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by

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ABSTRACT

Flocculation is a well-known phenomenon in marine science and sanitary engineering. Little, however, is known of the existence and nature of flocculated suspended sediment within the freshwater fluvial environment. We examined the suspended sediment characteristics of a Southern Ontario river in order to determine the nature of flocculated suspended sediment and the factors which may influence it. It was found that flocculated suspended sediment was the primary mode of fine-grained mineral sediment transport in the river. Flocs were composed of both organic and inorganic grains and interstitial voids. Bacterial content associated with suspended sediment, suspended solids concentration and particulate organic carbon are believed to be important controlling factors of flocculation. Flocculation is known to affect sediment deposition, and bacteria associated with flocs may play an important role in contaminant pathways.

RÉSUMÉ

La floculation est un phénomène bien connu dans les sciences marines et en génie sanitaire. Nous connaissons toutefois peu de choses sur l'existence et la nature des sédiments floculés en suspension dans les eaux douces fluviales. Nous avons examiné les caractéristiques des sédiments en suspension dans une rivière du sud de l'Ontario dans le but de déterminer la nature des sédiements floculés en suspension et les facteurs qui peuvent influer sur eaux. Nous avons découvert que les sédiments floculésen suspension constituaient la première forme de sédiments minéraux à grain fin transportés dans la rivière. Les flocons étaient composés de grains tant organiques qu'inorganiques et de vides intersticiels. La teneur en bactéries des sédiments en suspension, la concentration de solides en suspension et le carbone organique particulaire seraient des facteurs déterminantsde la floculation. La floculation est réputée influer sur la sédimentation, et les bactéries associées aux flocons pourraient jouer un rôle important dans le cheminement des contaminants.

MANAGEMENT PERSPECTIVE

Fine-grained sediment flocculation is a phenomenon which is not fully understood in the freshwater fluvial environment. This research is the first to quantify flocculation as the primary mode of transport for fine-grained mineral sediment in a river. As flocculation is known to alter the settling characteristics of particles, and potentially their ability to transport contaminants, there are important practical environmental consequences for flocculation in rivers. This report provides managers with a better understanding of the implications of flocculation that may be of use to develop improved sediment and contaminant transport models.

PERSPECTIVES DE GESTION

La floculation des sédiments à grain fin est un phénomène mal connu dans les eaux fluviales douces. Cette recherche est la première à quantifier la floculation comme mode principal de transport des sédiments minéraux à grain fin dans un cours d'eau. Comme la floculation est réputée modifier les caractéristiques de sédimentation des particules, voire leur capacité de transporter les contaminants, les conséquences environnementales pratiques de la floculation dans les cours d'eau sont importantes. Ce rapport permet aux gestionnaires de mieux comprendre les effets de la floculation qui pourraient être exploités dans la mise au point de modèles de transport des sédiments et des contaminants améliorés.

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INTRODUCTION

Sedimentation research typically characterizes suspended sediment as primary particles. This reflects standard sediment sizing techniques which chemically disaggregate sediment into primary mineral particles. Water agencies such as the United States Geologic Survey (1) and the Water Survey of Canada (2) typically use sizing techniques for <63 µm material which focus on settling behaviour of suspended particles that have been collected volumetrically, treated to inhibit organic growth, stored for some period of time, then agitated to "recreate" the sampled suspension. No assumptions are made about the state of dispersion or flocculation of the original sample and the resultant particle size distribution is an operationally defined characteristic.

Little is known of the true nature of particle size in river transport of silt-clay materials. This reflects the lack of instrumentation to measure nondestructively the in-situ particle size distribution. Researchers such as Ongley et al. (3) and Partheniades (4) have inferred that flocculated sediment is the probable state of primary particles in rivers. The distinction between primary mineral particles on the one hand, and flocculated aggregates on the other, have important consequences for sediment transport modelling of pathways, fate and effects of sediment-associated contaminants.

Flocs are composed of a complex matrix of organic and inorganic grains which are formed from the collision and sticking together of unstable primary particles or of smaller flocs (5). Flocculation influences sediment transport by affecting the effective size, density, and deposition and resuspension rates of sediment (6). Because many contaminants have a high affinity for fine-grained sediment, flocculation may also influence pollutant transport, deposition and remobilization in fluvial systems.

