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CONTENTS

Contents

Figures

Tables

Abstract

This report describes in detail many aspects of bentonite in Canada and includes sections on definitions, properties, identification, uses, specifications, history and production, trade, consumption, occurrence, reserves, exploration, mining, milling, laboratory investigation, technology, marketing and outlook.

World outlook is for a noteworthy increase in bentonite consumption in the immediate future. In the long term, some of this increase will possibly be affected by substitutes and more efficient usage.

Most of Canada's bentonite requirements in the foreseeable future will be for the swelling type. The main market for bentonite lies in Canada's industrial east, but no suitable deposits are found east of Manitoba. If a good-quality swelling bentonite could be located in Manitoba its proximity to main markets would assure its ready sale.

Although Canadian bentonite is competitive in quality for many uses, it has yet to be generally accepted for steel-foundry application and iron-ore-concentrate pelletizing. Canada's requirements for the latter were about 10,000 tons in 1962. By the end of 1965, they should increase to 100,000 tons a year with a consumption value of about $3 million. In the same period, consumption for all uses should reach a value of about $5½ million a year. Thus, a challenge and an opportunity exist for the establishment of a Canadian source of high-quality bentonite. Exploration for this commodity is relatively simple and inexpensive and several of the geological horizons described are of interest. The main problem will be in the testing and tailoring of the clay to meet consumers' specifications. The mining industry is urged to accept this challenge and, to be successful, the cooperation of the iron and steel industries is essential.

Incomplete preliminary testing indicates that a few Canadian bentonites show promise for iron-ore pelletizing. The Mines Branch is attempting to tailor these to meet the requirements of the pelletizing industry.

Résumé

Dans le présent rapport, l'auteur décrit minutieusement la bentonite au Canada, considérée sous bien des aspects. Il y traite notamment de définitions, de propriétés, d'identification, d'usages, de prescriptions techniques, de venues, de réserves, d'exploration, de l'extraction et du traitement du minerai, de recherches en laboratoire, de techniques, de mise en marché et perspectives.

On prévoit que, dans un avenir immédiat, la consommation de bentonite augmentera sensiblement dans le monde entier. Dans un avenir lointain, il se peut que cette augmentation soit ralentie du fait de succédanés et d'un emploi plus efficace.

Dans l'avenir prévisible, le Canada continuera de réclamer surtout de la bentonite gonflante. Au Manitoba, il y a un dépôt de bentonite gon-

flante de bonne qualité, qui deviendrait fort intéressant si l'on pouvait écouler en grande partie cette argile dans l'Est.

Le bentonite canadienne peut soutenir la concurrence du fait de sa qualité, qui la rend propre à bien des usages. Mais elle n'est pas encore couramment acceptée en sidérurgie ni dans le boulettage du concentré de minerai de fer. En 1962, le Canada en a absorbé environ 10,000 t à cette dernière fin. A la fin de 1965, ce besoin devrait atteindre 100,000 t par an, et la valeur de la bentonite utilisée devrait être d'environ $3,000,000. La valeur de celle qu'on consomme à tous les usages devrait être de près de $5,500,000 par an. La création d'une industrie canadienne de bentonite de qualité présente donc à la fois un défi et une occasion favorable. Les travaux de prospection nécessaires sont relativement simples et peu coûteux. Plusieurs des horizons géologiques décrits par l'auteur sont intéressants. La principale difficulté consistera à faire des essais sur ce genre d'argile et à la traiter de façon à satisfaire les consommateurs. L'industrie minière est instamment priée d'accepter ce défi. De plus, pour que l'industrie de la bentonite arrive à s'établir, la collaboration de l'industrie sidérurgique est une chose essentielle.

D'après les résultats des essais préliminaires et incomplets qu'on a faits, quelques types de bentonites semblent se prêter au boulettage du minerai de fer. La Direction des mines est en train de les préparer de façon à répondre aux exigences de l'industrie du boulettage.

INTRODUCTION

Commonly a little-appreciated industrial mineral commodity, bentonite has many unusual and complex properties. It plays a vital role in certain industries and is consumed in many others. In the last two decades, its consumption and uses have increased notably, although its greatest use is confined to four industries. The properties of bentonite vary with locality, and each bentonite has limited applications, although as a group its application is wide. Many types, particularly those lying between the better-quality swelling, and the highly adsorptive varieties, lack qualities that are commercially useful. However they may find limited use if they can be easily beneficiated and deposits lie reasonably close to markets.

The industry in Canada has developed a highly competitive activated bentonite for bleaching, and since 1959, has produced good-quality bentonite for well drilling and iron-foundry applications. The industry is commended for its efforts in developing products that have been so readily acceptable to many consumers. However, there remains the task of finding and developing a bentonite that is considered acceptable for use in the pelletizing of iron-ore concentrates and in steel foundries.

At the time of writing Canadian consumption of bentonite has an estimated value of $2.9 million a year, and indications point to this figure being doubled by the end of 1965. Such an abrupt upward trend in Canada's bentonite requirements provides a challenge to Canadian industry to meet the bulk of its requirements with domestic products. A vast field lies ahead for bentonite in the pelletizing of iron-ore concentrates. All bentonite for this purpose is now imported. Here then is a challenge to the Canadian mining industry to join in the relatively inexpensive exploration and evaluation of domestic deposits and stem the inflow of imported bentonite.

A domestic industry capable of competitively supplying a bentonite of pelletizing grade would assist in ensuring the consumption of bentonite for this purpose in Canada. The main consumers could cooperate by testing promising samples in the anticipation that a sufficient supply of pelletizing quality can be developed.

This report is presented as a general reference for bentonite in Canada because

1

of increased interest and bentonite's imminent importance to Canadian industry. Its prime purpose is to indicate the availability, general quality, methods of evaluation, uses and markets for the commodity. The Mines Branch has instituted programs to investigate in detail the properties and certain applications of bentonites from various Canadian occurrences. The results of this work will be published in another report.

DEFINITION

The term 'bentonite' was first used in print by W. C. Knight (1) in 1898. Disliking the terms 'soap clay' and 'mineral soap', used to describe clay with unusual properties occurring in the Cretaceous Fort Benton formation in Wyoming, Knight named it 'taylorite' in 1897 after Mr. W. Taylor, who was the first to mine the commodity in 1888 near Rock Candy Station, Wyoming. In 1898, the name was changed to 'bentonite' by Knight after he realized that 'taylorite' had been reserved previously for another mineral.

Prior to 1888, this variety of clay had been recognized and described in such countries as France and Sweden. The predominant mineral, essentially a hydrous aluminum silicate, was first called 'smectis' (later smectite) in 1788, but in 1847 it was also given the name 'montmorillonite' after the type occurrence at Montmorillon, France. The latter term has been most commonly used since. Later, C. S. Ross (2) and colleagues established the clay-mineral concept and named one of the clay-mineral groups 'montmorillonite'. The group also includes a mineral by that name.

Numerous definitions have been applied to the term 'bentonite'. Some of these are given below, by author and in chronological order.

Knight (1898) (1)—A variety of clay found extensively in Wyoming in the Fort Benton "group" of the Cretaceous. This clay was described as yellowish green, soft, greasy, unusually absorbent and capable of forming an emulsion with water.

Ross and Shannon (1926) (2)—"Bentonite is a rock composed essentially of a crystalline claylike mineral formed by the devitrification and the accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic glass. . . . The characteristic clay mineral . . . is usually the mineral montmorillonite but less often beidellite." They add that bentonites contain "75 per cent or more of the crystalline, claylike minerals montmorillonite or beidellite".

Davis and Vacher (1940) (3)—"Present trends are to designate the clays, that on wetting swell no more than ordinary clays, subbentonites or, preferably, metabentonites, a term indicating alteration or metamorphosis and accounting for the different physical, though similar chemical, properties and common origin".

Dana (1945) (4)—"The clay known as 'bentonite' . . . has been derived from the alteration of volcanic ash or tuff, is usually largely composed of montmorillonite".

Grim (1953) (5)—He accepts the first part of Ross' and Shannon's definition.

2

However, he does not comment on the minimum required percentage of montmorillonite or beidellite in his following statement ". . . the dominant clay-mineral component of bentonites is montmorillonite".

Grim (1962) (6)—"It may be desirable to restrict the term 'bentonite' to such alteration products which are composed of montmorillonite".

Thus there are numerous definitions based on mode of origin, swelling property, mineralogy, or on combinations of these factors. Most are not precise. Because most authorities do not agree on one common definition the term has created much confusion both in industry and in the literature. It is therefore with reservation that an additional definition is suggested. However, it is anticipated that this definition will be more suitable to industry and, in a collective manner, to mineralogists. Because similar minerals and mineral assemblages can have different origins, genetic specifications should be abolished. Also, like any other rock type, bentonite should be classified by its constituent minerals and not by the variable properties or uses resulting from an assemblage of these minerals. Bentonite, then, is regarded herein as a type of clay composed essentially (more than 50 per cent) of minerals of the montmorillonite group.

Although this definition is based on mineralogy, several subdivisions have been proposed, most of which have definite limits based on physical properties.

Until about 1924, bentonite was regarded as a clay with exceptional swelling characteristics that occurred principally in Wyoming. This variety was thus known as 'swelling', 'Wyoming', or 'western' bentonite. Subsequent to the work of Ross and associates (2) it was realized that there were other types, or 'subbentonites' that had swelling properties ranging down to those of most other clays. Such bentonites are found in parts of southern United States. Thus, the synonymous terms 'non-swelling' and 'southern' bentonites were derived. Numerous varieties are intermediate between these two roughly defined groups.

Active clays are those that have commercial decolorizing and purifying capacities, and inactive clays are those without these qualities. Some clays can be made active by treatment and are then termed 'activated'.

Nutting (7) proposed the following subclasses based solely on activity but gave no precise limits:

> "I Inactive and nearly inactivable montmorillonite clay.
> II Inactive but highly activable clays.
> III Active and highly activable clays.
> IV Active clays little affected in activity by acid treatment.
> V Active clays whose activity is lowered by acid leaching."

Davis and Vacher (3) proposed the following grouping based on swelling, colloidal, adsorptive and mainly osmotic properties:

Alkali bentonite—A bentonite containing easily replaceable alkali bases and having original properties that are not permanently destroyed by the action of sulphuric acid but can be restored by treatment with an alkali salt by regulated dialysis.

3

Alkali subbentonite—A bentonite containing easily replaceable alkali bases but having original properties that are destroyed by acid treatment.

Alkali-earth bentonite—A bentonite containing easily replaceable alkali-earth bases and, either before or after acid treatment, capable of being made to assume the properties of an alkali bentonite by treatment with an alkali salt followed by regular dialysis.

Alkali-earth-subbentonite—A bentonite containing easily replaceable alkali-earth bases which after treatment with acid is not capable of being made to assume the properties of an alkali bentonite.

For most purposes, the Davis and Vacher classification is more appropriate than Nutting's. However, for detailed industrial evaluation, these classifications are of no assistance because they do not take into consideration the combined effect of the many properties that are required for some of the important industrial applications. A suitable detailed classification for industry would be by usage. However, such a classification would be too voluminous.

Fuller's earth is a term related to bentonite, but it is derived from a particular application for clay. In ancient days fullers used natural clay in an aqueous slurry to remove dirt and oil from wool. Because it is a term based on usage there are numerous conflicting definitions. The following are examples:

Nutting (7)—"Active and highly activable clays . . . active clays little affected in activity by acid treatment . . . and active clays whose activity is lowered by acid leaching . . . are called fuller's earth".

Ladoo and Myers (8)—"Fuller's earth is an inexact term applied to certain natural clays that have a marked ability to adsorb coloring from oils of animal, vegetable, and mineral origin".

Grim (6)—" . . . the term is applied to any clay which has an adequate discolorizing and purifying capacity to be used commercially in oil refining without chemical treatment".

Rich (9)—"Fuller's earth, or naturally active clay, is prepared from bentonites".

Parsons (10)—"Fuller's earth is a variety of clay that has high capacity for adsorbing basic colors and can remove these colors from solution in animal, vegetable, or mineral oils, as well as from some other liquids, especially water."

de Polo (11)—"Fuller's earths are essentially montmorillonites resembling the sub-bentonites very closely".

The definition given by Grim seems to be the most appropriate. Depending on which definition is used, fuller's earth may be predominantly of montmorillonite-group minerals or some other mineral assemblage.

4

It appears, then, that most of these terms of classification either have not been defined or have been too loosely defined for technical use. Because classification by usage would be too unwieldly, and classification by property chiefly of academic interest, a very general grouping is suggested. The mineralogical grouping such as that of Davis and Vacher could be used by those not directly interested in end use. The writer shall refer to two groups of bentonites: the swelling type with a swelling index in water of at least 15 ml, and subbentonite, which includes all others. Although actual swelling properties are not normally of direct importance, they are related to some pertinent mineral characteristics. Besides, the term 'swelling' is in common usage. It should be realized that the term 'swelling' is a relative one and that, in fact, all clays swell when in contact with water. Subbentonites that have a swelling index of 7 ml or less shall be regarded as nonswelling bentonites.

PROPERTIES

General

The properties of clays are complex. Although explanations have been presented to indicate their behaviour, conflicting and imprecise hypotheses have been suggested for some properties. The difficulty in determining precisely the reasons for the behaviour of clays under certain conditions is complicated by their extremely fine particle size and is magnified in the case of bentonite because it has the greatest cation-exchange and swelling capacity of the clay minerals.

It is not within the scope of this report to describe in detail all that is known about properties of bentonite. However, most properties are reviewed briefly.

As with any industrial mineral, impurities affect chemical and physical characteristics. The effect of impurities may be considerable depending on their type and amount. Impurities are commonly quartz, cristobalite, minerals of other clay groups, feldspar, calcite, gypsum, volcanic ash and jarosite. Because industry is concerned primarily with bentonite containing high proportions of montmorillonite-group minerals, most of this report deals with virtually pure bentonite.

Chemical and Mineralogical

Minerals of the montmorillonite group are the chief constituents of bentonite. Ross and Shannon (2), in 1926 recognized that several monoclinic minerals resembled montmorillonite and established a group by that name. In 1945 Ross and Hendricks (12) proposed a classification for these minerals that included one named 'montmorillonite'. Although there is no general agreement on a precise classification, the montmorillonite group may be considered to consist of the minerals montmorillonite, beidellite, nontronite, hectorite, saponite and sauconite. Montmorillonite is a commonly occurring mineral and by far the most common of the group. Beidellite is next in abundance but is not common.

