1349

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

INVESTIGATION OF HEAVE IN BILLINGS SHALE BY MINERALOGICAL AND BIOGEOCHEMICAL METHODS

BY

E. PENNER, J. E. GILLOTT AND W. J. EDEN

Reprinted from
CANADIAN GEOTECHNICAL JOURNAL
VOL. VII, NO. 3, AUGUST 1970
p. 333

RESEARCH PAPER NO. 440
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA
August 1970

Price 10 cents

NRCC 11437

Investigation of heave in Billings shale by mineralogical and biogeochemical methods

E. Penner, J. E. Gillott, and W. J. Eden
Division of Building Research, National Research Council of Canada, Ottawa 7, Canada

Received February 9, 1970

A building founded on Billings Shale has suffered nearly 4 in. (10 cm) of heave to its basement floor slab. The heaved zone was thought to be associated with a fault zone in the shale, near which the rock was fractured and contained extensive pyrite intrusions. Investigations have shown the heave to be due to the weathering of the pyrite in the presence of autotrophic bacteria. Factors creating a favorable environment for this complex weathering process are discussed.

La dalle de béton au sous-sol d'un bâtiment fondé sur un schiste de la formation Billings a subi près de 4 po. (10 cm) de soulèvement. On a cru que la zone de soulèvement provenait d'une zone failleuse dans le schiste près de laquelle la roche était fracturée et contenait des intrusions importantes de pyrite. L'étude a montré que le soulèvement est attribuable à l'altération de la pyrite en présence de bactéries autotrophes. L'article discute des facteurs qui procurent une ambiance favorable à ce procédé complexe d'altération.

An unusual problem of shale expansion and heave involving the basement floor slab of the three-storey extension to the Bell Canada building on O'Connor Street in Ottawa, Ontario, has been investigated recently. A similar problem of shale heaving is described in a paper by Quigley and Vogan (1970) and Spanovich and Fewell (1969).

The original building was constructed in 1929; the extension was added in 1961 with all corresponding floors located at the same elevation. After the extension was completed, the basement floor started heaving in two locations extending over a floor area of some

NRCC 11437

Canadian Geotechnical Journal, 7, 333 (1970)

1063645

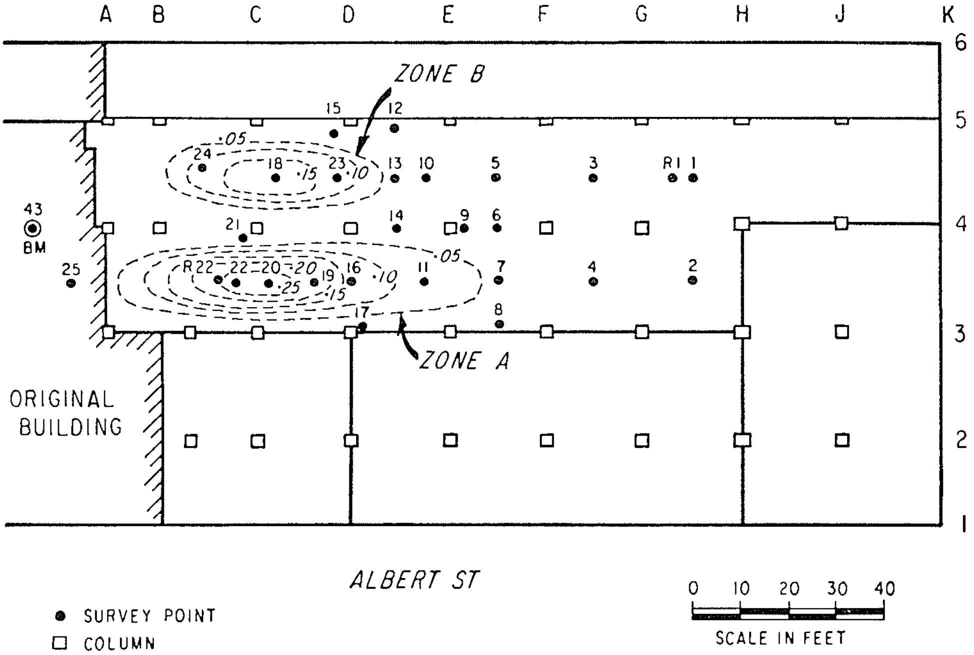

FIG. 1. Plan of extension to Bell Canada building showing contours of heave in feet of basement floor slab.

2400 square feet (223 square m) although there had been no heaving problems in the basement of the original structure. The heaved areas appear as two rounded domes as shown by the heave contours in Fig. 1.

