diffusion of souring ($H_2S$) through the porous medium column. Column distances 0 cm and 50 cm indicate the inlet and outlet of the column, respectively.

front part of the column (z = 0 to 10 cm) 9 d after inoculation. Hydrogen sulfide in the aqueous phase at that time was measured to be 13.9 $mg \cdot l^{-1}$ at z = 10 cm. No $H_2S$ was detected at sampling ports of z > 10 cm. With time the black spots diffused, merged, and expanded upward. Hydrogen sulfide in the aquous phase began to be detected at higher sampling ports of z = 20, 30, and 40 cm and at the outlet (effluent) on day 17, 22, 29, and 31, respectively (Fig. 1). The entire column turned black around day 31, but no bacterial cells were detected in the effluent until $H_2S$ had been produced throughout the column (day 31). This may be caused by a continuing attachment of bacterial cells to sand particles before the entire column was saturated with the bacteria and $H_2S$ was produced throughout. The cell count in the effluent after day 31 fluctuated between $10^5$ and $10^6$ $cells \cdot ml^{-1}$ (order of magnitude).

The $H_2S$ level in the effluent increased and began to oscillate (Fig. 2). The sulfate concentration in the effluent also oscillated (Fig. 2). The direction of oscillation of sulfate was opposite to that of $H_2S$. This, along with the fact that the sulfate consumption exceeded the $H_2S$ production as measured in the aqueous phase (Fig. 2), indicates that $H_2S$ was reacting (precipitating as ferrous sulfide) in the column.

Formate was the first organic acid consumed (Fig. 3). Formate was almost depleted by day 22, though $H_2S$ had not yet been produced throughout the column (Figs 1, 2, 3). Propionate, iso-butyrate and *n*-butyrate were utilized after the formate was consumed (Fig. 3). The level of acetate in the effluent increased as propionate, iso-butyrate and *n*-butyrate were consumed (Fig. 3), indicating that acetate was produced from these longer-chain organic acids.

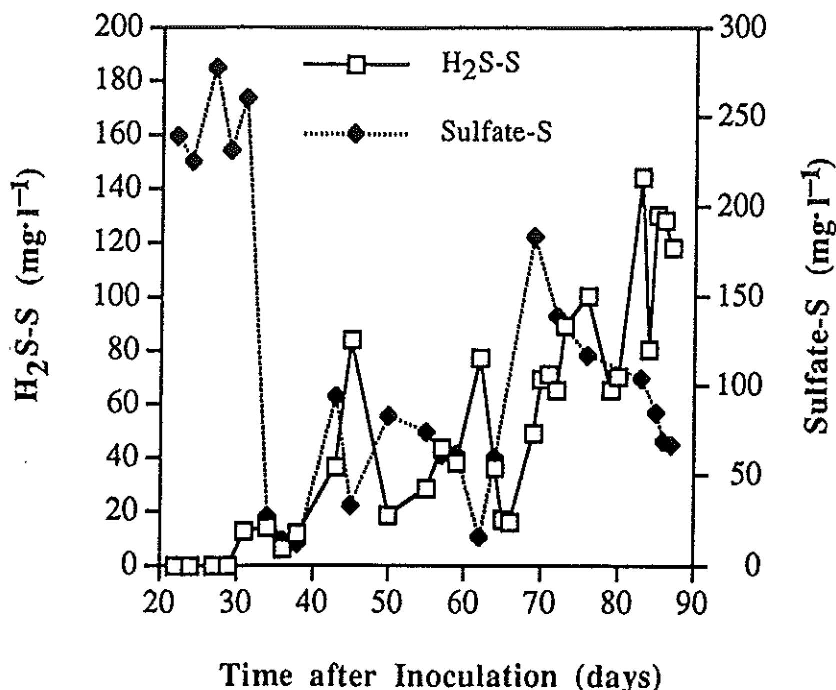


Fig. 2 Time course of souring in Berea-sand porous medium reactor – changes in effluent $H_2S$ and sulfate concentrations.