Theoretically, the basic formula for the group is $(OH)_4 Si_8 Al_4 O_{20}.n H_2O$, but owing to substitution in the crystal structure, this compound does not exist in nature. Aluminum commonly substitutes for silicon, and magnesium, iron, lithium and zinc for aluminum. These substitutions are responsible for the various minerals of the montmorillonite group.

5

Ross and Hendricks (12) derived the following empirical formula for the individual members:

Montmorillonite $(OH)_4 Si_8 (Al_{3.34}. Mg_{0.66}) O_{20}$
$$\downarrow$$
$$Na_{0.66}$$

Beidellite $(OH)_4 (Si_{6.34}. Al_{1.66}) Al_{4.34} O_{20}$

or
$$\downarrow$$
$$Na_{0.66}$$

Beidellite $(OH)_4 (Si_6 Al_2) Al_{4.44} O_{20}$
$$\downarrow$$
$$Na_{0.66}$$

Nontronite $(OH)_4 (Si_{7.34}. Al_{0.66}) Fe_4 O_{20}$

or
$$\downarrow$$
$$Na_{0.66}$$

Nontronite $(OH)_4 (Si_{6.34}. Al_{1.66}) Fe_{4.34} O_{20}$
$$\downarrow$$
$$Na_{0.66}$$

Hectorite $(OH)_4 Si_8 (Mg_{5.34}. Li_{0.66}) O_{20}$
$$\downarrow$$
$$Na_{0.66}$$

Saponite $(OH)_4 (Si_{7.34}. Al_{0.66}) Mg_6 O_{20}$

or
$$\downarrow$$
$$Na_{0.66}$$

Saponite $(OH)_4 (Si_{6.66}. Al_{1.34}) (Mg_{5.34}. Al_{0.66}) O_{20}$
$$\downarrow$$
$$Na_{0.66}$$
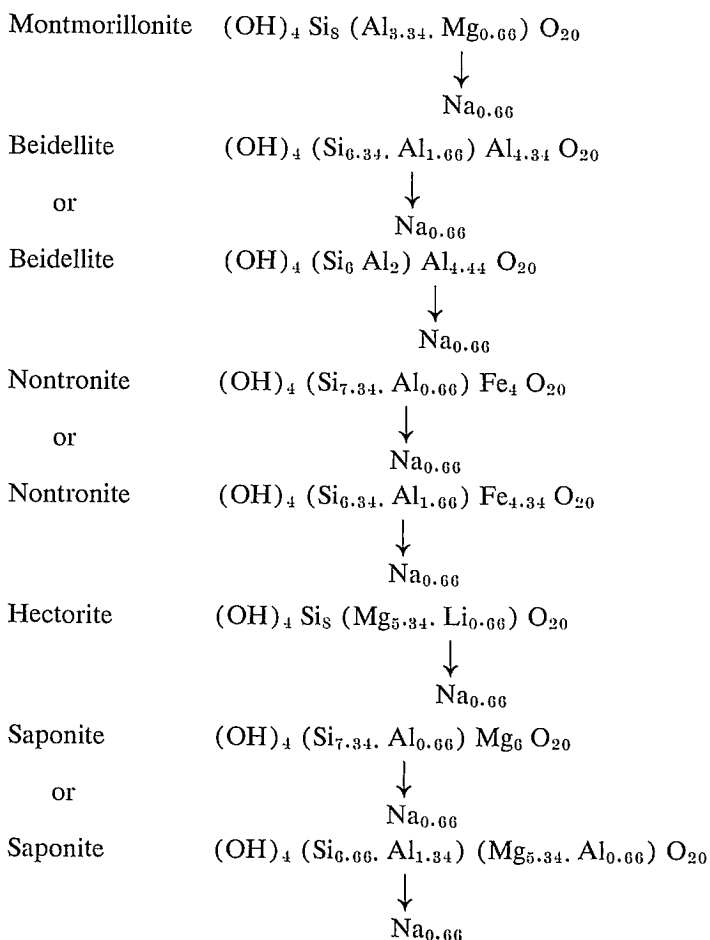
Interlayered water, which is variable in amount, has been omitted in these formulae and the charge deficiencies are indicated by arrows in terms of sodium. Since this work of Ross and Hendricks, the mineral sauconite $(OH)_4 (Si_{6.66}. Al_{1.34})$ $Zn_{4-5} (Mg, Al, Fe)_{2-1} O_{20}$ has been added to the list. In general, all formulae except possibly that for beidellite have been accepted.

A modified version of the crystal structure proposed by Hofmann, Endell and Wilm in 1933 is basically agreed upon by many, particularly Grim (6). This structure is presented diagramatically in Figure 1 and exemplifies montmorillonite as being composed of sheets of hydrous aluminum silicate elongated in the a and b directions and stacked in the c direction. Each sheet is 9.6 Angstrom units thick and is normally separated from another by polar molecules (usually water) and exchangeable cations. Sodium and calcium are common exchangeable cations and normally, when sodium is the exchange ion, one molecular layer of water is present. With calcium, there are two. Sodium ions favor the orderly arrangement

6

of water molecules between unit sheets and it is this arrangement that is basic to a gel. Consequently, montmorillonite with sodium as the predominant cation, forms gels more readily than those with calcium. These gels can be made fluid upon disruption of this oriented water layer.

$$n\ H_2O$$

6 O
4 Si
4 O + 2 OH
4 Al
4 O + 2 OH
4 Si
6 O

b axis
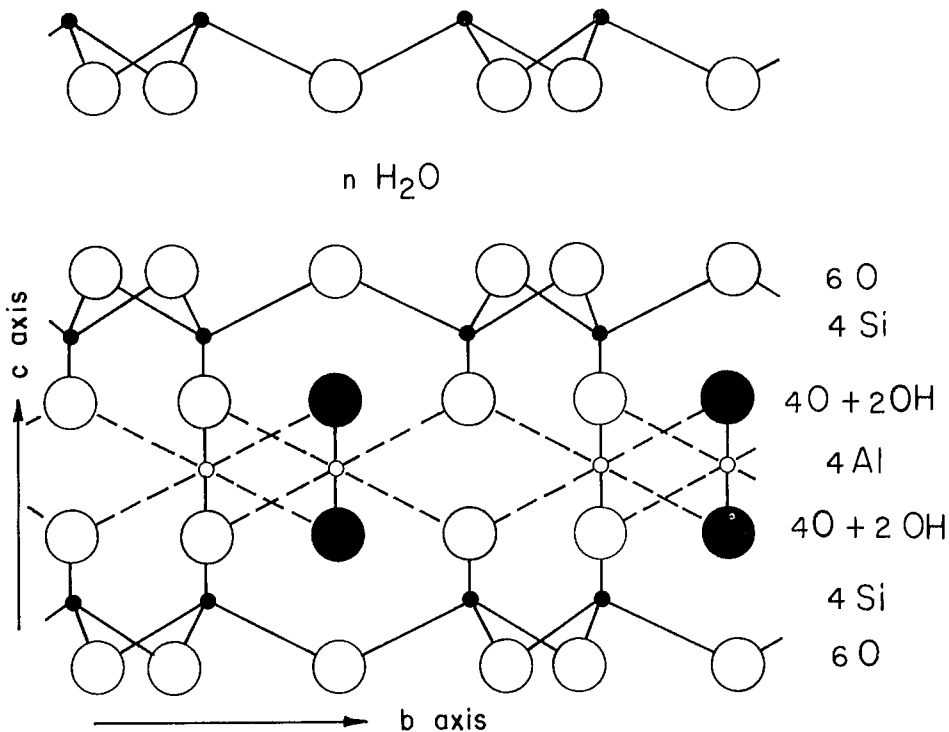
FIGURE 1. Diagramatic illustration of theoretical montmorillonite structure.

The distance between the aluminum silicate sheets may vary from zero to infinity depending on available moisture, but is normally about 3 or 6 Angstrom units depending on whether the exchangeable cation is sodium or calcium respectively. When equilibrium with water is attained this spacing increases more for predominantly sodium, or swelling bentonite, than for subbentonite with calcium and possibly magnesium as the main exchangeable cation.

Each sheet is composed of aluminum and substituting cations, in octahedral coordination with hydroxyl and oxygen ions, bonded between two layers of silica tetrahedra. Figure 1 indicates that these silica tetrahedra point inward. However, some of the variances in montmorillonite properties could be explained by assuming that some tetrahedra have reverse orientations (Grim (6)). Theoretically, the outside oxygen atoms of one unit sheet are directly opposite those of another, resulting in excellent cleavage between sheets. Variations in properties of otherwise apparently identical bentonite might be partly explained by random orientation of outside oxygen atoms in relation to those in adjoining layers (Grim (6)).

7

Owing to substitutions, each aluminum silicate sheet has a negative charge which varies with the degree of substitution in each sheet and which is satisfied by exchangeable cations. The closer a charge deficiency is to the surface, the stronger is the bond between sheets and the less is the propensity for adsorption between sheets.

Montmorillonites and zeolites exhibit much greater ion-exchange capacities than other minerals; far down the scale come all other minerals. A mineral exhibits ion exchange when it adsorbs ions that are stoichiometrically exchangeable for others in the presence of certain fluids. With montmorillonite, these ions become attached to the individual sheet surfaces and have great influence on mineral characteristics. Cation exchange is more common than anion exchange chiefly because of the prevalent type of substitution which produces a negative charge in the silicate sheet. The common exchangeable cations are calcium, sodium, magnesium and potassium. Little is known about the role of anion exchange in montmorillonite but the most common anions are sulphate and chloride.

Ion exchange is one of the most important phenomena in the industrial application of bentonite. It governs viscosity and thixotropism—bentonite's most commonly desired properties in industry. Noteworthy swelling occurs with bentonites having sodium as the exchangeable cation because of the clay's ability to adsorb relatively large quantities of polar materials, such as water, between the weakly bonded silicate sheets.

Table 1 depicts selected chemical analyses representing bentonites of several type localities.

TABLE 1

Chemical Analyses of Bentonites

Constituent	1	2	3	4	5	6	7	8
SiO_2	51.14	59.72	50.20	53.96	40.72	53.95	50.01	38.59
Al_2O_3	19.76	18.22	16.19	15.44	4.96	0.14	3.89	13.36
Fe_2O_3	0.83	4.15	4.13	1.12	29.57	0.03	0.21	3.41
FeO	—	—	Nil	Trace	0.71	—	—	—
MnO	Trace	—	—	—	—	—	—	—
MgO	3.22	2.08	4.12	6.99	0.74	25.89	25.61	1.18
CaO	1.62	1.46	2.18	0.80	1.98	0.16	1.31	0.94
K_2O	0.11	0.54	0.16	0.54	—	0.23	—	0.18
Na_2O	0.04	2.70	0.17	0.94	—	—	—	0.01
Li_2O	—	0.14	—	—	—	1.22	—	—
ZnO	—	—	—	—	—	—	—	23.50
TiO_2	Nil	—	0.20	0.19	0.02	3.04	<0.04	0.31
SO_3	—	0.59	—	—	—	—	—	—
H_2O-	14.81	5.87	15.58	14.22	15.46	9.29	12.02	8.05
H_2O+	7.99	5.55	7.57	6.34	6.66	5.61	7.28	10.39
Total	99.75	101.02	100.50	100.54	100.82	99.56	100.37	99.92

1. Essentially montmorillonite, Montmorillon, France, from Ross and Hendricks (12).
2. Swelling bentonite, essentially montmorillonite, Colony, Wyoming, calculated from D. J. Charette (13).

3. Subbentonite, essentially montmorillonite, Polkville, Mississippi, from Ross and Hendricks (12).
4. Subbentonite, essentially montmorillonite, San Diego county, California, from Ross and Hendricks (12).
5. Nontronite, Spokane, Washington, from Ross and Hendricks (12).
6. Hectorite, Hector, California, from P. F. Kerr et al. (14).
7. Saponite, Milford, Utah, from H. P. Cahoon (15).
8. Sauconite, Liberty mine, Meekers Grove, Wisconsin from C. S. Ross (16).

Chemical analyses of similar types of bentonites commonly differ, owing to impurities, substitution of atoms in the crystal structure, and ion exchange. For these reasons comparison of chemical analyses of members of the same type rarely indicate positively the quality for any particular application, except in the food industry.

Physical

Bentonite has widely varying physical properties because of its many possible chemical and mineralogical combinations. The more important physical properties are discussed here.

Physical characteristics are the direct result of various combinations of mineralogical and chemical phenomena, owing mainly to the contained montmorillonite minerals and partly because of mineral and chemical impurities. In the interest of clarity, the discussion in this section deals with bentonite that is free of mineral impurities. Normally, such extraneous materials have a modifying effect and reduce the usefulness of a clay. The common accompanying constituents are glass, cristobalite, other clay minerals, quartz, chlorite, biotite, feldspar and jarosite.

Bentonite in situ is commonly creamy or greenish grey but may be cream, grey, off-white, pink, dark green, buff, brown, black, or a mixture of these colors. In this state it may contain in the order of 40 per cent moisture depending on type, climate and topography. When dried, its color is lighter, usually cream or buff. Weathering causes oxidation of certain ferruginous contaminants and normally produces a darker yellowish or brownish tint. Outcrops exhibit a partly dry, crumbly crust, that is usually less than one foot thick in dry weather. This crust may contain some 25 to 30 per cent moisture whereas the remainder retains its moisture, and is waxy in appearance and sticky. When dried to about 30 per cent moisture or less, the clay loses its conchoidal parting and its occasional shaly structure and forms irregular crumbly masses owing to contraction. The surface of the outcrop then exhibits a highly granular, mud-cracked, or cauliflower- or popcorn-like texture.

Montmorillonite minerals are comprised of fine-grained micaceous-like sheets that can be easily subdivided in aqueous solutions into unit-celled particles about 0.003 micron thick (17) and less than 0.1 micron in their long dimension. The thickness of these units is much less than those of other clays. Surface area is extremely difficult to measure because of hygroscopy and small particle size. Dyal and Hendricks (18) have calculated the theoretical specific surface area of pure montmorillonite to be 810 m²/gm, equivalent to about 91 acres a pound. Diamond and Kinter (17) obtained values up to 749 m²/gm for a commercial bentonite

9

by glycerol retention methods. Consequently, surface area is a most significant property of this clay.