Flocculation is believed to be a dynamic process; floc size changes continuously depending on the rate of aggregation and disaggregation (7). This rate is highly dependent on site specific variables such as fluid shear, suspended sediment concentration, mineralogy and grain size distribution, dissolved chemicals, pH, temperature, particulate and dissolved organic matter, and biological organisms (5,6,8,9). Each of these variables may interact to promote coagulation by phenomena such as collision, sorption and electrochemical flocculation. The flocculation process is not, however, fully understood, especially in freshwater river systems. Research into flocculation is largely derived from marine, estuarine, lacustrine and sanitary engineering fields. In our review of the primary literature no research was found specifically devoted to the study of flocculation in rivers.

To improve our understanding of the significance of flocculation in the fluvial environment we examined the characteristics of suspended particulate matter in Oakville Sixteen-Mile Creek, Southern Ontario, Canada. Our objectives were to: 1) examine the structure of flocculated material in the fluvial system; 2) quantify the significance of flocculated material in the transport of fine-grained mineral sediment; and 3) determine possible important controlling factors of fine-grained sediment flocculation in rivers.

Two sample sites were used for data collection on Oakville Sixteen-Mile Creek which drains into Lake Ontario between Toronto and Hamilton. Site 1 is a harbour which receives sewage effluent from the sewage treatment plant in the town of Milton. Other sources of particulate matter come from stormwater runoff from urban, agricultural and forested areas. Additional pollution results from extensive pleasure craft traffic during open water periods. Site 2 is approximately 20 km upstream and receives only surface and subsurface runoff from forested and low density agricultural land. This site is relatively clean in comparison, exhibiting lower concentrations of major ions, particulate organic carbon and suspended solids during base flow periods.

MATERIALS & METHODS

The direct observation, microscopic-digitization technique of Droppo (10) was employed for analysis of floc structure and size.

This methods uses some procedures originally developed for the analysis of plankton; equipment includes settling chambers, an inverted microscope with a 35 mm camera accessory and a translucent digitizer interfaced with a microcomputer. In general, a water sample is collected in a settling chamber where the suspended solids settle out onto an inverted microscope slide. The slide is placed on an inverted microscope and transparencies (slides) are taken of the flocs through the microscope. The transparencies are then projected onto a translucent digitizer where to floc perimeters are traced with a mouse to obtain digital output.

Bacteriological analysis was performed using the acridine orange direct microscopic procedure of Rao et al. (11) with a phase contrast microscope and a 1.0 μm Nuclepore filter. A 1.0 μm filter was used to allow free floating bacteria, generally between 0.3 and 0.7 μm in diameter (12), to pass through the filter and to trap the floc and floc bound bacteria for subsequent counting (13). Although this method is not totally effective in retaining only floc-bound bacteria, it does allow for semi-quantitative estimates of bacterial populations.

Analysis of major ions and particulate organic carbon (POC) was performed using the methods of Environment Canada (14). Suspended solids concentration was determined by filtering a known sample volume onto a tared 0.45 μm Millipore filter. Temperature, pH, conductivity and turbidity were recorded for each sampling period using a thermometer, a digital cole-Parmer pH meter, a digital Cole-Parmer conductivity meter and a HF-Scientific Inc. turbidity meter.

RESULTS AND DISCUSSION

Our observations indicate that flocculation of suspended solids does occur in the freshwater fluvial system (Figure 1). Individual grains exist predominantly within aggregate matrices rather than as primary particles. Microscopic observation reveal the coexistence of organic and inorganic grains within the matrix of the flocs along with interstitial voids.

Digital analysis of a field sample before (flocculated) and after sonication (primary particles), indicates that the primary grain sizes ranging from 1 to 2.6 microns are entirely incorporated into the matrices of the flocs (Figure 2). The flocculated distribution is significantly shifted into the larger size classes while the majority of the primary particles are in small size classes.

A comparison of floc and primary sediment volumes transported in a suspension indicates that flocs represent a significant proportion of the suspended solid phase. Over the sampling period (June 15, 1988 to April 1, 1989) flocs composed of 2 or more particles, comprised only 10 to 27% of the total number of particles, but represent 92 to 97% of the total volume of suspended sediment (as calculated from volumetric estimates based upon individually digitized floc and primary particle areas) (10). This finding is similar to Schubel and Kana (15) for an estuarine environment where flocs of 3 or more particles made up only 11% of the total number of particles but nearly 97% of the total sediment volume.