*Substrate Consumption along the Column*

Substrate utilization and $H_2S$ production along the column were monitored after $H_2S$ production had "stabilized" (stable fluctuation within a certain range). Measurements along the column were made for three successive days before the end of the experiment. Means and standard deviations ($n$ = 3) were calculated (Figs 4, 5). Concentration gradients for the substrates (organic acids and sulfate) and $H_2S$ were generated along the column (Figs 4, 5). Most of the substrates (organic acids and sulfate) were consumed within the first 30 cm of the 50 cm column (Figs 4, 5) and the highest $H_2S$ production was also found at the front part of the column (Fig. 5). Formate was consumed very quickly and was not detected at the first sampling port (z = 5 cm). The concentration of acetate increased as the propionate, iso- and $n$- butyrates were consumed (Fig. 4), as acetate was produced from these longer chain organic acids through incomplete oxidation. The cell density in the aqueous phase along the column was stable at an order of magnitude of $10^7$ cells·ml$^{-1}$. These bacterial cells are presumed to be mostly SRB since the batch cultures that were used to inoculate the column were enriched with SRB. The cell density in the effluent was approximately one order of magnitude lower than in the column, which is probably due to entrapment of bacterial cells in the porous medium.

The average volumetric sulfate reduction rate in the porous medium after $H_2S$ production had stabilized was calculated using data for the first 30 cm of the column, where most of the biotransformation occurred. The data are sulfate-S levels at 297 ± 28 and 78 ± 7 mg·l$^{-1}$ at z = 0 and 30 cm, respectively, and a superficial flow velocity of 27.4 ± 4.2 cm·d$^{-1}$. The average sulfate reduction rate was calculated to be 203 ± 51 mg sulfate-