Bentonite is highly hygroscopic, and when pulverized and dried to about 5 per cent moisture, will adsorb moisture rapidly. Calcium-based bentonite will adsorb moisture more rapidly than swelling bentonite up to a point, but the latter has a greater capacity for water. When bentonite, in particular the swelling variety, is saturated with moisture under quiescent conditions, it will not adsorb more water because, on saturation the water retained between the unit sheets prevents the penetration of additional water. When pulverized to minus 200 mesh, the swelling variety may adsorb up to 5 times its dry weight of water and may increase in volume, or swell, up to about 30 times its original dry bulk volume without agitation. A good swelling bentonite will expand to more than 15 times its original dry volume. Bentonite requires much more water to attain plasticity and has a higher maximum plasticity than other clays. The swelling variety attains the greatest plasticity. An important consideration in certain uses is the rate of adsorption, or more specifically, the rate at which a clay becomes stable under prevailing conditions.

In water, high-quality nonswelling bentonite crumbles, whereas swelling bentonite forms colloidal gels which exhibit thixotropy, the ability of some gels to become fluid when agitated and revert to their original state when quiescent. Aqueous suspensions of swelling bentonite have greater viscosities, gel strengths and thixotropies than for given concentrations of any other clay. A 15-centipoise mud can be produced with 4 to 6 per cent of a good swelling clay. These phenomena are related to the more orderly orientation of water molecules in sodium-based bentonites. As with bentonite in the plastic state, a commonly important economic consideration is the time taken for the mixture to become completely stable and to attain its maximum viscosity.

Bentonite has emulsifying properties and is effective as an emulsifying agent for oil-water mixtures, particularly in well drilling.

By adsorption, absorption and chemical activity, bentonite can collect many types of inorganic and organic compounds, sometimes selectively. Subbentonites low in iron, and particularly with a high replacement of aluminum by magnesium, may be suitable for bleaching or decolorizing fluids or as catalysts in the cracking of petroleum. Aluminum-rich bentonites are not as readily soluble in sulphuric acid as are those containing a high proportion of magnesium. Not all bentonites with the above characteristics can be economically beneficiated by acid leaching to compete as catalysts or for use in bleaching. Ions of iron, aluminum, the alkalies, calcium, etc., must be structurally positioned where they can be leached readily by acid to produce a material with a high surface area, fast-filtering characteristics, low oil retention, and suitable recoverability without a collapse of crystal structure. In decolorizing, bentonites remove undesirable chemicals or colored materials from animal, vegetable and mineral oils by adsorption in a manner similar to that previously described for the adsorption of cations and anions. These clays are used in the cracking of petroleum primarily because of their high adsorptive power for

organic fluids and because of the requirements mentioned above. Owing to these same properties, subbentonite has noteworthy dehydrating and deodorizing powers.

In the plastic or moist state, the maximum green strength of bentonite is much greater than that of all other clay minerals with the exception of attapulgite, which is comparable in this respect (6). Calcium-based bentonite has a higher maximum green strength than the swelling type.

When subjected to heat, bentonite passes through several stages of dehydration. At temperatures of about 100° to 150°C, the moisture in the pores and adhering to particle surfaces is driven off, resulting in considerable shrinkage. According to White (9), the per cent linear drying shrinkage of montmorillonite is 12 to 23 per cent as compared with 3 to 10 per cent for kaolinite. In industry, to facilitate milling and handling, this free moisture is commonly reduced to 6 to 8 per cent but may vary from 3 to 10 per cent. At temperatures between about 100° to 500°C, interlayer water is expelled and, when completely driven off, swelling properties disappear. Hofmann and Endell (20) indicate that the rate of loss of swelling properties varies with the exchangeable cation, and that sodium bentonites lose this characteristic at 390° to 490°C and calcium bentonites at 300° to 390°C. These temperatures may vary depending on the heating rate. Hydroxyl ions are gradually driven out of the crystal structure between about 400° and 750°C. Normally the structure of montmorillonite remains intact until temperatures of 800° to 900°C are reached. Like most other clays, bentonite will bloat or expand at around 550°C, owing to the expulsion of water and alkalies from between the mineral sheets. When water of crystallization is being driven off, the clay will shrink and crack.

An important difference between bentonite with sodium as the principal exchangeable cation, and bentonite with calcium as the main cation, is that the former retains more of its water of crystallization up to about 800°C, near the temperature of incipient fusion. This greater stability at high temperature and the high surface coverage of the sodium bentonite gel, are the principal reasons for the selection of the swelling type for industrial applications at temperatures above 400°C. The result normally is a higher dry and fired strength for the sodium-based mineral.

Depending on the type, bentonite has a wide range of dry strength somewhat comparable with other clays, but along with attapulgite, it usually has a greater dry strength than others. Bentonite is compeletly fused at about 1,500°C depending, of course, on the type and amount of contained impurity.

When used as a bonding agent with silica sand, an increase in bentonite content may increase green strength until the clay content reaches about 10 per cent. Maximum green strength is developed at around 7 per cent in good-quality, calcium-based bentonite, and around 8 per cent in swelling bentonite. The maximum dry compressive strength of swelling bentonite is usually several times that for similar proportions of other clays.

Consequently, it is evident that the exchangeable cation in bentonite governs

many of its physical properties. These properties can vary considerably depending on the types and relative proportions of contained cations. In some instances, the ease of replacement or exchangeability of such cations is an important factor when evaluating this clay.

Identification

There are numerous tests to assist in identifying bentonite, although only a few of these are normally applied. X-ray analysis is required for precise identification. Other methods are of secondary importance and commonly are of more assistance in determining the quality for various applications than for precise identification.

The initial observation can be made in the field and is facilitated by the fact that bentonite outcrops display three unique surficial characteristics. They support virtually no vegetation, are remarkably resistant to erosion by wind and water compared with their accompanying formations, and display a highly mud-cracked surface in dry weather. Bentonite outcrops commonly occupy knolls and, in particular, occur as prominent bare shoulders along the sides of hills and valleys (Figure 6). Their surfaces exhibit pronounced mud-cracking in dry weather to
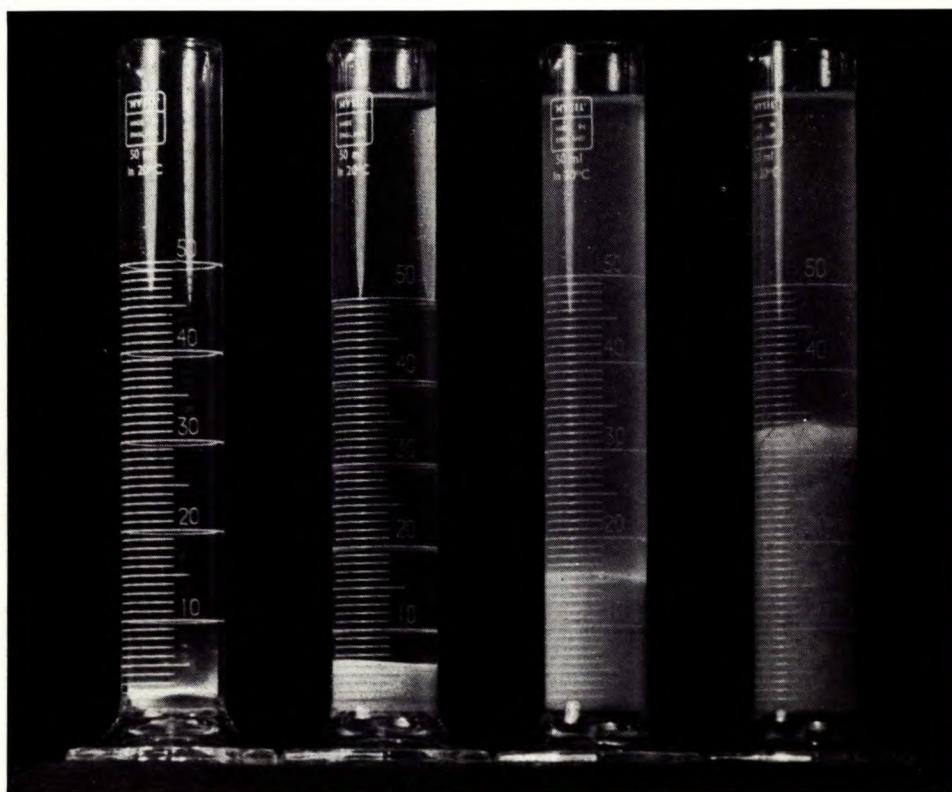

FIGURE 2. Swelling tests, showing from left to right, 2 gm of dry bentonite with a true volume of 0.76 cc and a bulk volume of less than 2 cc; 2 gm of high-quality nonswelling bentonite in water; 2 gm of low-quality swelling type in water; and 2 gm of high-quality swelling bentonite in water.

12

produce what has been described as a cauliflower or popcorn structure, Figure 7. When wet, these outcrops are extremely slippery and difficult to walk on. Wet bentonite is highly unctuous and adheres tenaciously to most materials.

X-ray diffraction is the most convenient, positive means by which the constituent minerals can be identified. X-ray analyses normally require confirmation by ethylene glycerol saturation techniques, which indicate the degree and uniformity of expansion between the crystallographic sheets. Because of variations in degree of crystallinity, particle size, non-mineral constituents and standards, quantitative determinations by X-ray diffraction analyses are subject to error. Consequently, there is no current conclusive quantitative mineralogical analysis for this commodity although that provided by X-ray diffraction is considered the most reliable.

The third test, which can be applied in the field, is to determine whether the bentonite is the swelling variety. This is usually accomplished with samples in the 8 to 10 mesh-size range but there is little discrepancy with low- to moderate-swelling materials if other particle sizes are used. Two grams of bentonite dried at not more than 100°C are added in 0.1-gram lots to a 100-ml glass graduate filled with distilled water. Each addition is made as soon as the previous one has settled. The volume of the gel is noted one hour after the last portion is added. A moderately swelling bentonite will produce about 15 to 20 ml of gel, a good variety about 25 ml, and an excellent grade will produce about 30 ml or more of gel. This test is simple and is quite adequate to determine whether the material is basically a swelling type—the type currently in large demand in Canada. Figure 2 illustrates this test, although 50-ml graduates were used for photographic purposes.

Another simple and useful test involves determination of the colloidal content, a direct indication of the proportion of sodium-based montmorillonite minerals. Good swelling bentonites commonly have colloidal contents of more than 70 per cent, whereas good nonswelling bentonites usually have less than 10 per cent colloidal material. With the latter type of result, it is necessary to identify the constituent minerals to be certain that the clay is bentonite. This is perhaps the most reliable preliminary test for estimating the quality of a swelling bentonite.

Chemical analyses are rarely required in industry for the swelling type and are not commonly used to assist in the actual identification of either type.

Staining tests are rarely used in the identification of this commodity and are not conclusive owing to the effects of mineral mixtures and mineral and chemical impurities. They are, however, of assistance in the field as a rapid means for obtaining a probable identification. Several reagents may be used but benzidine is the most popular. Bentonite turns green with aniline, pink or yellow with toluidine, dull or black with amine and alternately green, blue and purple with dimethylaniline. Benzidine produces bluish colors which, after leaching with concentrated hydrochloric acid followed by washing, turn purple-blue or red-purple with a concentrated solution of safranine Y in nitrobenzene and yellow or green with a saturated solution of malachite green nitrobenzene.

Differential thermal analysis, where the heat of reaction of a mineral assemblage is compared with that of a standard material, provides data that vary with and are dependent upon, mineral constituents. This method gives an indication of

13

predominant constituent minerals and is commonly used in conjunction with X-ray diffraction analysis.

Summary

Bentonites can be mixtures of many minerals of varying properties. These properties are relatively numerous and some are unusual. Many of them can be affected readily and substantially by numerous types of treatment. Because of the fine-grained nature, the numerous properties, and the various possible atomic and ionic arrangements of this clay, it is impossible to predict accurately the behaviour, and thus the possible uses, of bentonite by basic chemical, mineralogical and thermal studies. Tests are, however, of great assistance and some are essential when determining the industrial application of bentonite. However, exhaustive physical laboratory testing followed by pilot-plant or actual industrial application is essential for the determination of the comparative industrial quality.

USES AND SPECIFICATIONS

General

Perhaps the most important function of montmorillonite is the role it plays in adsorbing and retaining moisture in the prairie regions of Canada and the United States. On the other hand, it has the dubious distinction of being the principal mineral which gives prairie gumbo its unctuous properties.

Bentonite has numerous uses and usually constitutes a small part of the final product in which it is an ingredient. It constitutes about 5 per cent of the weight in well-drilling fluids, up to 10 per cent in foundry molding and about 0.5 to 0.8 per cent in iron-ore pelletizing. Consumption of the swelling variety is much greater that that of the other because it finds wide application in the three most common uses for bentonite: in well drilling, foundry molding and pelletizing. However, most bentonites fall into the semiswelling category. The few that exhibit minor swelling and colloidal properties are of value to industry. The others, representing most bentonite deposits, normally are of no current economic use.

Despite its widespread use, bentonite in its natural or synthetically altered state is used only as a filler, binder, adsorbent and absorbent (Figure 3). Most of it is used as a filler and binder.

BENTONITE $\Big\langle$ Swelling   —Filling, binding, adsorption and absorption.
Nonswelling—Adsorption and absorption, filling and binding
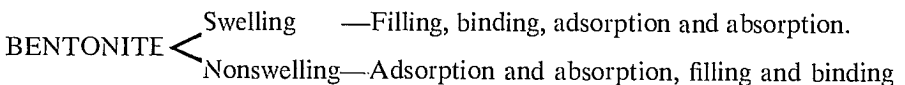
Figure 3—General bentonite uses.

As a filler bentonite imparts desirable physical properties and substitutes for more expensive materials while remaining relatively chemically inert. In some filler applications bentonite's physical properties may become partly altered as it comes into contact with chemicals incorporated in a product, but under these conditions the bentonite does not lose its identity. In drilling fluids, for instance, ion substitution may occur from either natural or other causes and this in effect is a change in

14

chemistry owing to ion substitution. But basically there is no chemical reaction to form new chemical compounds.

As a binder, bentonite also serves as a filler unless it comes in contact with a reactive chemical or until the temperature is increased to the 800°-900°C range or higher. Around this temperature the montmorillonite structure begins to break down and chemical reaction results in a ceramic bond. The binding action in the pre-ceramic stage is normally equally as important in industry as that in the ceramic state. Thus, bentonite can serve as a binder either in the capacity of a filler, as the result of a normal chemical reaction, or as a ceramic bond. Swelling bentonites are normally employed for this use but some nonswelling bentonites are also used.