The median floc size, measured as equivalent spherical diameter, from % by number distributions, is generally close to 9 µm, with floc sizes rarely exceeding 60 µm. Very infrequently flocs are sized up to 150 µm (10). Bale and Morris (16), using a Malvern particle sizer in situ, (which measures the particle distribution by volume) found flocs larger than 188 µm in the Tamar Estuary. Macro flocs, up to a few centimetres in diameter in a marine environment, have been observed by a number of researchers with a variety of methods as discussed by Kranck and Milligan (17). Rao et al. (18) found the predominant size fraction in the Yamaska River in Quebec, Canada to be between 20-40 µm using wet serving techniques. As the above methods use different basic measurement properties of the particles, and as the floc composition may vary between environments, a direct comparison is difficult. However, the apparent smaller size of the freshwater fluvial flocs may in part be due to the low salt content of the water allowing a larger electrochemical double layer around the fine particles. This would restrict the degree of flocculation as the forces of attraction required for aggregation in freshwater would need to be greater than those in salt water to overcome the stronger repulsive forces.

Using graphic means of floc size distributions, we measured changes in floc size between Sites 1 and 2 for the summer base flow and the spring high flow periods. In summer, flocs were consistently larger at Site 1. During the spring melt period, the site which possessed the largest floc size varied substantially. While a number of variables believed to influence flocculation were measured in conjunction with floc size, only the suspended solids and POC concentrations demonstrate a strong relationship with floc size (10).

In 88% of the samples taken in the summer and spring period combined, suspended solids concentrations are highest at the site with the largest floc size. As suspended solids concentration increases, the inter-particle spaces decrease resulting in increased frequency of collision. Whether a collision results in particle aggregation or floc disaggregation is highly dependent on the turbulence or fluid shear of the environment and on the composition of the particles (9).

In 78% of the samples, particulate organic carbon (POC) concentrations are highest at the site with the largest floc size. POC incorporates many forms of organic material (decaying plant matter, algae, diatoms, bacteria, etc.) which may help promote flocculation and stabilize flocs. Kranck (19) illustrated experimentally for salt water conditions, that organic material flocculates faster and more completely than inorganic material. Kranck (20) also observed that the addition of particulate organic matter (POM) to a glacial till/salt water suspension promoted aggregation to a greater degree than either the POM or till alone. Our results suggest that POC may also be important for the flocculation process in the freshwater fluvial environment. Other variables such as temperature, pH, conductivity, major ions, and bacteria associated with suspended sediment did not show any apparent trends with floc size.

While no specific trend is observed between attached bacteria and floc size, it is evident that some relationship does exist between bacteria and flocculation. The attachment of bacteria to particulate matter is partially promoted by the solids acting as a source of nutrients (nitrogen, phosphorous and carbon) (21-23). Bacterial attachment is also related to the ability of some bacteria to secrete an extracellular polymeric fiber (7). This material is a sticky substance which helps to bond particles together upon collision (8). Experiments by Biddanda (8) in saline water with bacteria-POM suspensions and bacteria-killed controls indicate that viable bacteria and their polymeric exudates are required for floc formation. Paerl (24-26), demonstrated experimentally using marine and lacustrine waters that detrital floc build up was due to bacterial uptake of labelled DOC (glucose and acetate) and resultant extracellular exudates. The numbers of attached bacteria for the Oakville Sixteen-Mile Creek ranged from 0.76 to 15.7 x 10^7 and 1.74 to 11.24 x 10^7 /mg suspended solids for Site 1 and Site 2 respectively over the sampling period (10). These counts are similar to those of Cammen and Walker (21) for detrital suspended particulate matter in the Bay of Fundy. Figure 3 illustrates the large number of bacteria associated with the suspended solids. Palmateer et al. (27), while not concerned with flocculation, demonstrated the same relationship with the suspended sediments of the Ausable River in Western Ontario. With the reduced influence of electrochemical flocculation in freshwater, bacteria may be the dominant factor in promoting flocculation.