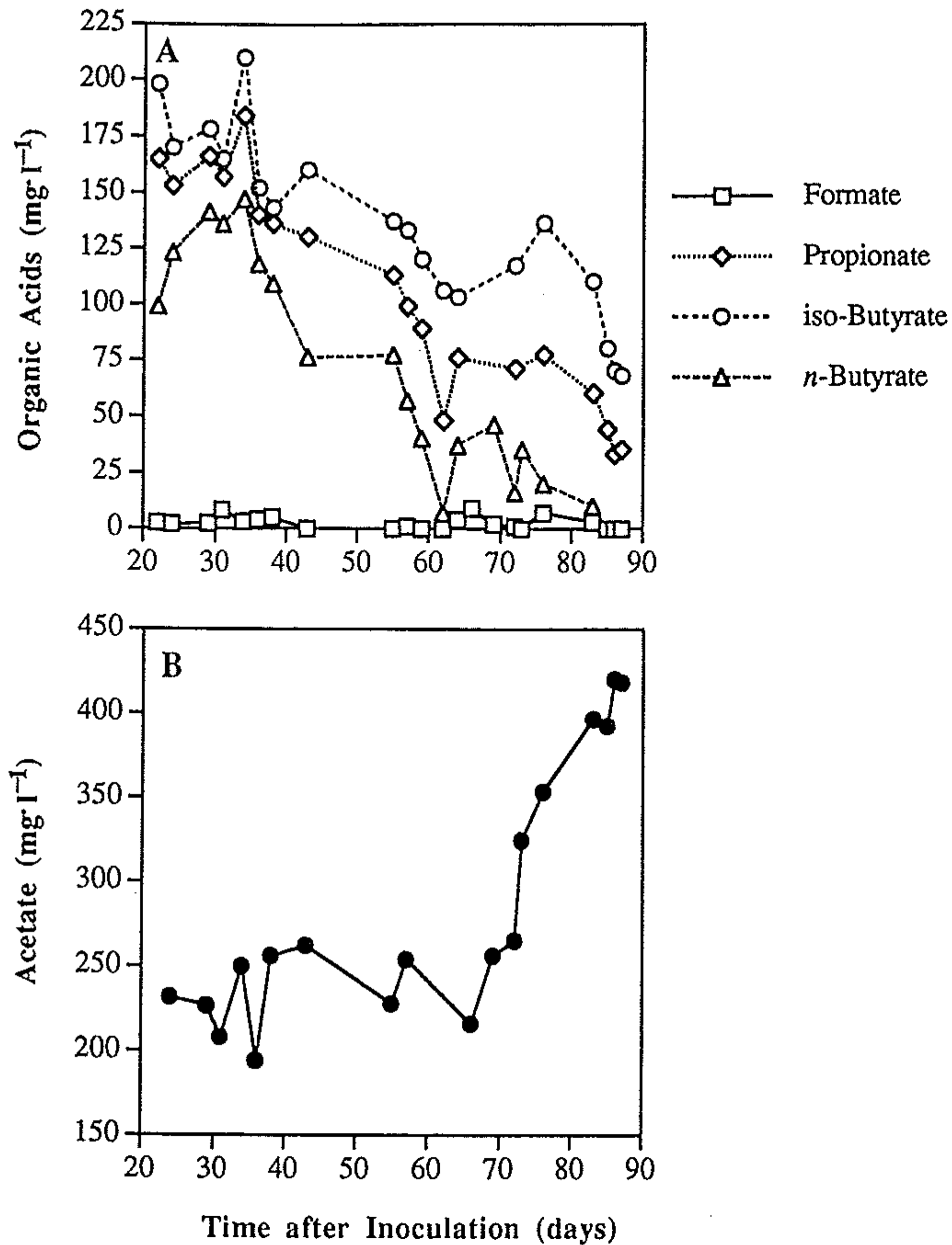


Fig. 3 Time course of souring in Berea-sand porous medium reactor – changes in effluent organic acid concentrations. A = formate, propionate, iso- and *n*-butyrates; B = acetate.