Adsorption occurs when one material adheres to another owing to mutual attraction. It is generally regarded as a surface phenomenon. Bentonite is highly hygroscopic and has an affinity for many solids, gases and some liquids. Adsorption is an important property of this clay and is particularly well developed in the non-swelling type. These properties are of commercial significance.

As indicated in the previous section, the physical properties of bentonites may be changed within wide limits by the application of chemical additives. In industry, such additives are used on occasion to regulate viscosity, gel strength, water loss, effects of impurities, specific gravity and fired bonding strength. It is not the purpose of this paper to discuss in detail all the possible chemical means of altering physical properties of bentonite. However, it should be kept in mind that, although certain types of bentonites are normally employed for the following uses, some other types of bentonites may be tailored to meet a specific application by the use of additives.

All specifications provided in this report are of a general nature. They may or may not apply specifically to those of a particular consumer and are commonly subject to change depending upon economic or other circumstances. Suppliers and prospective suppliers should attempt to attain as closely as possible the specifications of the particular consumers he wishes to supply, rather than provide a product that is generally acceptable in one given country.

Filling and Binding

Well Drilling

Bentonite's widest application is in well-drilling muds. Here, it acts as a filler by imparting preferred physical characteristics that may be altered by chemicals. The swelling variety, or a bentonite with swelling properties sufficiently improved by chemical additives, is the type normally used.

Most holes for oil and gas are drilled using a fluid medium. Water is by far the most common liquid medium but oil, oil in water, and on occasion, water in oil are also used. Water alone is a poor medium but when mixed with bentonite it produces the most commonly used well-drilling fluid. In well drilling, the fluid, previously prepared in a tank or pond, is forced down the hole through the centre of the rods and bit, and rises between the rods and hole wall to the surface, carrying the cuttings. It is then separated from the cuttings and returned to the supply pond. Depending upon drilling conditions and quality of clay, the percentage of

15

bentonite in such a water-bentonite fluid may vary from 2 to 30 per cent. In the last decade, media other than water and clay have been used, depending upon drilling conditions. The viscosity and gel strength of the mud should be such that the cuttings are floated with the optimum of ease while maintaining a specific gravity that is suitable for bit rotation. Under normal drilling conditions a mud viscosity of about 15 centipoises is preferred.

By forming thin impervious coatings on drill-hole walls bentonite retains drilling fluids in the holes, assists in maintaining uniformity of the fluid, and helps to prevent fluid contamination, the escape of gases, and sloughing and dissolution of hole walls. Geologically incompetent formations and those containing oil, gas, water and readily soluble salts change drilling fluid characteristics by forming emulsions, by altering the concentration, or by introducing or modifying an electrolyte.

A bentonite-bearing mud can provide the necessary viscosity readily to remove drill cuttings and float them to the surface. When drilling is not in progress, such as when bits and rods are being changed, bentonite's thixotropic gel strength prevents settling. The clay increases drilling speeds and reduces abrasion by increasing lubrication on the rods and bits.

There are at least three general specifications for well-drilling bentonite but the most common is given below. No specification is complete without a precise explanation of test procedures and these are described under 'Laboratory Investigation'.

Dry particle size—air floated, minimum 90 per cent minus 200 mesh.

Moisture — not greater than 10 per cent at 90°C, and not sufficient to hinder free flowing.

Sand content — maximum 3 per cent plus 200 mesh by wet screening, and preferably none over 200 mesh.

Yield — requirements generally range from 60 to 130 barrels of 15-centipoise mud per ton of clay. Normally a minimum yield of 90 barrels is desired.

Gel strength — initial gel strength should be at least 5 grams and the 10-minute gel strength a minimum of 40 grams, Stormer.

pH — should be greater than 6.0 and, in some cases, more than 12.0.

Wall-building characteristics — maximum loss of 15cc of filtrate in 30 minutes at a pressure 100 lb/sq in.

Foundries

Bentonite's second largest application is as a binder in foundry molds. These molds are comprised essentially of a mixture of sand and clay. Bentonite is the clay most commonly used. Oil may be added to replace some of the water that is added to the mixture, and coal and other binders may be used to impart special characteristics.

16

Water is mixed with the ingredients in amounts sufficient to produce optimum strength and plasticity. The water content and mixing time are important variables in the process. The foundry mold, which is shaped from this mixture, receives the molten metal. As a result, bentonite must be a competent binder in the green, dry, and fired states. It must form a strong ceramic bond at elevated temperatures so that optimum use can be made of the mold. When the mold deteriorates beyond usefulness it may be crushed and part of the sand recovered. In a similar manner, bentonite is used in foundry cores and also as an ingredient in core and mold washes.

Swelling bentonite commonly serves the above applications, but some non-swelling bentonite is competitive for some foundry purposes. Because the swelling variety has a higher fired strength, it is the preferred clay for higher temperature applications, such as in steel molding. Also, because steel is commonly molded in foundries where other metals are molded, foundrymen prefer to use one type of bentonite and commonly use the swelling variety. Depending on economics and quality, the amount of bentonite used in a mold commonly varies between 6 and 10 per cent.

The particle size of commercial bentonites for foundry use varies widely and may range from about 65 to 95 per cent minus 200 mesh. A size of 90 to 95 per cent minus 200 mesh is the most common. Tentative specifications have been published for 'western bentonite' for use in steel foundries by the Steel Founders' Society of America (21). They apply to a 'western bentonite' in which "the ratio of sodium ion to calcium ion in the base exchange is approximately 1.7 to 1." The pertinent requirements of this specification are as follows:

Property	Minimum	Maximum
Moisture	6%	12%
pH	8.2	—
CaO	—	0.70%
Liquid limit	600	850

In evaluating clay for this application it is common practice to determine the green compressive strength, green deformation, green shear strength, green tensile strength and dry compressive strength of various mixtures of foundry sand and the specific bentonite. Good-quality bentonite for steel-foundry use will produce molds having characteristics approximating the following, depending on the test procedure followed:

Green compressive strength	8.5 psi
Green deformation	2.5%
Green shear strength	2.5 psi
Green tensile strength	24.0 oz/in^2
Dry compressive strength	95.0 psi

Iron-Ore-Concentrate Pelletizing

In Canada, the next largest application of this clay is in pelletizing iron-ore concentrates. Unconcentrated, and by-product iron ore could also be agglomerated

17

with bentonite. The concentrates consist mainly of magnetite, hematite, or mixtures of the two, that have been upgraded, usually by magnetic or spiral concentration, or both. The particle size of the concentrate is commonly reduced to between 70 and 90 per cent minus 325 mesh by grinding. The moisture content of the concentrate is regulated at about 10 per cent before pelletizing. If the particle size is small enough, it is possible to pelletize without a binder other than water, but current practice is to add a small proportion of bentonite to ensure uniform, uninterrupted production of a high-quality product. Current specifications and the need to control closely the tremendous volumes of material passing through large pelletizing plants, are the main reasons for the consumption of quite large proportions of bentonite by this industry. It is probable that research will assist this relatively young North American iron-ore pelletizing industry to reduce the proportion of bentonite in pellets. Bentonite is not usually required for pelletizing sintered or roasted iron oxide.

How large a part bentonite plays in reducing excessive moisture in iron-ore concentrates by adsorption and absorption, is not known. Good-quality swelling bentonite, by adsorbing up to 5 times its dry weight of water, could adsorb and absorb about 3 per cent of the approximate 10-per-cent moisture in a concentrate. This eliminates the need for additional costly filtering to reduce plasticity to that required for suitable agglomeration.

In general, the pelletizing process involves the addition of about 12 to 18 lb of bentonite per long ton of dry concentrate, followed by brief, but often incomplete mixing. Water may also be added depending on the moisture content of the concentrate. The mixture is fed either to balling drums, discs or cones, where it is formed into green pellets by a rolling motion and discharged over screens. Those pellets under about ⅜ in. are returned to the balling circuit and the remainder are conveyed to vertical furnaces or horizontal kilns where they are dried and hardened at temperatures up to about 1,350°C. The resulting hematite pellets are screened and those under about ⅜ in. are returned for further processing. The remainder is the final product, which is shipped to blast furnaces. As in foundry molds, bentonite must serve as a competent binder during the handling and processing of pellets in the green, dry, and fired states.

Owing to its superior dry-bonding strength and strength at high temperatures, swelling bentonite is preferred over the nonswelling variety for iron-ore pelletizing. The particle size of bentonite for this use is about 80 per cent minus 200 mesh and a moisture content of 6 to 8 per cent is preferred. Some consumers prefer this clay with a minimum yield of 80 to 120 bbl/ton and with a minimum pH of 8.0.

Although there may be a general relationship between pelletizing characteristics and particle size, yield and pH, the final test for evaluating a bentonite is the quality of green, dried and fired pellets made with a standard percentage of that bentonite. Because iron-ore concentrates from various plants differ in particle size, particle shape, surface area, surface tension and chemical and mineralogical content, it cannot be assumed that a given percentage of one bentonite will produce the same quality of green, dried and fired pellet for each type of concentrate. Hematite, for instance, is usually more difficult to pelletize than magnetite. How-

ever, each company has minimum physical and chemical requirements for its green, dried and fired pellets. The physical properties must be such that the pellets will retain their shape without disintegration during processing and handling and be amenable to reduction in the blast furnace. Chemically, they should contain a maximum iron content and a minimum amount of impurities, within economic limits. Bentonite in this case is a chemical impurity and, if added at a rate of 0.6 per cent, will decrease the iron content of the concentrate by about that amount. Thus, the best quality of bentonite for pelletizing a particular concentrate is that which is required in the smallest amount to produce a pellet having the desired physical properties. The cost price of a clay will assist in determining the relative economics of using that clay, but unless the bentonite is of a certain quality, the price is normally of no significance.

For a given iron-ore concentrate, the quality of a bentonite may be assessed by comparing with a standard bentonite, either (a) the quantity required to produce minimum pellet physical properties, or (b) the properties produced by the addition of a prescribed quantity of bentonite. Many laboratories, particularly those with pelletizing plants using bentonite, prefer to use the latter method with equipment and procedures simulating those used in their plants. Aside from the concentrate characteristics, many factors influence the evaluation of these pellets, including moisture content, mixing period, size of pellet, and testing procedure and equipment. But, mainly because of variable concentrate properties and pellet-plant processing, it is difficult to standardize specifications.

To give one example, which should not be regarded as standard for the industry, the minimum average specifications used by Pickands Mather & Co. as given by Merklin and De Vaney (22) for pellets $\frac{3}{8}$ to 1 in. in diameter made with 0.6 per cent bentonite and 10 per cent moisture are as follows:

Green drop number	—	5.00
Green compressive strength	—	12.0 psi
Dry compressive strength	—	30.0 psi
Fired compressive strength	—	1500 psi
"Good" tumble index	—	85

Many scientists prefer a much smaller pellet and pellet-size range, such as $-\frac{5}{8} + \frac{3}{8}$ in. This size more closely conforms to that used by industry and of course has different minimum requirements than for other sizes. In addition, consumers may specify such requirements as a minimum yield of 85 bbl/short ton, a maximum grit content of 5 per cent plus 325 mesh, a minimum pH of 8.0 and a minimum of 80 per cent colloids. However, except for actual performance in the blast furnace, the final criteria are comparative drop, tumble, and green, dry, and fired compressive tests.

Other Binding Uses

Bentonite may also be used to pelletize other types of mineral concentrates and by-products. Feeds for animals and poultry are commonly pelletized with nonswelling bentonite because of the superior green strength of this type.

19

Swelling bentonite in small proportions is used to provide a bond in brake linings and as a plasticizer in the production of refractory, abrasive and ceramic mixes. Because of its high shrinking characteristics during drying, it is added in minor amounts for its plasticity and green and dry strength only, and not because of its ceramic properties. Its usual relatively high iron content products a buff to reddish color after firing, which limits its application in white products. In particular, bentonite may be added to raw materials for the production of brick, tile, sewer pipe, flue lining, conduit, whiteware and stoneware products. In porcelain enamels and glazes it is used as a suspending agent.

In their natural state, bentonites are not usually more than weakly pozzolanic. That is, in the presence of lime they do not have strong cementing properties. When calcined, particularly at the optimum temperature (somewhere between 540° and 1,000°C), these properties are increased greatly. Bentonite plays an important role in soils stabilized with lime. Upon the addition of lime, cation exchange occurs converting the soil to a friable and easily workable mix. After compaction, pozzolanic action occurs between the lime and clay, and excess lime forms carbonates to produce a stable mantle that resists water penetration and has low to moderate strength.

Other Filling Uses

There are numerous other filler applications. Unless otherwise specified, normal requirements are for high-quality bentonite with a particle size ranging from 80 to 94 per cent minus 325 mesh. Minimum specified moisture content is variable. In oil-well 'cement', up to about 12 per cent swelling bentonite may be added to decrease slurry density to assist in keeping solids in suspension by thixotropic action, to increase plasticity, and to retard water loss. Bechtner (6, p. 351) claims that swelling bentonite in amounts up to about 0.5 per cent does not decrease concrete strength but improves workability, aggregate dispersion and impermeability. The same general rule applies for mortars and refractories. Because bentonite adsorbs a large proportion of water, substantial amounts of it used as a concrete additive would decrease concrete strength. In combination with water and possibly with other materials as well, swelling bentonite is used as a grouting material. Commonly it is a constituent in concrete grout used in underground developments where it serves the same purposes as in oil-well concrete. When applied in relatively large proportions, its water-impedance properties and minute gel particle size are most important. The bentonite grout swells in fissures and open spaces and, if properly applied, will thoroughly fill these spaces. Providing pressures are not excessive, and calcium ions are not available in sufficient amounts to convert the clay to a nonswelling type, it will retain its moisture tightly and become impervious, reducing the penetration of moisture. With moderate or high water pressures, it is common to use a mixture of predominantly cement or chemicals to keep the grout in place. A similar application of swelling bentonite is in the reduction of seepage from ponds, settling basins, dams and other hydraulic reservoirs. These structures may be treated by the 'blanket', 'mixed-blanket', 'sprinkle' or 'sedimentation' method. In the first method, a layer about ⅓ in. thick is placed on the bottom

of the drained reservoir after about 4 in. of soil have been removed and the area smoothed. About 4 in. of soil are replaced and the bed is rolled. In the mixed blanket method, about the same amount of bentonite is spread on the drained floor, mixed into the top 4 in. and packed. Granular bentonite is sprinkled onto the filled reservoir in the sprinkle method but in the sedimentation method it is dispersed by flowing water.