CONCLUSION

This research is the first to quantify that flocculation is the primary mode of transport of fine-grained mineral sediment in a river. Although there are substantially more primary than flocculated particles in suspension, the flocculated particles represent greater than 90% of the total suspended solid volume in Oakville Sixteen-Mile Creek. These river flocs are relatively small compared with flocs reported from other aquatic environments. The large number of attached bacteria is consistent with marine and lacustrine observations. We demonstrated that floc size may vary both temporally and spatially in relation to suspended solid and particulate organic carbon concentrations. Further research is required, however, on the effect of these and other variables on floc size.

The significance of flocculated sediment for sediment transport models has been addressed by Krishnappan (28) and Krishnappan and Ongley (29). They have demonstrated that the settling characteristics of flocs can be significantly different from primary particles. Experimental investigations by Rao (18) suggests that flocs may account for the largest component of a soluble industrial (contaminant) dye. Association of bacteria with flocs may have important implications both for the presence of sediment-associated organic contaminants, and for biochemical alteration of parent contaminants. Although these environmental implications of flocculated sediment transport are still largely unknown, evidence thus far suggests that flocculation in rivers may have important practical consequences for sediment and contaminant transport modeling.

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REFERENCES

1. Guy, H.P. in Techniques of Water-Resources Investigations of the United States Geological Survey. United States Department of the Interior, Washington, 1969 .
2. Environment Canada, in Laboratory Procedures for Sediment Analyses. (Water Resources Branch, Ottawa, Canada, 1987 .
3. Ongley, E.D.; Bynoe, M.C.; Percival, J.B. Can. J. Earth Sci. 1981, 18, 1365-1379.
4. Partheniades E. in 17 International Colloquium on Ocean Hydrodynamics, Liege, Belgium May 17-19 1985; p. 515-550.
5. Kranck, K., Nature. 1973, 246, 348-350.
6. Tsai, C.H.; Iacobellis, S.; Lick, W., J. of Great Lakes Res. 1987, 13, 135-146.
7. Zabawa, C.F., Science. 1978, 202, 49-51.
8. Biddanda, B.A., Mar. Ecol. Prog. Ser. 1985, 20, 241-251.
9. Krone, R.B. in Estuarine Transport Processes, B. Kjerfve, Ed.; University of South Carolina Press, Columbia, South Carolina, 1978 , p. 177-190.
10. Droppo, I.G., Unpublished Thesis, McMaster University 1989 .
11. Rao, S.S.; Jurkovic, A.A.; Dutka, B.J., JTEVA. 1984, 12, 56-59.
12. Hobbie, J.E.; Daley, R.J.; Jasper, S., Appl. Environ. Microbiol. 1977, 33, 1225-1228.
13. Droppo, I.G.; Ongley, E.D. in Sediment and the Environment, R.J. Hadley and E.D. Ongley, Eds. International Association of Hydrologic Sciences, Third Scientific Assembly, Baltimore, Maryland, May 10-19, IAHS pub. No. 184, 1989, pp. 95-103.

14. Environment Canada. Analytical Methods Manual. Inland Waters Directorate, Water Quality Branch, Canada Centre for Inland Waters, Burlington, Ontario Canada, 1979.

15. Schubel, J.R.; Kana, T.W., Powder Tech. 1972, 6, 9-16.

16. Bale, A.J.; Morris, A.W., Estuarine, Coastal and Shelf Science. 1987, 24, 253-263.

17. Kranck, K.; Milligan, T., Mar. Ecol. Prog. Ser. 1980, 3, 19-24.

18. Rao, S.S.; Weng, J.H.; Krishnappan, B.G., NWRI Contribution # 88-104, CCIW, Burlington, Ontario, Canada, 1988.

19. Kranck, K., Naturaliste Can. 1979, 106, 163-173.

20. Kranck, K. in The Estuary as a Filter Academic Press, Inc., New York, 1984; p. 159-175.

21. Cammen, L.M.; Walker, J.A., Can. J. Fish. Aquat. Sci. 1982, 39, 1655-1663.

22. K.C. Marshall, Interfaces in Microbial Ecology Harvard Press, Cambridge, 1976.

23. Jannasch, H.W.; Pritchard; P.H. in Proceedings of the IBP-UNESCO Symposium on Detritus and Its Role in Aquatic Ecosystems. Pallanza, Italy, May 23-27. Mem. 1st. Ital. Idrobiol. 1972, 29, 289-308.