The basement floor space is being used at present for generators, batteries, and switching units. Heaving of the floor has necessitated continual realignment of this equipment. In addition, a non-loadbearing partition wall had to be freed from the ceiling to avoid damage to the first floor. The object of the present investigation was to establish the cause of heave and to suggest remedial measures.

Position of Interior Column Footings and Floor Slab with Reference to the Shale

The interior column footings were 8 by 8 by 4 ft (2.44 × 2.44 × 1.22 m) thick and these footings and the reinforced basement floor slab were placed at about 9 ft (2.75 m) and 5 ft (1.53 m) respectively below the original shale level. The reinforced concrete slab is about 12 in. (30.5 cm) thick including the finishing course. It was placed on a 6-in. (15.3-cm) layer of crushed limestone which also contains a system of drainage tiles. The thickness of the overburden above the shale before construction was approximately 9 ft (2.75 m). This material consisted of undefined rubble from previous construction with a layer of sand lying directly on the shale surface.

Heave Rates

Since April 1967, when precise level surveys were initiated, the position of maximum displacement in zone A has heaved 2.04 in. which is 0.07 in./month (5.18 cm, 0.18 cm/month). The total heave since construction is 3.72 in. (9.45 cm). For zone B, the total heave is 2.16 in. (5.5 cm) and the heave rate during the survey period has been 0.02 in./month (0.05 cm/month). The heave rates in both zones have been approximately linear since measurements were begun. Figure 2 shows the heave in zone A as a function of time. The numbers on the graph identify the survey locations that appear also on the plan of the extension in Fig. 1.

Geology

The building is founded on the northern

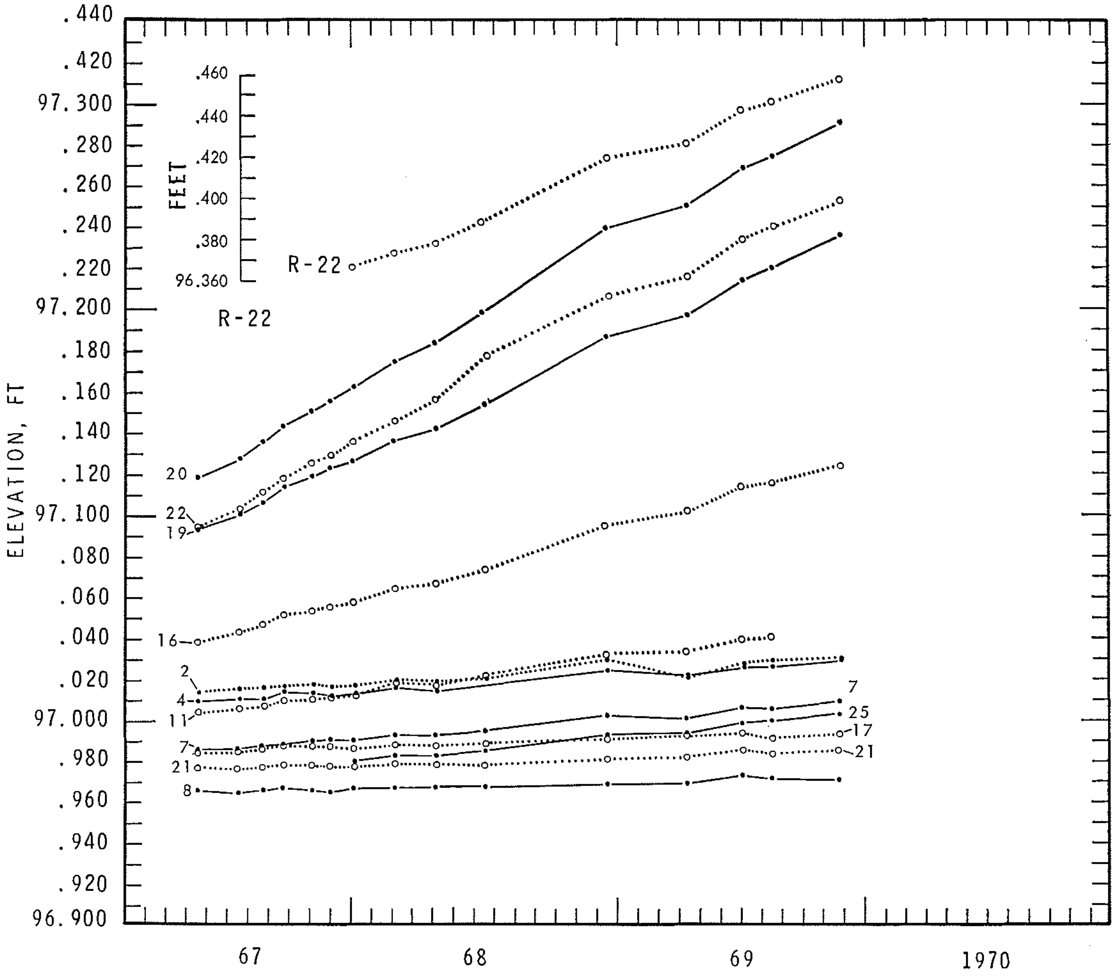

FIG. 2. Bell building floor movements zone A.