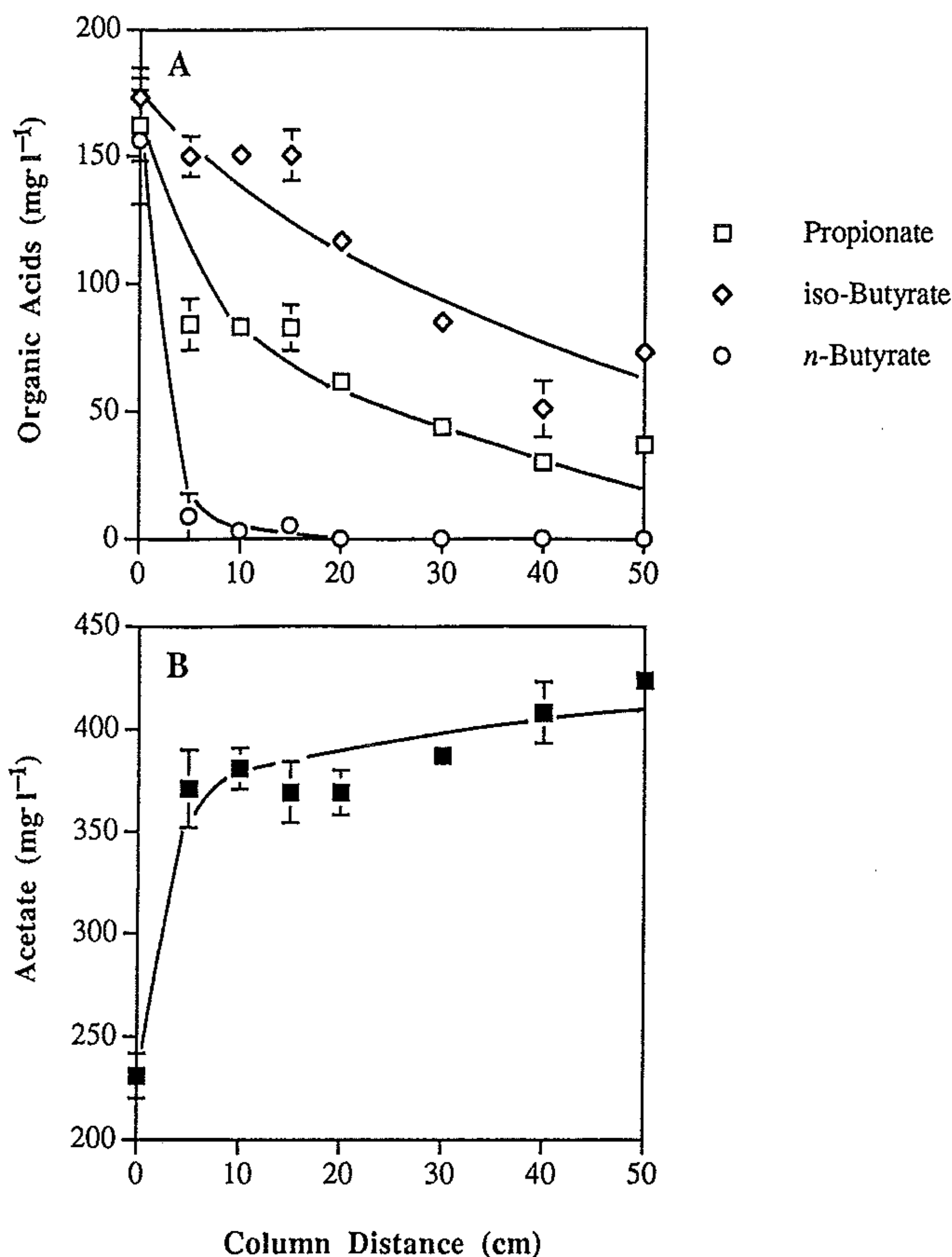


Fig. 4 Organic acid concentration gradients in the column after $H_2S$ production had stabilized. Column distances 0 cm and 50 cm indicate the inlet and the outlet of the column, respectively. Means and standard deviations represent measurements from 3 successive days ($n = 3$) before the end of the experiment. Data points where error bars are not presented indicate that errors are smaller than or equal to the size of the symbol. A = propionate, iso- and $n$-butyrates; B = acetate. Formate was depleted very quickly and was not detected at the first sampling port ($z = 5$ cm) of the column.

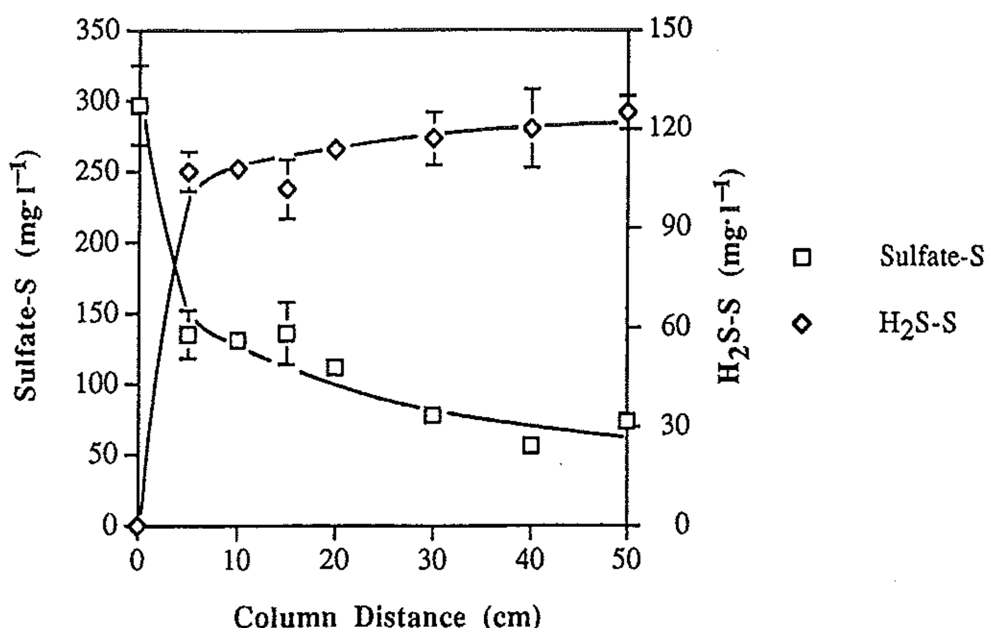


Fig. 5 Sulfate and $H_2S$ concentration gradients in the column after $H_2S$ production had stabilized. Column distances 0 cm and 50 cm indicate the inlet and the outlet of the column, respectively. Means and standard deviations represent measurements from 3 successive days ($n$ = 3) before the end of the experiment. Data points where error bars are not presented indicate that errors are smaller than or equal to the size of the symbol.