24. Paerl, H.W., Microb. Ecol. 1975, 2, 73-83.

25. Paerl, H.W., Limnol. Oceanogr. 1974, 19, 966-972.

26. Paerl, H.W., Science. 1973, 180, 496-972.

27. Palmateer, G.A., et al. Tox. Assess. 1989, 4.

28. Krishnappan, B.G., NWRI Contribution no. 89-143, CCIW,Burlington, Ontario, Canada, 1988 .

29. Krishnappan, B.G.; Ongley, E.D., NWRI Contribution no. 89-108,CCIW, Burlington, Ontario, Canada, 1989.

FIGURE LEGENDS

Figure 1 Naturally flocculated suspension (November, 17, 1987, Site 1) (10).

Figure 2 Comparison of flocculated and dispersed suspended sediment (March 15, 1989, Site 1) (10).

Figure 3 Bacteria colonized on a floc (bright dots and rods are the bacteria) (10).

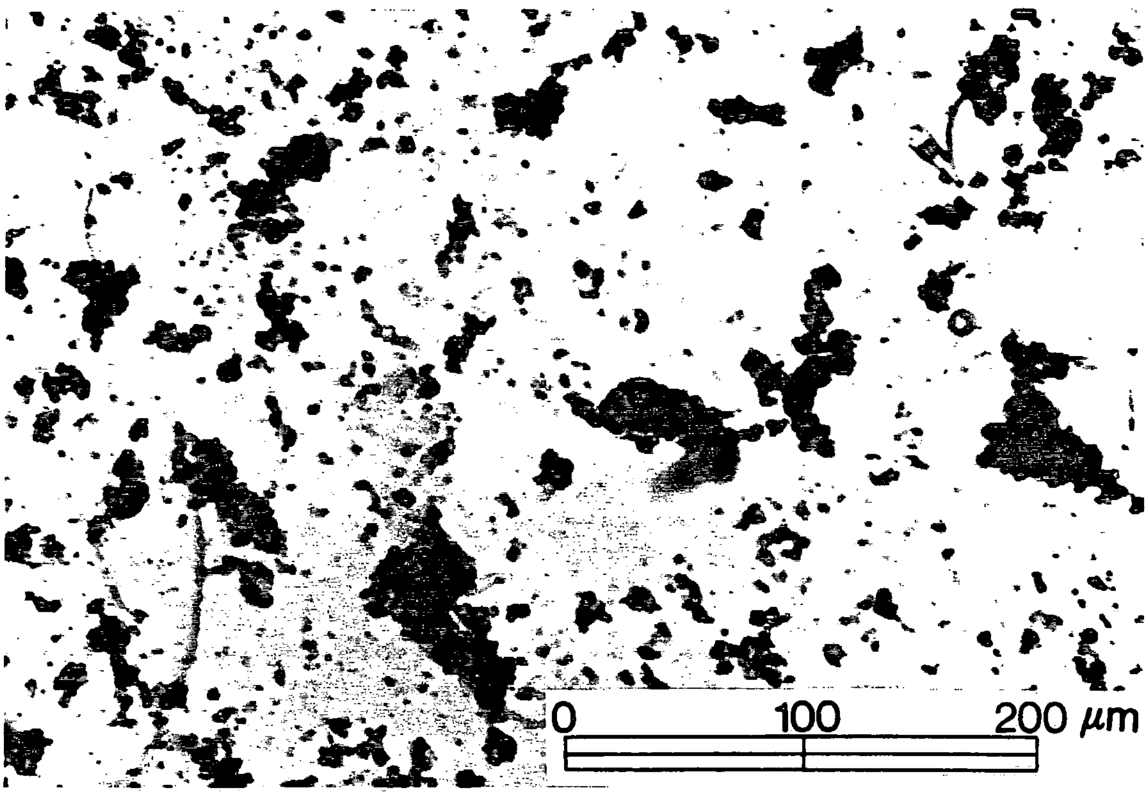

Figure 1. Naturally flocculated suspension (November 17, 1987, Site 1) (10).