reaches of the Billings formation, a black pyritiferous and fissile shale. The Billings formation is about 20 ft (6.1 m) thick at this location and lies conformably on interbedded limestone and shales of the Eastview formation. These deposits belong to the Ordovician system and were formed some 450 m.y. ago. Palaeozoic rocks of this area are cut by two major sets of faults (Wilson 1946). The Bell Canada building is situated about 1½ miles (2.41 km) northeast of the Gloucester fault, a major dislocation which trends NW–SE. The rocks are thought to be cut by numerous minor faults which may be of considerable significance in the present problem. A minor fault was observed in an excavation immediately south of the Bell building which appeared to have a strike in the direction of the heaved areas.

Investigation

Good cores were obtained in non-heaved areas but attempts to obtain shale cores from the upper portion of the heaved zones below the floor were not successful. A pit was hand dug subsequently in the center of the dome (zone A) for observation and sampling.

In the top 2½ to 3 ft (0.76 to 0.91 m), the shale, although horizontally layered, was soft and crumbly (moist but not wet) blending gradually into very competent hard material. The individual shale laminae ranged in thickness from a few millimeters at the surface to

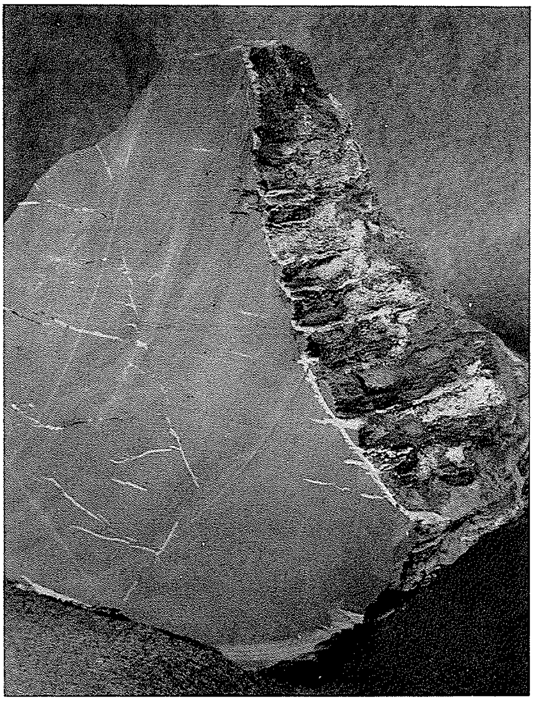

FIG. 3. Unaltered shale. Depth 4.5 ft zone A. White streaks in photograph are pyrite. Sample oriented as found in deposit.

several centimeters at the transition zone. Here the shale could be removed with a hand shovel; below the transition zone, jack hammers had to be used for excavation. Joint surfaces and shale laminae in the altered zone were heavily coated with yellowish-brown powder and colorless crystals later identified by X-ray diffraction powder patterns as jarosite and gypsum respectively. The so-called gypsum crystals were also associated with a considerable amount of hemihydrate or bassanite ($CaSO_4 \cdot \frac{1}{2}H_2O$). There were also other oxidation products but in much smaller quantities, and a small amount of visible pyrite, although heavily weathered, still remained.

It was shown from chemical analysis that the unaltered shale everywhere below the building contained pyritic sulfur ranging from 1.3 to 1.6%. Below the altered zone, visible pyrite was abundant in joints and shale partings (Fig. 3) beneath strongly heaved areas. Very little visible pyrite was contained in the shale outside the heaved areas. The pyrite shown in Fig. 3 is thought to be of hydrothermal origin and to have entered the rock through cracks, partings and probably via faults.

Two types of ground-up shale samples from the altered zone were analyzed using X-rays. One was taken from the soft mushy material between the laminae and the second from the laminae. These samples were shown to be similar, containing mostly quartz and clay minerals represented by illite, chlorite and mixed layer minerals. Solvation with glycerol resulted in some enhancement of a broad reflection at about 18 Å, indicating the presence of a swelling component. The samples also contained some pyrite, jarosite, gypsum, and bassanite.