$S{\cdot}l^{-1}{\cdot}d^{-1}$ (= total $H_2S$-S produced$\cdot l^{-1}{\cdot}d^{-1}$ since sulfur content was used as the basis). It was assumed that the sulfate consumed was completely used for microbial sulfate reduction, as previous experiments indicated that the sulfate concentration did not change throughout a sterile reactor column.

## DISCUSSION

### *Dynamics*

Although SRB are routinely identified in oil field waters (Rozanova & Pivoravora, 1988; Rosnes *et al.*, 1991; Beeder *et al.*, 1994), few papers have been published regarding the metabolic activity and $H_2S$ production in porous medium using field microbial consortia. This study investigated microbial souring in porous medium under simulated oil reservoir conditions (SRB, carbon sources, nutrients, porous medium and high temperature). The results indicate that souring initially occurred at the front part of the column and moved progressively up the column (Fig. 1). The movement of souring ($H_2S$) also indicates the adsorption, desorption and growth of SRB along the column, as no bacterial cells were detected in the effluent until $H_2S$ had been produced throughout.

Formate was the best carbon and energy source for the SRB in the inoculum, as it was the first organic acid used (Fig. 3). In the column, formate was depleted very quickly and was not detected at the first sampling port (z = 5 cm). After 33 d, *n*-butyrate was the second most favorable carbon source for SRB (Fig. 3), as it was consumed faster than the

other organic acids (propionate, iso-butyrate and acetate) in the column (Fig. 4). Acetate was produced from longer-chain organic acids, as many SRB have only an incomplete TCA cycle and, therefore, cannot oxidize acetate; rather they accumulate acetate as an end product (Stanier *et al.*, 1986).

It should be noted that biotransformation in porous medium is a dynamic process. Microbial processes here include attachment, detachment, and growth of cells in the porous medium (Cunningham *et al.*, 1990). Continuous biomass accumulation and an increase in pressure drop in porous medium columns have been reported for different porous medium reactor systems, nutrient feeds, and microbial compositions (Shaw *et al.*, 1985; Geesey *et al.*, 1987; MacLeod *et al.*, 1988). Steady state results were not reported in their work. Biomass may still have been accumulating in the present reactor column though $H_2S$ production had stabilized (fluctuation within a certain range). Data on nutrient utilization and product formation in the column simply represent the experimental trends of souring in the present reactor system. The reported average volumetric sulfate reduction rate represents an order-of-magnitude estimate, since continuous biomass buildup in the porous medium may create diffusion limitations for the sulfate and the other nutrients.

*Stoichiometry*

There was an imbalance between the sulfate-S reduced (245 $mg \cdot l^{-1}$) and the $H_2S$-S produced (125 $mg \cdot l^{-1}$) in the column after sulfate consumption had stabilized (Fig. 5). Part of the difference (120 $mg \cdot l^{-1}$ or 3.8 m*M*) could be explained by scavenging of $H_2S$ as FeS by $Fe^{2+}$ present in the influent. However, the $Fe^{2+}$ contained in the influent (7.5 μ*M*) was far less than the amount required to significantly scavenge $H_2S$. The porous medium (Berea sand) contained $Fe^{2+}$ which probably also contributed to the scavenging. It also is possible that $H_2S$ accumulated as a gas phase in the column, as in a reservoir (Ligthelm *et al.*, 1991).