As a filler in paper, the swelling variety is used to improve opacity, smoothness, printability, softness and absorption. Because of its adsorptive properties, it is excellent for dispersing pitch, but its buff color normally prevents the use of appreciable quantities. In pesticides and herbicides the clay serves as a weighting agent and as a diluent for granular and dusting compounds. It serves the same purpose in horticultural sprays, solutions and animal dips, but also imparts beneficial adhesive properties that increase the effectiveness by adhering to an object and retaining the contained toxicity for long periods. This same property makes swelling bentonite competitive as a water carrier in firefighting. During the last decade, the use of aircraft in 'bombing' forest fires with fire-retardant fluids has become economical and relatively effective for extinguishing small fires and controlling the spread of larger fires. This method is now used in several countries and has obvious advantages in quickly snuffing out and confining freshly started fires, particularly in mountainous or remote regions. Too frequently, water is the only fluid used as the fire retardant, particularly in central and eastern Canada. Although additives such as bentonite require more complex mixing facilities and longer pick-up periods after the first load has been delivered, a bentonite slurry is from 1½ to 3 times more effective than water in keeping temperature below the combustion point. More important is the ability of this slurry to adhere to foliage and other combustible materials rather than fall to the ground. In addition, much more accurate 'bombings' can be accomplished with the denser slurry. Bentonite is used in an aqueous slurry containing about ¾ to 1 lb of the clay per gallon. Its cost is thus negligible in comparison with total costs. A pink pigment is normally added to outline the areas treated. The slurry is released from aircraft at elevations of about 100 to 200 feet and is effective as a fire retardant for 2 to 3 hours. It clings to foliage, is non-toxic to plants and animals, and has little abrasive and corrosive effect on equipment.

Bentonite is used as an extender and emulsifier in rubber, linoleum and oilcloth. In cosmetics and pharmaceuticals it serves as an extender, and it adds a smooth, soapy consistency to creams. In medicines it acts as a filler and laxative. Swelling bentonite is an appropriate filler in soaps and detergents because of its soft, soapy consistency. Bentonite may be added to some soaps in proportions up to 40 per cent. For the same reason it is used in cleaning and polishing compounds. In paints, this clay functions as an extender and, because of its thixotropic nature, it is a suspending agent. It has the property of forming a homogeneous mixture with the oils and pigments because of its adsorptive characteristics. It also improves spreadability and is used in both oil- and water-based paints. Swelling bentonite has many other applications as an emulsifying and wetting agent. In glues and adhesives it has found limited use.

21

Both the binding and filling properties of this clay are used in the production of masonry and concrete lightweight aggregates. For this purpose the clay is heated rapidly to incipient fusion in a rotary kiln or sintering furnace where it expands owing to escaping gases. It is then cooled and a fused clinker is formed, having a large percentage of impervious pores. Depending on its size, the product may be crushed before being screened into various fractions. ASTM Designation: C 330-60 T, for lightweight aggregate for structural concrete, specifies a maximum dry loose weight of 70 lb/cu ft for fine aggregate (minus ⅜ in.); 55 lb/cu ft for coarse aggregate (minus 1, plus 0.047 in.); and 65 lb/cu ft for combined fine and coarse aggregate.

Bentones are products of the reaction of organic compounds with bentonite. These compounds replace inorganic cations in the clay resulting in a product that exhibits improved viscosity and thixotropy. Bentones are used in paint, lacquer, resin, adhesives and inks to improve the suspension of solids.

Adsorption and Absorption

Most bentonite employed for its adsorptive properties finds use in clarifying mineral, vegetable and animal oils and waxes. In general, swelling bentonites exhibit less pronounced adsorptive characteristics than nonswelling varieties and, for that reason, the nonswelling type is normally used for adsorptive purposes.

The adsorptive and absorptive efficiencies of some nonswelling bentonites may be greatly improved by acid leaching to produce activated bentonite, a process discussed later. Most commercial activated clays have adsorptive properties far superior to those of natural bentonite. For decolorizing fluids and as catalysts, activated bentonite has become the most popular variety. For other adsorptive and absorptive uses, both the natural and the activated types are used, depending on economics. No specification is universal for these uses, but individual consumers have their own specifications and any new product must compare favorably to be competitive.

Such oils as mineral, linseed, cottonseed, rapeseed, coconut, corn, palm, sesame, poppyseed, peanut, olive, sunflower, castor, seal, whale, cod, and those of other fish may be clarified by bentonite. Tallow, lard, turpentine, cleaning fluids, vinegar, wine, beer, syrups and other beverages may also be purified, but usually swelling bentonite is used for wine, beer, syrups and other beverages. The clay, either in the granular or pulverized form, may be mixed with the hot oil or fluid and recovered by filtering, or it may be used as a filter precoat normally in the granular state. Bentonite adsorbs impurities such as wax, tar and foreign material, leaving a clearer product. During the decolorizing process, temperatures may be above or below the boiling point of the fluid, and the contact time or filtration rate can vary widely, depending on the process and fluid. Granular bentonite may be between 10 and 100 mesh in particle size and the pulverized material is usually minus 100 mesh. In the process using the clay as an additive, as much of the fluid is removed as is economically feasible and the waste bentonite is discarded. After being used in the filtering process, the clay may be repurified by calcination and then reused.

Generally, bentonite for all adsorptive and absorptive applications should

have high adsorption qualities, low impurities such as iron and salts, a high specific surface area, and it must not impart objectionable odors or tastes during use. Depending on the quality required, adsorbent clays may be calcined above 200°C to produce a more uniform product which is not readily agglomerated by the adsorbed materials. In addition, for decolorization, bentonite should have a high filtering rate, retain only small amounts of oil, be easily separated from oils, and regain much of its adsorptive properties, and retain its general particle size during regeneration. Clay that is of excellent quality for clarifying a vegetable oil may not be suitable for use with another oil or for other adsorptive uses. To be of high quality, a clay must be tailored for each specific use with close cooperation with the consumer. Depending on economics, the minimum acceptable quality is usually equivalent to that of the clay being used by the consumer. Consequently, comparative testing with a standard is essential.

Another main use of activated bentonite is as a catalyst in refining mineral oils. It is also used to a minor extent as a catalyst for other oils. In this process, vaporized crude oil is adsorbed for a few seconds by the catalyst at a temperature of about 500°C. During contact, the vapor cracks, or separates into various lighter hydrocarbon components and carbon is left as a residue with the catalyst. As in decolorizing, the catalyst may be employed as a granular bed or it may have a smaller particle size and become fluidized with the vaporized oils. In either case, it is normally removed after a short period in the cracking chamber, regenerated by calcination to remove the adsorbed carbon, and recirculated until it loses its economical efficiency. As a result, large quantities of the catalyst are in continuous circulation in this process. For this purpose, the activated clay is either sized to minus 100 mesh for the fluidized method of processing, or compacted into ⅛- or ¼-in. spheres, cylinders or oval-shaped briquettes for the granular-bed technique. It is then calcined to about 600°C to promote stability during the cracking process. Basically its application is to provide a large surface area which promotes maximum reactor capacity by reducing the cracking period and by increasing the amount of reacting fluid over a given period.

In water and sewage treatment, bentonite adsorbs impurities and coagulates bacteria. In the process, it 'softens' the water by removing calcium and magnesium salts by base exchange. The clay is rejuvenated by the addition of a soluble sodium compound such as sodium chloride, whereas that contaminated with sewage is either discarded or calcined and chemically treated.

The pulverized clay is used to stabilize colors in inks and dyes. It has been applied as a filling agent for textiles, and its adsorptive properties are important in herbicides, pesticides, cosmetics, therapeutics, soaps, cleansers and polishes. Both granular and pulverized clay find use in deodorizing and dehumidifying, and as soil conditioners. In agriculture, bentonite may assist in retaining moisture, and by ion exchange it may reduce the loss of fertilizers by surface run-off. The calcined granular fraction is commonly used for absorbing liquids, such as in animal bedding. Bentonite can adsorb printer's ink from paper during the repulping of waste paper. It is also used to adsorb grease, oil, and moisture from floors and similar surfaces.

HISTORY AND PRODUCTION

Canada was a pioneer in the use of bentonite but it wasn't until about 1943 that Canada's production became noteworthy. In 1874, Selwyn (23) reported the recovery and use of 'soap clay' by women at Fort Edmonton, Alberta, for washing blankets. This clay was obtained near St. Albert mission and was brought some nine miles to Fort Edmonton. An analysis showed that it was essentially a hydrous aluminum silicate. Although a number of Canadian deposits of what is now known as 'bentonite' were known prior to 1912, they were not recorded systematically along with other clays until the reports of Ries, Keele and MacLean were issued during the period 1912 to 1914 (24 to 29). By 1915, these three geologists had published general information on bentonite deposits in most of the areas in which this clay occurs in Canada.

In 1912, Ries and Keele (24) described a Cretaceous clay from near Irvine, southeastern Alberta, as being "a very smooth, plastic, sticky clay, which cracked badly during air drying". In 1913 (25) they labelled a 7-in. horizon a few miles east of Tantallon, Saskatchewan, as being 'bentonite (?)'. That same year they identified a deposit of "greenish-yellow clay resembling axle grease and known as 'bentonite' or 'soap clay' " near Camrose, Alberta. In the same report they mention a 9-ft bed of bentonite near Quilchena, British Columbia. In 1914, MacLean (29) recognized "heavy, waxy, tenacious clay, probably consisting largely of collodial material, very similar to bentonite" in Dead Horse and Pembina valleys, southern Manitoba. In 1915, Ries (27) referred to clays that were probably bentonites in the Princeton area of British Columbia, and Keele (28) identified what appeared to be "bentonite or soap clay" at Virden, Manitoba, and near Nevis, Alberta. Numerous individuals have since examined and provided more detailed reports on Canadian bentonite deposits including Bannatyne (30) in Manitoba, Worcester (31) in Saskatchewan, Byrne (32) in Alberta, and Spence (33) in Canada generally.

According to official records (34), bentonite was first produced in Canada in 1926 from a deposit near Princeton, British Columbia. The material was shipped by Princeton Collieries Company to England. Except for 1927, 1929, 1939 and 1942, production continued from deposits in that vicinity until 1944. A Mr. F. Glover was responsible for much of this production which was shipped mainly to Vancouver for processing. It was used chiefly in petroleum refining, in foundries, and as a concrete admixture.

In Alberta, Claynett Distributors Ltd., produced bentonite prior to 1930 and possibly as early as 1927 from near Edson for use as a filler in cosmetics and toilet preparations. However, official records indicate that shipments of Alberta bentonite commenced in 1938 and were continuous until 1957. This clay was recovered from the Drumheller area and most was produced by G. L. Kidd near Drumheller and by Aetna Coals Limited at East Coulee. It was shipped to Alberta Mud Company and to Western Clay and Chemical Supply Company at Calgary for processing, mainly for use in well drilling and foundries. Sovereign Coal Mining Company at Wayne, and Western Gem and Jewel Collieries, Limited at Cambria,

shipped small amounts. In 1959, Magcobar Mining Company Limited constructed a milling plant at Rosalind, Alberta, and commenced processing swelling bentonite from deposits nine miles south of the village. The bulk of production is used in well drilling but some finds application in foundries and other industries as well. In 1960, Baroid of Canada, Ltd. started milling bentonite at Onoway. The raw clay is obtained nearby and the product is used in well drilling and foundries. Magcobar and Baroid are the only producers of Alberta bentonite and the only producers of swelling bentonite in Canada.

No shipments other than those for experimental purposes have originated from Saskatchewan.

Except for 1938, subbentonite has been produced continuously in Manitoba since 1937. All has come from deposits in the Morden district, southern Manitoba. Small and unknown amounts were shipped between 1934 and 1937 by P. Wollke and J. E. O'Day. These deposits were worked by J. E. O'Day in 1938, Spencer and Sons in 1939, and O'Day and Spencer in 1940. In 1940, Pembina Mountain Clays Ltd. was incorporated to exploit the Spencer deposit, which is four miles north of Thornhill. During that year the company built a drying and grinding plant at Winnipeg. In 1942 it added an activation unit to its Winnipeg plant and in
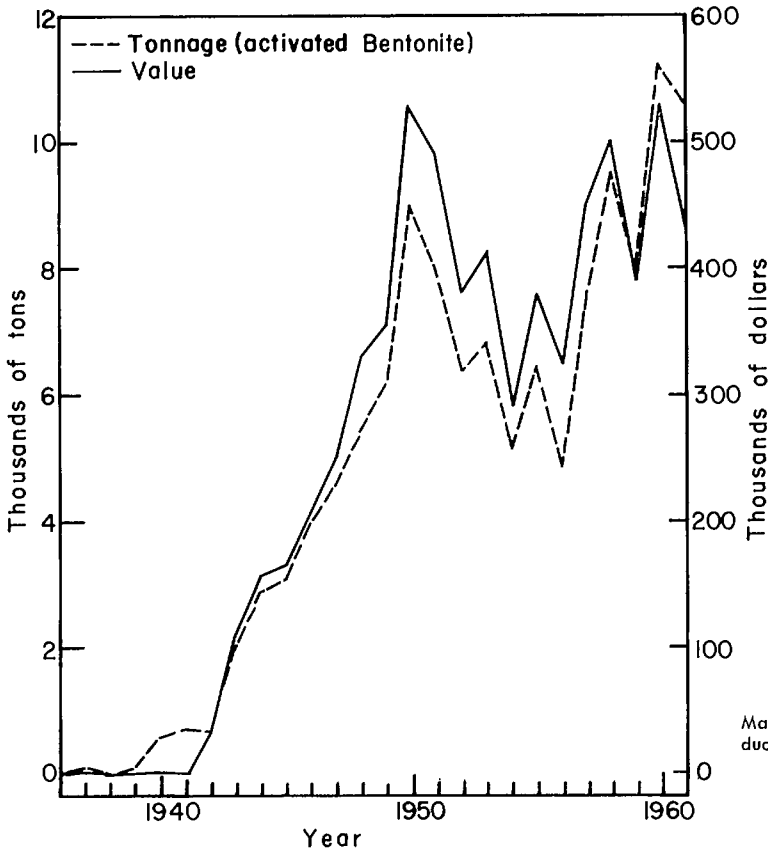

FIGURE 4
Manitoba bentonite pro-
duction, after Bannatyne
(30).