The extensive pyrite intrusions below the altered zone (below $2\frac{1}{2}$ to 3 ft (0.75 to 0.91 m)), the alteration products of pyrite, and the low pH environment in the altered strata, suggested that autotrophic bacteria might be involved in the weathering process. Autotrophic bacterial oxidation is a common phenomenon in many coal mines and is sometimes used in extracting metal economically from low grade pyritiferous ores (Harrison *et al.* 1966; Kuznetsov *et al.* 1963). These bacteria grow and multiply by using the energy from the oxidation of inorganic compounds. Proteinaceous body material is produced from atmospheric CO_2 and other nutrients, such as nitrogen, contained in the shale.

The existence of microorganisms in the altered shale belonging to the Ferrobacillus–Thiobacillus group was established by the Soil Research Institute, Canada Department of Agriculture. Subsequently, a scanning electron micrograph of the bacteria was obtained (Fig. 4). Scrapings from the altered shale were used to inoculate inorganic growth media. It was shown that the organisms found were capable of oxidizing ferrous iron to ferric iron. These bacteria require an acid environment, the optimum being around pH 2.2. pH measurements in the altered shale showed the environment was acid, ranging from pH 2.8 to 4.4. These bacteria are known to go into dormancy above pH 4.5. In the unaltered shale from the pit and from cores taken elsewhere in a non-heaving area, the pH was in excess of 7.

The oxidation reactions occurring in the shale alteration process are thought to be as follows (Harrison *et al.* 1966; Kuznetsov *et al.* 1963):

$$[1]\quad \underset{\text{pyrite}}{2FeS_2} + 2H_2O + 7O_2 \rightarrow \underset{\text{ferrous sulfate}}{2FeSO_4} + 2H_2SO_4$$

$$[2]\quad \underset{\text{ferrous sulfate}}{4FeSO_4} + O_2 + 2H_2SO_4 \rightarrow \underset{\text{ferric sulfate}}{2Fe_2(SO_4)_3} + 2H_2O$$

$$[3]\quad \underset{\text{ferric sulfate}}{7Fe_2(SO_4)_3} + \underset{\text{pyrite}}{FeS_2} + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$$

Reaction [1] is believed to be entirely chemical although some workers believe the oxidation of sulfide is assisted by autotrophic bacteria. Reaction [2] is thought to be entirely due to the Ferrobacillus–Thiobacillus microorganisms since this reaction cannot proceed chemically in an acid environment. Reaction [3] oxidizes more pyrite by reacting with ferric sulfate, a strong oxidizing agent produced in [2]. One of the products of [3] is ferrous sulfate which the autotrophes oxidize again according to reaction [2]. More sulfuric acid is produced by the process than is utilized.

The gypsum and hemihydrate (bassanite) is thought to form from the reaction of sulfuric acid with calcite (a constituent of Billings shale). Jarosite [$KFe_3(SO_4)_2(OH)_6$], a main reaction product found, is essentially insoluble in water and forms most readily in an acid environment. The potassium content of jarosite is thought to come from the degradation of the clay minerals and/or by base exchange in the highly acid environment.

Heaving occurs because the molar volumes of the reaction products is greater than the unaltered components. The increase from pyrite to jarosite is 115%, from calcite to gypsum is 103%, and calcite to bassanite is 189%. All facets of the weathering reactions are not understood, nor is the exact disposition of the minerals before and after oxidation, hence

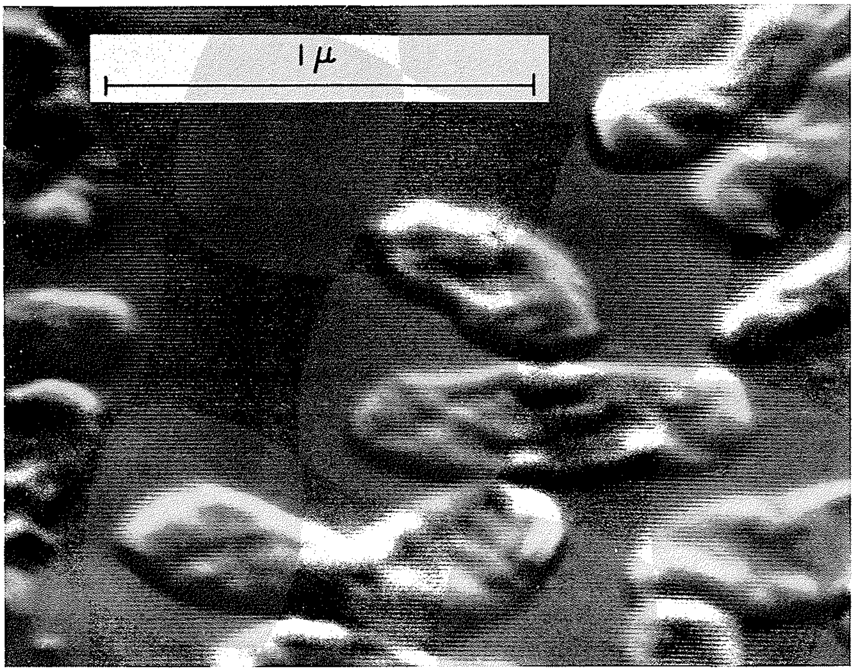

FIG. 4. Scanning electron micrograph of the Ferrobacillus–Thiobacillus bacteria isolated from the altered shale.