This phenomenon also explains the slow progression of the $H_2S$ front in the column at unsteady state (Fig. 1). For example, $H_2S$ was measured at day 9 at z = 10 cm, while 8 d later (at day 17) the $H_2S$ advanced 10 cm (to z = 20 cm) only. With a flow rate of 650 $ml \cdot d^{-1}$ and a void volume of 479 ml, a complete exchange should have occurred within one day. There must have been a significant $H_2S$ sink along the section (0 to 20 cm), which was confirmed by an increase in the intensity of black color (FeS) in the section.

The amounts of sulfate (electron acceptor) which can be reduced with the amount of organic acids (electron donors) used were calculated, assuming 1) complete oxidation of all the organic acids to $CO_2$, and 2) complete oxidation of formate with incomplete oxidation of the longer-chain organic acids to acetate. Acetate itself was assumed not to be utilized in both calculations. The amounts of organic acids consumed in the entire column were 200 (4.3), 158 (1.8), 110 (1.3), and 138 $mg \cdot l^{-1}$ (1.9 m*M*) for formate, *n*-butyrate, iso-butyrate, and propionate, respectively (Fig. 4). With complete oxidation, one mole of formate, *n*-butyrate, iso-butyrate, and propionate can reduce 0.25, 2.5, 2.5, and 1.75 moles of sulfate, respectively (based on an electron balance). With incomplete oxidation of the longer-chain organic acids to acetate, one mole of *n*-butyrate, iso-butyrate, and propionate can reduce 0.5, 1.5, and 0.75 moles of sulfate, respectively (one mole of iso-butyrate can produce one mole of acetate only due to its structure). Based on this information, 389 $mg \cdot l^{-1}$ of sulfate-S should be reduced if all the organic acids have been completely oxidized to $CO_2$, while 171 $mg \cdot l^{-1}$ of sulfate-S should be reduced if the longer-chain organic acids have been incompletely oxidized to acetate. The measured reduction of sulfate-S, 245 $mg \cdot l^{-1}$ (Fig. 5), is between the values calculated from the two

scenarios. This indicates that incomplete oxidation (to acetate) as well as complete oxidation (to $CO_2$) for the longer-chain organic acids has occurred in the system for the SRB. The extent of the incomplete oxidation of the longer-chain acids to acetate will be understated if some acetate also has been utilized. Conversely, the extent of complete oxidation will be understated if methanogens and other fermenters, which uptake organic acids or their metabolites without reducing $SO_4^{2-}$, have grown in the system. In addition, balance calculations for organic acids within the first 10 cm of the column (Fig. 4) indicate that incomplete oxidation of propionate and iso-butyrate is insufficient to account for the dramatic increase of acetate in the section. Part of the *n*- butyrate in the section must have been incompletely oxidized to acetate.

*Comparison with Previous Work*

Produced waters from different oil fields may contain different SRB. *Desulfotomaculum* species are common and widespread in North Sea oil field waters (Rosnes *et al.*. 1991), while *Thermodesulfobacterium* species are common in oil-bearing strata of Apsheron and Western Siberia (Rozanova & Pivoravora, 1988). The results were compared with previous work on the Alaska Kuparuk field inoculum (ARCO Oil Company; Chen *et al.*, 1994b), using the same reactor system and porous medium under the same operating conditions. It should be noted that although the system did not completely simulate reservoir conditions (*e.g.* high pressure; reservoir pressures of 200 to 500 atm are difficult to simulate with lab equipment), the comparison is on the same basis and the differences, if any, should be able to help identify parameters affecting souring in porous medium.