25

1945 a drying and grinding plant was built at Morden, Man. The Miami deposit at Twin Sisters Butte was the main source of bentonite from 1954 to 1960, but in 1960 the Spencer deposit again became the main source. Laporte Industries Limited of England purchased a majority interest in Pembina Mountain Clays Ltd. in 1958 but relinquished control in 1963. Several other companies have been formed to exploit bentonite deposits in the Miami-Brown area but none has recorded commercial production.

Initially, Manitoba bentonite was used chiefly in foundries. By 1937 the National Research Council had recognized that this clay possessed excellent bleaching properties. Since 1943 the main use for Manitoba bentonite has been in bleaching various oils.

Available figures on production are mainly of an historic nature because complete, current production statistics for Canadian bentonite are not available. Table 2 indicates virtually continuous production since 1926 with Alberta and Manitoba the producing provinces since 1945. All the output of swelling bentonite has been from Alberta. Figure 4 shows shipments of Manitoba bentonite.

TABLE 2
Bentonite Production (Shipments) in Canada, by Provinces

Year	Manitoba Tons	Manitoba $	Alberta Tons	Alberta $	British Columbia Tons	British Columbia $	Canada Tons	Canada $
1926					30	150	30	150
1927					—	—	—	—
1928					20	100	20	100
1929					—	—	—	—
1930					74	1,396	74	1,396
1931					187	935	187	935
1932					7	176	7	176
1933					55	1,363	55	1,363
1934					63	1,578	63	1,578
1935					41	781	41	781
1936					120	180	120	180
1937	132	1,154			31	817	163	1,971
1938	—	—	1,136	3,444	43	215	1,179	3,659
1939	99	591	889	2,850	—	—	988	3,441
1940	710	2,023	714	2,240	45	225	1,469	4,488
1941	760	1,330	1,317	5,882	95	618	2,172	7,830
1942	660	38,800	956	5,404		—	1,616	44,204
1943		110,428		5,262		1,357		117,047
1944		160,268		2,076		1,504		163,848
1945		169,551		1,248				170,799
1946		207,572		4,253				211,825
1947		253,786		4,541				258,327
1948		336,003		3,710				339,713
1949		360,591		7,277				367,868
1950		533,390		1,483				534,873
1951		496,403		3,153				499,556
1952		385,448		3,094				388,542
1953		*		*				418,633
1954 - 1962		*		*				*

Source: Dominion Bureau of Statistics, except for the year 1926 (34). *Not available.

26

Table 6 shows that 1961 Canadian consumption was approximately 63,300 tons and exports (Table 4) were 5,200 tons. This total of 68,500 tons, less estimated imports of 34,000 tons results in a calculated production of 34,500 tons valued at $1 million in 1961. More than two-thirds of this was the swelling type from Alberta. This was used chiefly by the well-drilling industry and, to a small extent, by foundries and in feed pelletizing. Subbentonite was produced in Manitoba primarily for the bleaching and feed-pelletizing industries.

Because of the confusion in terminology between 'bentonite' and 'fuller's earth', and because some countries, such as Canada, combine bentonite production statistics with others, it is difficult to establish world production. Table 3 is a list of available production statistics for many countries for the years shown and is only an indication of actual bentonite production.

TABLE 3
World Production of Bentonite[1]

Country	Year	Production short tons	Terminology Used
Australia	1960	101	fuller's earth
	1960	428	bentonite
Austria	1960	3,614	bentonite
Algeria	1956	87,676	fuller's earth
Argentina	1956	22,046	bentonite
Canada	1961	36,000[2]	bentonite
Cyprus	1960	245[3]	bentonite
West Germany	1960	70,000[2]	bentonite
India	1961	2,097	bentonite
	1957	5,116	fuller's earth
Italy	1959	66,609	bentonite
Morocco	1961	42,560	fuller's earth
Mozambique	1960	44	bentonite
New Zealand	1960	2,435	bentonite
Republic of South Africa	1961	4,527	bentonite
	1961	792	fuller's earth
Spain	1960	5,332	bentonite
Tanganyika	1958	86	bentonite
United States	1961	1,307,191	bentonite
	1961	422,181	fuller's earth
Yugoslavia	1959	5,368	bentonite

Main sources: "Statistical Summary of the Mineral Industry 1955-60", Mineral Resources Division, Overseas Geological Surveys. Mineral Trade Notes, United States Department of the Interior, Bureau of Mines. [1]Incomplete. [2]Estimated. [3]Exports.

Indications are that some of the 'fuller's earth' reported in Table 3 would be classified as 'bentonite' by this writer's terminology. In any case, the United States produces by far the largest tonnage of bentonite and fuller's earth. Canada ranks sixth in this incomplete list. In general, bentonite produced in Algeria, Morocco, Italy, Argentina, Hungary, Yugoslavia, New Zealand and Australia does not have swelling properties and yields equal to those of Wyoming bentonite. Germany, the United Kingdom, and Japan chiefly produce the nonswelling subbentonite type.

TRADE

Despite its being a low-priced commodity, good-quality bentonite enjoys world-wide trade. Canada imports swelling bentonite, activated bentonite and subbentonite mainly from the United States. Tables 4 and 5 include available but incomplete import statistics.

TABLE 4

Canadian Bentonite Trade[1]

	1962		1961	
	Short Tons	$	Short Tons	$
Imports				
Activated clay[2]				
United States		934,465		1,006,916
Fuller's earth				
United States		165,282		150,576
West Germany		4,346		4,619
Britain		3,187		1,807
Total		172,815		157,002
Clay for use in drilling mud				
United States	14,954	416,800	14,224	364,252
Exports				
Earths or clays artificially activated[3]				
United States	4,029	149,132	4,503	191,841
Bentonite[3]				
United States	112	7,323	669	49,431

Source: Dominion Bureau of Statistics with exceptions as indicated. [1]Incomplete. [2]Includes clay catalysts in addition to adsorptive clays. [3]From exports of activated clays to the United States as given by the U.S. Department of Commerce in its "United States Imports of Merchandise for Consumption (Report FT 110)".

TABLE 5

Canadian Bentonite Trade, 1952-62

Year	Imports[1] $	Exports[3]			
		Wrought or manufactured		Earths or clays artificially activated	
		Short Tons	$	Short Tons	$
1952	460,734	112	2,879		
1953	443,510	103	2,754	5	2,240
1954	835,433	91	2,426		
1955	1,247,355	685	25,664	792	47,916
1956	1,484,124	340	12,755	1,822	112,670
1957	1,536,512	—	—	4,271	248,783
1958	980,585	—	—	5,284	258,416
1959	1,082,593	784	25,200	4,851	226,416
1960	1,590,441[2]	—	—	5,892	248,418
1961	1,528,170[2]	669	49,432	4,503	191,841
1962	1,524,080[2]	112	7,323	4,029	149,132

Source: Dominion Bureau of Statistics. [1]Incomplete and relating to activated clays for oil refining They include clay catalysts in addition to adsorptive clays. [2]Increase in totals is due in part to an increase in the survey coverage and includes fuller's earth and clay for well drilling. [3]Exports to the United States only. From Report FT 110, U.S. Department of Commerce.

Imports are significant in value and, in 1961, amounted to an estimated 34,000 tons of bentonite valued at about $1 million. For 1962, they totalled an estimated 38,000 tons and included part of the fuller's earth, valued at $172,800; part of the activated clay and clay catalysts, valued at $934,500; most of 15,000 tons for well drilling, valued at $416,800; and an estimated 18,000 tons for pelletizing and foundry use.

Exports of the pulverized commodity have been small and intermittent and have gone to the United States (Table 4). In 1962 they amounted to 112 tons valued at $7,300. Canadian exports of activated bentonite go to the United States from Manitoba and have been continuous since 1955. In 1962 they amounted to 4,000 tons valued at $149,000.

CONSUMPTION

Bentonite consumption has been confined mainly to the twentieth century and to the United States, principally because of its use in the well-drilling industry. The United States is by far the world's largest consumer of bentonite for well drilling. In North America, about 30 per cent of the total is consumed in well drilling and 20 per cent in foundries.

In 1921, quality-controlled swelling bentonite was first marketed from Wyoming; and nonswelling bentonite from Mississippi about 1935. Consumption of this clay has increased manyfold since the establishment of the first Wyoming operation. Total current consumption of bentonite in the world and even in North America is difficult to determine because of differences, in terminology for the non-swelling variety and the confusion caused by use of the term 'fuller's earth'.

Canada's consumption since 1952 is given in Table 6. In 1961, it was 63,200 tons valued at an estimated $2.9 million at the consuming plants. Table 7 shows that 58 per cent was used in well drilling, 20 per cent in iron and steel foundries and 16

TABLE 6
Canadian Bentonite Consumption, 1952-61

Year	Short Tons	
	Bentonite	Fuller's Earth
1952	30,622	8,620
1953	35,167	15,982
1954	23,844	1,732
1955	28,821	1,565
1956	30,562	1,783
1957	26,105	1,654
1958	23,429	1,595
1959	60,258*	
1960	64,871*	
1961	63,268*	

Source: Dominion Bureau of Statistics except where otherwise indicated. *Increase in totals is due in part to an increase in the survey coverage, particularly in well-drilling. It includes fuller's earth and has been compiled from data provided by the Dominion Bureau of Statistics.

per cent in pelletizing iron-ore concentrates. In 1963, consumption for iron-ore pelletizing should closely approach that for well drilling. Except for petroleum refining, consumption for other uses is negligible. These include applications in the paper, paint, asbestos products, animal- and vegetable-oil, starch, polish, herbicide and pesticide, pharmaceutical, gypsum products, rubber, adhesives and agricultural feed industries.

TABLE 7
Canadian Bentontie Consumption by Use, 1960-61

Consuming Industry	Short Tons	
	1960	1961
Well drilling	39,144	36,664
Iron and steel foundries	13,283	12,912
Pelletizing iron-ore concentrates	8,500e	10,213
Petroleum refining	1,871	2,265
Paper	277	227
Vegetable and animal oil	86	152
Paint	145	65
Miscellaneous nonmetallic products	1,565	770
Total	64,871e	63,268

Source: Compiled in part from data provided by the Dominion Bureau of Statistics. e Estimated.

Only the swelling type was used in well drilling and in pelletizing iron-ore concentrates. It was the predominant type used in foundries. The drilling market is principally in western Canada, and that for pelletizing is in eastern Canada. The foundry market is principally in eastern Canada.

Of the 63,000 tons consumed in 1961, only about 5,000 tons, or 8 per cent, were of the nonswelling variety. Thus, it is evident that Canada's requirements are predominantly for the swelling type. This preference became even more pronounced in 1963 and will continue to increase for the immediate future, at least. Virtually all this increase has resulted from the use of swelling bentonite in the pelletizing of iron-ore concentrates. Starting in 1955, Marmoraton Mining Co., Ltd. used bentonite for this purpose at its operations near Marmora, Ontario. Hilton Mines, Ltd., near Bristol, Quebec, followed in 1958. In 1963, the large plant of Carol Pellet Company began using bentonite at Labrador City, Labrador, as did Lowphos Ore, Ltd. near Capreol, Ontario. As indicated in Table 8, construction in progress and proposed for similar types of pelletizing plants could be completed within about two years by Jones & Laughlin Steel Corp., Boston township, Ontario; Wabush Mines, Pointe Noire, Que.; and Caland Ore Co. Ltd., Steep Rock Lake, Ontario. The Caland plant is to process the ore rather than the concentrate. Indications are that other major iron-ore producers will announce plans for pellet production in the near future.

Consumption in pellet production was 10,200 tons in 1961, about the same in 1962, and should triple in 1963 (Table 8). Assuming that bentonite remains competitive and is required in current percentages as a pelletizing agent, Canada's
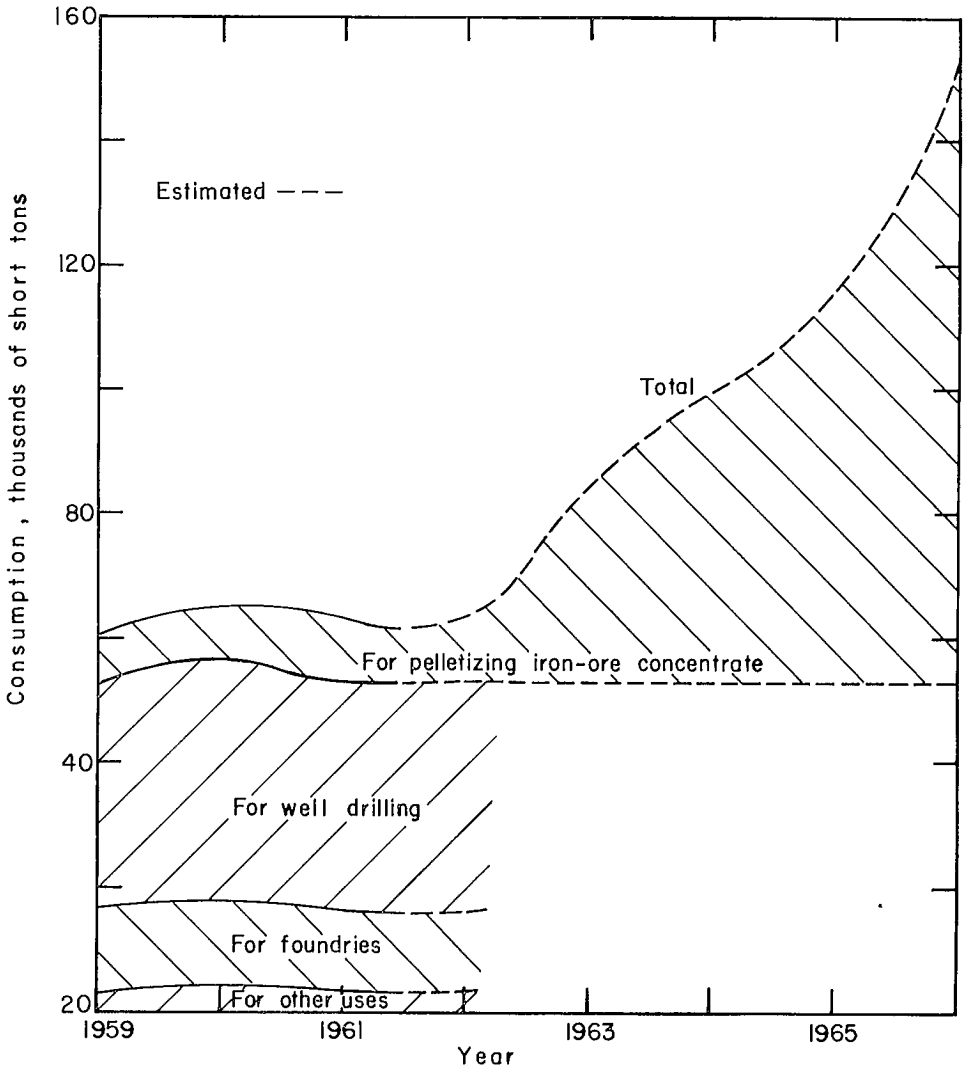
FIGURE 5. Current and predicted Canadian consumption, by use.

consumption for this use alone could be as high as 100,000 tons a year by the end of 1965 (see Table 8 and Figure 5). The total annual consumption would then be about 155,000 tons valued at some $5½ million at the consuming plant, about 97 per cent being of the swelling type. This extra requirement of 92,000 tons over the 63,000 tons consumed in 1961 must come from imports or from domestic production. All bentonite requirements for the pelletizing of iron-ore concentrates have, to date, been met from United States sources. Thus, a challenge and opportunity exist for the establishment of a high-quality Canadian source of swelling bentonite. To this end, the cooperation of the iron and steel and the iron-ore industries is essential. As demonstrated by preliminary laboratory tests, some

31

Canadian bentonites, with additives, have some pertinent properties at least equivalent to those required for equal amounts of 'standard' bentonite. Further testing is now being carried out by the Mines Branch.