these volume increases cannot rigorously confirm that the suggested reactions are responsible for the heaving of the shale. The depositional components, reaction products, and environmental conditions are strong evidence, however, that weathering associated with autotrophic bacterial oxidation is responsible for the expansion of the shale.

Concluding Remarks

The shale expansion and floor heave seem to be the result of a complex combination of factors.

(1) The water table, at present located 13 ft (3.96 m) below the floor level, appears to have dropped since the building was constructed. Air entry, supplying the necessary oxygen and carbon dioxide, has been facilitated by the underfloor drainage system and crushed rock layer.

(2) The basement area is generally quite warm (about 30 °C) which enhances the bacterial growth rate. The optimum growth temperature for these autotrophic bacteria is thought to be around 35 °C.

(3) The shale was rich in pyrite (in joints and shale partings) in the heaved area beneath the altered layer, supplying the necessary materials to support the process of alteration. Very little visible pyrite was found elsewhere in the unaltered shale. Faulted zones also facilitate entry of air and this may have assisted the establishing of proper conditions for bacterial growth.

It is believed that if biogenic oxidation could be halted it would break the chain of oxidation reactions and heaving would probably not continue. This might be done by chemical disinfection, killing the bacteria, or by creating an unfavorable environment for bacterial growth. The latter might be achieved by keeping the shale flooded thereby cutting out the needed supply of air and/or permanently raising the pH of the shale environment above the tolerant level.

Assuming the oxidation process is moving downward, there is the possibility that it will reach the depth of the interior footings between the two heaving zones. Should crystallization pressures of jarosite, gypsum and other reaction products, exceed the footing loads, heave of the interior columns would result.

There are at least three undesirable side effects that must be considered when contemplating any aqueous treatment to halt bacterial growth. The shale is at present relatively dry thus:

(1) moisture uptake by the swelling component of clay may induce some expansion;
(2) hydration of the bassanite ($CaSO_4 \cdot \frac{1}{2}H_2O$) to gypsum ($CaSO_4 \cdot 2H_2O$) involves a volume increase;
(3) undesirable reactions between the solution used and the shale and its components.

Allowing bacterial oxidation to continue is thought to be unwise, however, because of the potential heave of the column footings in that vicinity. In any case, the present heave rate of the two zones is excessive and is creating unacceptable misalignments to the equipment now located in that area of the basement floor.

Acknowledgments

The authors express their appreciation to Dr. K. C. Ivarson of the Soil Research Institute, Canada Department of Agriculture, for the microbiological studies and advice, to Dr. D. S. Russell, Division of Chemistry, National Research Council of Canada, to Mr. V. F. Harrison, Mines Branch, Department of Energy, Mines and Resources, for sulfide and sulfate analyses, and to Dr. R. M. Quigley for his assistance in the early stages of the investigation. This note is a contribution of the Division of Building Research, National Research Council of Canada and is published with the approval of the Director of the Division.

HARRISON, V. F., GOW, W. A., and IVARSON, K. C. 1966. Leaching of uranium from Elliot Lake ore in the presence of bacteria. Can. Mining J., **87**, No. 5, pp. 64–67.

KUZNETSOV, S. I., IVANOV, M. V., and LYALIKOVA, N. N. Introduction to geological microbiology. (*Translator*, P. T. Broneer) (*Editor, English edition*, C. H. Oppenheimer). McGraw-Hill Book Co. Inc., New York. 1963. 252 pp.

QUIGLEY, R. M. and VOGAN, R. W. 1970. Black shale heaving at Ottawa, Canada. Can. Geotech. J. **7**, pp. 106–112.

SPANOVICH, M. and FEWELL, R. B. 1969. The subject is pyrite. Charette Pennsylvania Journal of Architecture, **49**, No. 1. pp. 15–16.

WILSON, A. E. 1946. Geology of the Ottawa – St. Lawrence Lowland. Ontario and Quebec Geological Survey Memoir 241, No. 2474. Canada Department of Mines and Resources. 65 pp.