This comparison is summarized in Table 1. The Kuparuk field inoculum utilized *n*-butyrate as the preferred carbon source while the Ninian field inoculum used formate preferentially. Since the operating conditions are the same, this indicates that the two oil field inocula have different SRB compositions (SRB species were not identified in either inoculum). Also, the overall biomass yields, based on organic acids, for these two field inocula are markedly different (Table 1), suggesting that the SRB community structures of the two inocula are not the same. Despite the difference in SRB composition, the two oil field inocula share several common characteristics for souring in the reactor system. Most of the substrates (organic acids and sulfate) were consumed at the front part of the column (first 30 cm) for both inocula. Relatively higher volumetric substrate consumption rates (organic acids and sulfate) and a relatively higher volumetric $H_2S$ production rate also were found at the front part of the column for both inocula. The average volumetric sulfate reduction rate in the present reactor system for the Ninian inoculum after $H_2S$ production had stabilized (203 ± 51 mg sulfate-S·l·$d^{-1}$) was very close to that for the Kuparuk inoculum (201 ± 62 mg sulfate-S·$l^{-1}$·$d^{-1}$). The same experimental trends (rates and location) of souring for both inocula indicate that abiotic parameters, as well as biological factors, may play an important role for souring in the reactor system.

It had been reported that the grain size affected penetration and metabolic activity of several *E. coli* strains in glass-bead porous medium (Sharma & McInerney, 1994). In their modeling study, Jones *et al.* (1993) found that internal mass transfer resistance was the rate-limiting step for the biotransformation by *Pseudomonas aeruginosa* in a diatomaceous earth packed column. Previous results on souring induced by *Desulfovibro desulfuricans* in sea-sand porous medium indicated that microbial diffusion dominated the souring process (Chen *et al.*, 1994a). These studies indicate that physical properties (such as permeability) and transport phenomena may play important roles for biotransformation in porous medium. Results on the different inocula further strengthen the possibility of these abiotic factors as important parameters.

**Table 1** Comparison of souring in a Berea sand column using microbial inocula from different oil fields with the same nutrients and operating conditions

| Parameters | North Sea Ninian field inoculum | Alaska Kuparuk field inoculum[a] |
|---|---|---|
| Best carbon source[b] | Formate | *n*-Butyrate |
| Overall biomass yield on organic acids ($g \cdot g^{-1}$)[c] | 0.0003 ± 0.0001 | 0.0008 ± 0.0002 |
| Section of column with highest utilization of substrates[d] | Front part | Front part |
| Section of column with highest production of $H_2S$[d] | Front part | Front part |
| Volumetric sulfate reduction rate in porous medium mg sulfate-$S \cdot l^{-1} \cdot d^{-1}$)[d] | 203 ± 51 | 201 ± 62[e] |

[a] Chen *et al.* (1994b)
[b] Carbon source consumed fastest and not detected at the first sampling port ($z = 5$ cm) of the column.
[c] Overall biomass yield calculated based on the total amount of the organic acids (acetate excluded) consumed in the column and the amount of biomass generated (which was accounted for by bacterial cells in the effluent) at steady state.
[d] After $H_2S$ production had stabilized.
[e] Calculation based on a superficial flow velocity of 27.4 ± 4.2 $cm \cdot d^{-1}$ and sulfate-S levels at 300 ± 15 and 85 ± 35 $mg \cdot l^{-1}$ at $z = 0$ and 30 cm, respectively.

## CONCLUSIONS

The study extended previous work on Alaska Kuparuk oil field waters to investigate microbial souring with a North Sea Ninian oil field water sample as the inoculum. Results indicated that formate was the preferred carbon and energy source for the Ninian field inoculum, as opposed to the *n*-butyrate used by the Kuparuk field inoculum. The overall biomass yields, based on organic acids, for the two mocula also are different. However, the same experimental trends of souring were observed. Most of the substrates (organic acids and sulfate) were consumed at the front part of the column and concentration gradients for the substrates and the product ($H_2S$) were generated along the column, as have been observed for the Kuparuk field waters. Stoichiometry calculations indicate that a high proportion of the $H_2S$ produced was trapped in the column as FeS and possibly as a gas phase. The longer-chain organic acids (propionate, iso- and *n*-butyrates) underwent incomplete oxidation to acetate as well as complete oxidation to $CO_2$ by the SRB in the reactor system. The same experimental trends of souring in the reactor system with the two different oil field inocula which contained different SRB indicate that biological parameters are not the only factors which direct souring in the system.

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