TABLE 8

Iron-Ore Pelletizing Plants in Operation, under Construction, and Proposed

Company	Initial Date of Production	Rated Pellet Output per year (long tons)	Estimated Consumption Capacity of Bentonite (short tons)	
			1963	1966
Marmoraton Mining Co., Ltd., near Marmora, Ontario	1955	450,000	4,000	4,000
Hilton Mines, Ltd., near Bristol, Quebec	1958	800,000	6,000	6,000
Carol Pellet Company, Labrador City, Labrador	1963	5,500,000	23,000	41,000
Lowphos Ore, Ltd., near Capreol, Ontario	1963	600,000	1,500	4,500
Jones & Lauglin Steel Corp., Boston township, Ontario	1964*	1,000,000	—	7,500
Wabush Mines, Pointe Noire, Que.	1965*	4,900,000	—	37,000
Caland Ore Co. Ltd. Steep Rock Lake, Ontario	1965*	1,000,000	—	7,500
			34,500	107,500

*Scheduled date for initial production.

MARKETING, PRICES AND TARIFFS

Practically all the output of domestic bentonite is bagged. Major consumers, particularly those who import for pelletizing, receive almost all their supplies in bulk, usually in hopper cars. For those companies with large requirements, unusual transportation costs, or special requirements, shipments may be in the crude form with the clay partly dried and less than 2 inches in particle size.

Because of the lack of commercial bentonite deposits in certain parts of the world, such as in eastern Canada, bentonite can be shipped by rail or water great distances and still sold on an economic basis. For the swelling variety, the costs of transportation may be many times the cost of production.

Virtually all well-drilling bentonite is sold by the producer to service-supply companies which usually then re-sell it, f.o.b. wellhead, along with their mud-testing services, to drilling companies; most bentonite for foundry use is also sold by the producer to foundry-supply companies which distribute it to the consumer, whereas shipments for iron-ore pelletizing are normally arranged between the producer and consumer.

Prices vary with the type, quality and quantity involved. In 1962, the price of the bagged domestic drilling-quality bentonite fell from about $56 to $40 a ton at the well head in western Canada. Imported, bagged clay for drilling averaged

$27.87 a ton, up from $25.61 in 1961. According to United States trade statistics, the average value for bagged, Canadian activated clay exported to that country in 1962 was $37.01 a ton, down from $42.60 in 1961.

In the United States, car lots of bagged swelling bentonite cost about $14 a ton, f.o.b. mine, and from $7 to $8 a ton in bulk. Crude bentonite is cheaper, but its price is not normally quoted.

Canada's bentonite industry, which has yet to secure an appreciable share of the domestic foundry and pelletizing markets, has no tariff protection from foreign swelling bentonite and from some nonswelling bentonite. Basically, all non-activated bentonite is not subject to Canadian tariffs. Despite this lack of protection, mainly domestic bentonite is used by the Canadian well-drilling industry, primarily because Alberta producers are located comparatively close to their market. Such is not the case with the other main markets for non-activated bentonite.

Canadian and United States tariffs are given below.

	British Preferential	Most Favored Nation	General
Canada			
Clays, not manufactured further than ground	free	free	free
Activated clays			
For refining oils	10%	10%	25%
Not for refining oils	15%	20%	25%
United States			
Bentonite, per long ton			
Unwrought and unmanufactured	37½¢		
Wrought and manufactured	81¼¢		
Clays, artificially activated	⅒¢ per lb plus 12½% ad valorem		

OCCURRENCE

General

Usually bentonite is found in formations of Cretaceous age but it also occurs in rocks of other ages such as Ordovician, Devonian, Miocene, Eocene and Oligocene. In North America, the chief source is mainly in or near Upper Cretaceous formations. Most geologists have designated the main horizons in Wyoming and North Dakota as being in the upper part of the Lower Cretaceous, although some have placed them in the lower Upper Cretaceous.

Although bentonite occurs in many countries, it is mined extensively in only a few. However, mainly swelling and semiswelling bentonites are available in Algeria, Canada, Morocco, Orange Free State, Rumania, Russia, Spain, United States, Yugoslavia and Greece. Other bentonites are available in some of these countries as well as in Argentina, Australia, Britain, Chile, China, France, Germany, Hungary, India, Italy, Japan, Mexico, New Zealand, Peru, Poland and the State

of South Africa. The swelling bentonite deposits of the Wyoming-South Dakota region are recognized as the most extensive high-quality occurrences of this type in the world.

Although many theories of origin have been advanced for bentonite, most authorities agree that bentonite found interbedded with sediments originated from air-transported volcanic ash which was mainly deposited in quiescent or slowly flowing bodies of water. During and after deposition, the contained glass became at least partly devitrified and altered to hydrous silicates. Alkalies and silica were partly removed by leaching, and iron and gypsum were added. After induration the resulting deposit was altered further by weathering. Some deposits were displaced or moved by faulting, slumping and glaciation. Evidence for this theory includes bentonite's close association with volcanic ash deposits, its volcanic ash content and relict texture, its occurrence in thin uniform beds extending over large areas, and its preponderance adjacent to regions having a recent volcanic history.

This clay is occasionally found interlayered with glassy and non-vitreous volcanic rocks in such a manner as to suggest a different origin than these rocks, with subsequent alteration by processes similar to those described previously. Montmorillonite minerals are also products of hydrothermal alteration and are not known to occur as large deposits when of this derivation.

Bentonite outcrops, particularly those of the swelling variety, are unique and distinctive. Except along deeply eroded gullies, they are commonly the main or only visible outcrops. Bentonite outcrops commonly form cappings on prominent shoulders on hillsides. These features are indicated in Figure 6, and result from bentonite's resistance to non-glacial erosion. Rain penetration is very shallow because as the surface becomes wet it swells to form an impervious, sticky, adhesive

FIGURE 6. A 10-ft. thick bentonite bed of the Tertiary Ravenscrag formation immediately west of St. Victor, Sask. The bed caps this large shoulder which is truncated by the valley on the right and is part of a higher hill to the left of the picture.

34

coating that is extremely resistant to water erosion. The result is commonly a well pronounced horizontal shoulder, the top of which is almost completely bentonite. The sediments formerly overlying the bentonite have been removed by erosion whereas the underlying sediments have remained almost intact, protected by the overlying bentonite.

Bentonite commonly occurs in relatively thin, uniform, finely and well stratified flat-lying beds that extend over large areas, except where disturbed by erosion. A few deposits are lens-like and some are irregular owing to glaciation, faulting and slumping. Virtually all Canadian deposits are closely associated with volcanic ash.

Mainly because of continual swelling and shrinking, vegetation on bentonite outcrops is uncommon. In dry weather, the outer 6 to 24 inches is relatively granular, has a cauliflower-like surface and a highly porous texture owing to extensive shrinkage during drying (Figure 7).

FIGURE 7. Typical sun-dried surface of an outcrop of swelling bentonite.

This outer crust normally takes on a dried appearance quickly and is commonly buff to grey for swelling bentonite and a cream color for the high-quality non-swelling type. When wet, the surface is gelatinous, sticky, and extremely slippery. Regardless of the amount of surface moisture, the underlying bentonite is moist and

35

generally has a waxy appearance and either a shaley or conchoidal parting. It usually contains at least 30 to 45 per cent moisture.

United States

Because most of the world's bentonite is recovered from deposits in the United States, brief mention is made of the more important occurrences in that country.

The world's outstanding occurrences of the swelling type are in the Wyoming-South Dakota region. They are most predominant in northeast Wyoming, western South Dakota and in north-central Wyoming. About two-thirds of the United States production originates in Wyoming. More than 90 per cent of this comes from the Cretaceous Clay Spur bentonite bed at the top of the Mowry shale formation, although bentonite is common in other parts of the Mowry and overlying Belle Fourche shales. The bentonite beds are relatively flat lying, remarkably continuous over large areas, and up to 15 ft or more in thickness (35). The more noteworthy sections of the Clay Spur are normally 2½ to 4 ft thick. Better grades of this bentonite have a swelling index of more than 30 ml, a yield of more than 100 bbl/ton, a viscosity of more than 30 centipoises, and initial and 10-minute gel strengths of more than 30 and 60 grams, respectively, for a 6-per-cent clay slurry.

About one-sixth of the United States output comes from Mississippi and is mainly used for its adsorptive qualities. Most is recovered from the Upper Cretaceous deposits of Monroe county and the Eocene and Oligocene beds of Smith and Pearl River counties.

Bentonite of Eocene age outcrops over a large area of eastern Texas. The clay is mined chiefly for its adsorptive properties in Karnes, Jasper, Gonzales, Fayette, and other counties.

Californian bentonites are used chiefly for oil refining, principally from Inyo and Otay counties. A large deposit of the nonswelling variety occurs along Puerco Valley, Arizona.

Canada

The principal Canadian bentonite deposits are confined to western Canada where there has been abundant Mesozoic and Cenozoic deposition of volcanic dust that has partly escaped glaciation and other erosional processes. Montmorillonite has been identified in eastern Canadian formations but has not been found in sufficient concentrations to warrant serious economic interest. In general, the large western deposits are of Cretaceous and Tertiary age. In eastern Canada montmorillonite occurrences are commonly of lower Devonian age.

British Columbia

Incomplete records indicate that all British Columbia production came from deposits in the Princeton area from 1926 to 1944. In this district, bentonite is associated with coal of the Princeton group and is of Tertiary age. According to Spence (33), the bentonite generally occurs in two distinct beds between two lignite seams and is separated by a 4-in. lignite seam. Spence indicates that the top bed

36

is 11 feet thick and is brown in the top three feet and yellow in the remainder. The lower bed is yellow and three feet thick. These beds occur near Princeton, particularly in the workings of the former Princeton B.C. Colliery Company and of Princeton Coal and Land Company. They also outcrop between Princeton and Allenby, at and in the vicinity of the railway cut about a mile south of Princeton. Apparently most of the small production from this area was consumed in the refining of oil.

In 1952 and 1953, Princeton Properties investigated a 10- to 11-ft bentonite horizon on Lots 388 and 2049, immediately south of Princeton. Some samples from this horizon were of the swelling variety.

Ries and Keele (25) reported a 9-ft, light buff bed that is associated with lignite and occurs two miles south of Quilchena. Keele reported bentonite at Seventeen Mile House and in the Deadman River valley. Montmorillonite also occurs in the Quesnel area, and lower Upper Cretaceous bentonite has been traced intermittently for 250 miles in Glacier National Park. Undoubtedly there are numerous bentonite deposits in British Columbia that have not yet been recorded.

Alberta

Although bentonite in Alberta is common in formations of Cretaceous and Tertiary age, it is found in relatively thick deposits only in Upper Cretaceous rocks. With one exception, at Walsh, all noteworthy deposits have been found in the youngest (Edmonton) and second youngest (Bearpaw) Upper Cretaceous formations or their equivalents. The Walsh deposit is in the next youngest, the Oldman formation.

Beds of Edmonton bentonite have been found up to 30 ft thick. They commonly are in bentonitic shale, and grade laterally into bentonitic shale and clay. Volcanic ash often occurs in thin seams in the bentonite or near the bentonite contacts. Seams of carbonaceous material commonly occur along the contacts.

Although bentonite of the Bearpaw formation at Dorothy is up to 29 ft thick, it is usually less than 1 ft thick in other areas. However, it is relatively uniform and can often be traced for great distances. Volcanic ash commonly accompanies the clay.

Usually, Alberta bentonite is of the swelling and semiswelling types and has received the most attention to date.

The following descriptions of the more noteworthy outcropping deposits have been compiled by the writer from personal examination of most of the deposits. The reports of Russell and Landes (37), Allan and Sanderson (38) and Byrne (32) have been draw upon for data on the remaining deposits, particularly for stratigraphic interpretations. Locations are shown in Figure 8. There are many other such deposits in Alberta.