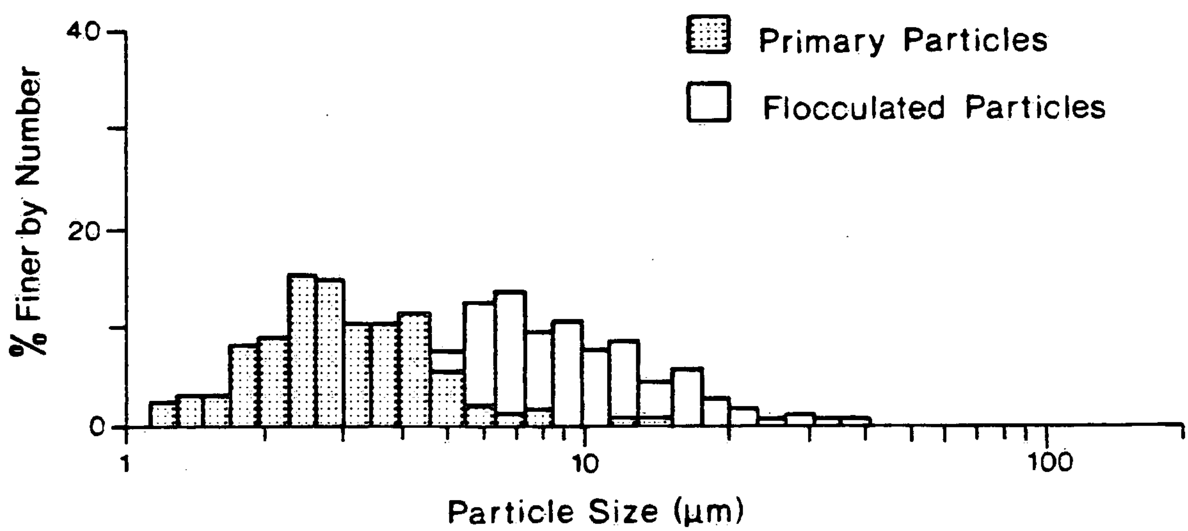

Figure 2 Comparison of flocculated and dispersed suspended sediment (March 15, 1989, Site 1) (10).

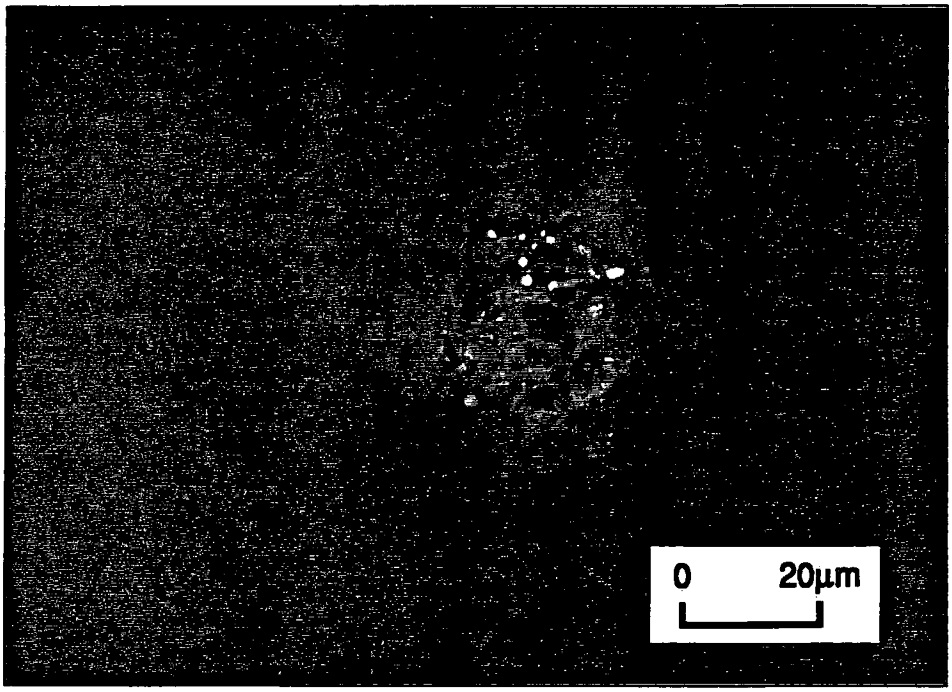

Figure 3. Bacteria colonized on a floc (bright dots and rods are the bacteria) (10).

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