1.* *Rosalind*—The Rosalind deposits were recognized to be of major proportions about 1958 by Magcobar Mining Company, Limited. They consist of several zones of bentonite along and near the Battle River valley, about nine miles south

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*Numbers refer to locations on map in Figure 8.

of Rosalind. The host rocks are shale and sandstone of the Edmonton formation which, except for minor local folds, are practically flat-lying.
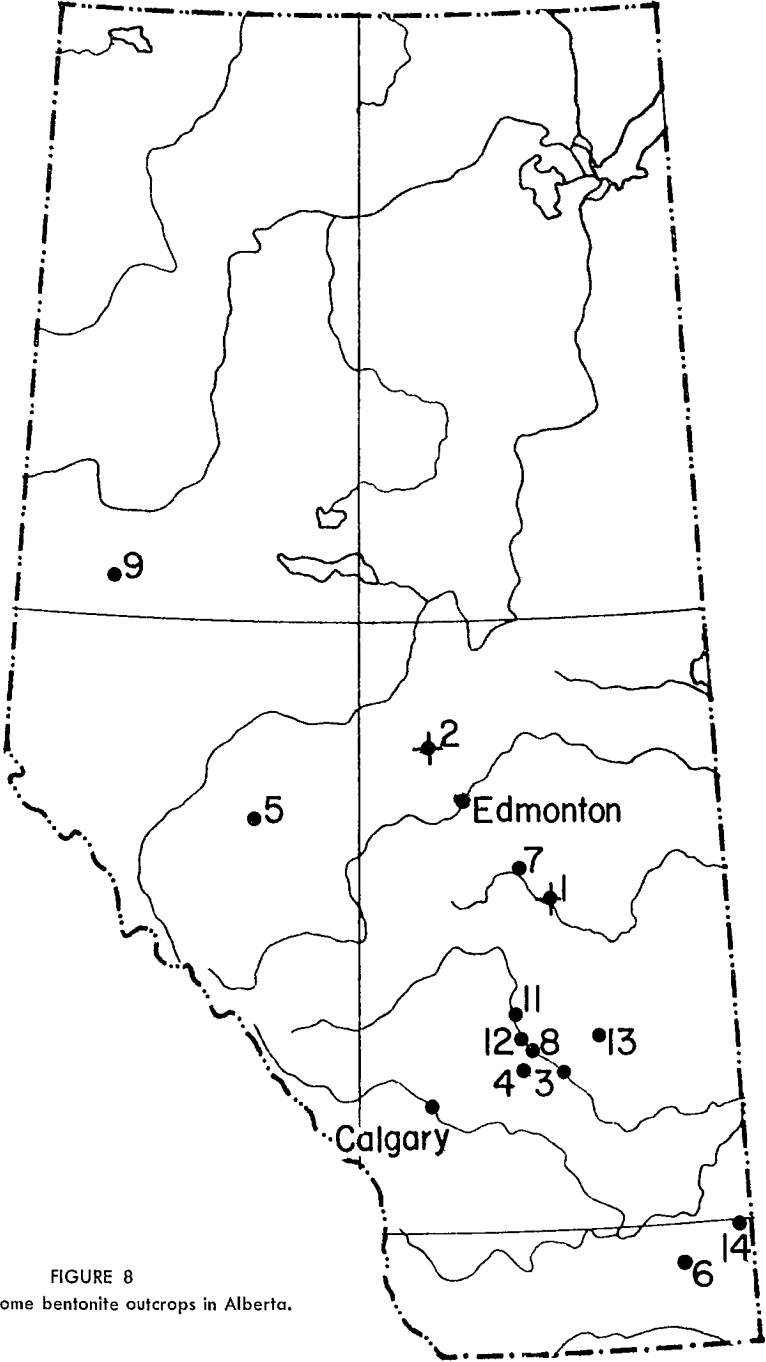

FIGURE 8
Location of some bentonite outcrops in Alberta.

38

The main zone is along the south side of the valley, in the north half of Sec. 31, Tp. 42, Rge. 17, west of the 4th meridian. It has been outlined for a width of 500 ft and for a distance of 3,600 ft along the valley. Magcobar Mining Company estimates a reserve of about 1 million tons. The bentonite is from 8½ to 10½ ft thick and is overlain by up to 25 ft of overburden (Figure 9). Individual seams are up to 1 ft thick, and when undried are greenish grey, greenish black and brownish grey. Small amounts of red iron oxide are present. This deposit is underlain by black carbonaceous shale.

FIGURE 9

Ten-foot main zone of Magcobar Mining Company Limited near Rosalind, Alta.; partly exposed and ready for mining (middle bench).

Other bentonite zones are in the immediate area of the main deposit. One is about half a mile to the north and, as reported by Magcobar Mining Company, contains about 300,000 tons of bentonite. In Sec. 19, Tp. 43, Rge. 17, west of the 4th meridian a 5-ft bed is said to contain more than a million tons of bentonite.

As with virtually all such deposits, bentonite characteristics vary laterally and vertically in each occurrence. This necessitates stringent quality control by detailed testing, and careful mining and blending.

2. *Onoway*—This deposit consists of a group of bentonite zones about 12 miles northwest of Onoway. It is mainly in the northwest quarter of Sec. 7, Tp. 56, Rge. 2, west of the 5th meridian, and part is owned and the remainder leased by Baroid of Canada, Ltd. Overburden varies from 2 to 50 ft, but averages 6 to 7 ft over the main zone being mined.

Believed to be part of the Edmonton formation, the bentonite is in scattered lenses up to 5 ft thick and averaging 2 to 2½ ft. It is bedded, has sharp contacts, and is greenish cream, changing to buff when dry. The various lenses are irregular vertically and horizontally. They generally are not continuous, hence exploration and development are difficult.

Incomplete estimates indicate a reserve of about 300,000 tons.

3. *Dorothy*—Tremendous tonnages of bentonite outcrop for several miles along both sides of the Red Deer River valley in the vicinity of Dorothy. The bentonite member is well defined and outcrops are clearly visible. It is mainly from 20 to 29 ft thick and although large tonnages have little or no overburden, the main deposit extends into the valley sides under deep overburden. The tops of the outcrops exhibit striking examples of erosion-resistant shoulders jutting out from near the base of the valley sides.

The deposit is in the upper Bearpaw formation, overlain by Edmonton sandstone and underlain by grey shale. It contains some sandstone and several narrow seams of volcanic ash. The bentonite varies from yellowish grey to greenish grey to steel grey and, when dry, is steel grey.

4. *Beynon*—Bentonite of the Edmonton formation outcrops along the Rosebud River in the southeast quarter of Sec. 32, Tp. 27, Rge. 20, west of the 4th meridian. It is 3½ ft thick and overlain by light overburden and a 2½-ft coal seam.

5. *Bickerdike*—An off-white bentonite bed of the Saunders formation (upper Upper Cretaceous) outcrops along the McLeod River in Sec. 6, Tp. 52, Rge. 18, west of the 5th meridian. About 1930, small quantities of bentonite were mined from this 7-foot-thick bed and used by an Edmonton firm in the manufacture of cosmetics.

6. *Bullshead Butte*—Bearpaw bentonite outcrops in the area surrounding the Cypress hills and is fairly well exposed around Bullshead Butte and Irvine. At the former locality in the northeast quarter of Sec. 2, Tp. 8, Rge. 7, west of the 4th meridian a 2-ft bed of buffish grey bentonite outcrops.

7. *Camrose*—Edmonton bentonite, averaging about 3 ft thick, outcrops along the creek immediately south of Camrose.

8. *Drumheller*—Several Edmonton bentonite beds outcrop near Drumheller. The main bed, 2½ to 3 ft thick, outcrops for a few miles along the Red Deer River and has been mined intermittently in the northwest quarter of Sec. 14, Tp. 29, Rge. 20, west of the 4th meridian. This bentonite horizon is overlain by bentonitic sandstone and underlain by dark brown shale.

9. *Grande Prairie*—In the southeast quarter of Sec. 27, Tp. 72, Rge. 4, west of the 6th meridan, about 12 miles northeast of Grande Prairie, bentonite up to 4 ft thick occurs in a number of lenses. It has been designated as part of the Wapiti formation, Upper Cretaceous age.

10. *Lynx Creek*—In the lower part of the Vimy member, lower Alberta group, Upper Cretaceous series, a bed of light cream and grey bentonite up to 4 ft thick has been observed along several rivers from south of Nordegg to near Crowsnest. The properties of this bentonite are not known.

11. *Morrin*—Edmonton bentonite outcrops along the sides of the Red Deer River valley in the vicinity of Morrin bridge, 5 miles west of Morrin. One bed is 5 ft thick and is yellow to steel grey. It is underlain by shale and tuff and overlain by shale and many tens of feet of overburden.

12. *Newcastle*—Silty bentonite of the Edmonton formation outcrops in the southeast quarter of Sec. 9, Tp. 29, Rge. 20, west of the 4th meridian. It occurs in beds up to 10 ft thick under light overburden.

13. *Sheerness*—A greenish buff bentonite varying from 1 to 5 ft thick occurs above the coal member at the property of Western Dominion Coal Mines. It is part of the Edmonton formation.

14. *Walsh*—In the southwest quarter of Sec. 28, Tp. 11, Rge. 1, west of the 4th meridian a 5-ft bentonite bed occurs, possibly in the Oldman formation. It is under light overburden and is buffish grey.

Saskatchewan

Saskatchewan also has many bentonite occurrences (Figure 10). The largest are in formations of Upper Cretaceous and Lower Tertiary age and occur in three
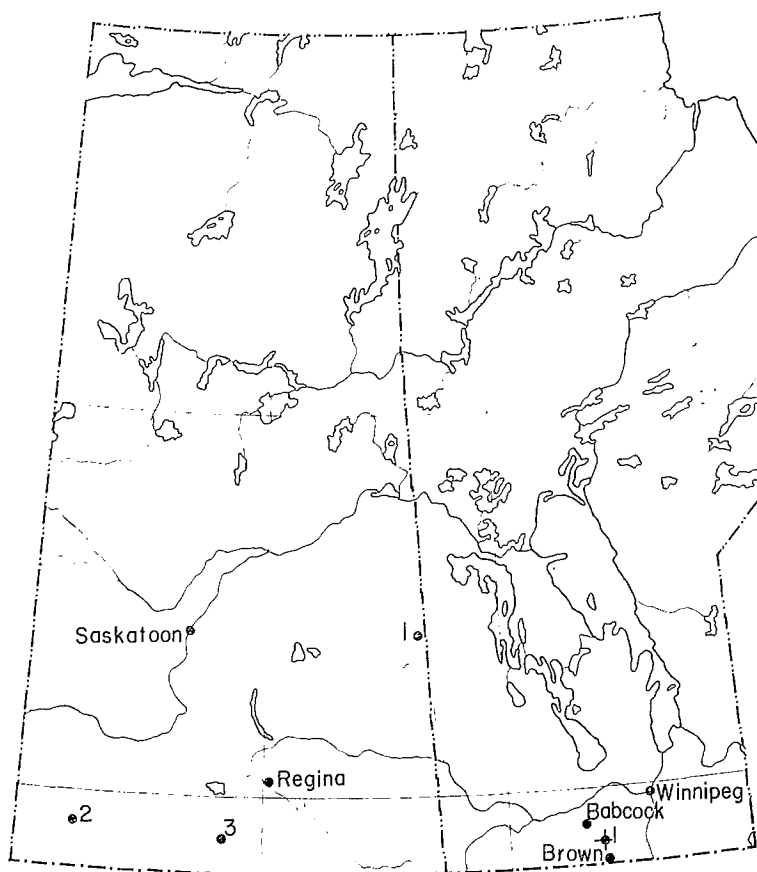

FIGURE 10

Location of main bentonite outcrop areas of Saskatchewan and Manitoba.

41

areas of the province, in eastern Saskatchewan near Pelly, in the south-central part near St. Victor, and in the southwestern part near Eastend. In general they are thinner and exhibit a lower swelling capacity than the larger deposits of Alberta.

1.* *Pelly*—Nonswelling bentonite occurs in the Pembina member, Vermilion River formation, Upper Cretaceous age, northeast of Pelly along the Swan River. It has a light yellowish buff color and one bed is about 2 ft thick. This member is folded and embedded in dark grey shale.

2. *Eastend*—Along the Frenchman River valley, particularly in the vicinity of Knollys, Eastend and Ravenscrag, an extensive horizon of Upper Cretaceous bentonite outcrops as the Battle formation. At Knollys, three seams of greenish grey bentonite have a total thickness of 11 ft. Worcester (31) estimates that the deposit contains at least two million tons of bentonite. In addition, a 6-ft bed occurs lower in the stratigraphic sequence.

3. *St. Victor*—Numerous large outcrops of Tertiary bentonite occur in the Ravenscrag formation immediately west of St. Victor and for many miles along valleys west to Twelve Mile Lake, north to Lake of The Rivers and southeast through the Big Muddy Valley to Montana. Overburden varies up to several tens of feet in thickness but considerable bentonite is available under less than 20 ft of overburden. The outcropping clay commonly has formed extensive cappings on the shoulders of hills, particularly near St. Victor. The exposed surface is buffish to steel grey but underlying bentonite is buff to greenish buff. Near St. Victor the horizon in places is up to 10 ft thick and contains two narrow seams of black carbonaceous material. Immediately west of Pickthall the main bentonite horizon is normally at least 7 to 8 ft thick. It contains narrow carbonaceous seams, one of which is up to 8 in. thick. The bentonite is underlain by a carbonaceous horizon that overlies bentonitic sandstone.

More than a million tons of bentonite have been outlined by Worcester (31) in the area lying 18 miles south of Pickthall, near Rockglen.

In Saskatchewan, Upper Cretaceous bentonite also outcrops near Macklin, Niedpath and elsewhere.

Manitoba

In this province, bentonite has been noted only in Upper Cretaceous formations. It occurs mainly near the base of the Pembina member of the Vermilion River formation and in the overlying Millwood member of the Riding Mountain formation. In addition, thin beds are in the Odanah member of the Riding Mountain formation and in the Favel formation. The host formations are invariably black shale.

The bentonite horizons of the Pembina and Millwood members outcrop at several places along the Pembina Mountain escarpment from Babcock southeast for a distance of 35 miles to the North Dakota boundary, and then westerly along the Pembina River valley (Figure 10).

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*Numbers refer to locations on map in Figure 10.

The lower Pembina member has been mined chiefly at two localities, the Miami pit, three miles southwest of Miami in the southeast quarter of Sec. 26, Tp. 4, Rge. 7, west of the principal meridian; and the Spencer pit four and a half miles farther southeast in Sec. 31 and 32, Tp. 3, Rge. 6. These areas are indicated by number 1 in Figure 10. In these areas, near and along the top of the escarpment, much of the overlying Pembina, Millwood and Odanah formations have been removed by erosion. Overburden formerly overlying the Miami pit was mainly 4 to 10 ft deep but the remaining overburden is much thicker, particularly to the west towards the top of the escarpment. Similarly, overburden at the Spencer pit used to be heavier than at the current faces. It currently varies in thickness from 10 to 15 ft to as much as 30 ft in places.

Although there are variations in thickness, the Pembina bentonite beds and interbedded shale are remarkably uniform for a clay and are sharply bedded. The log of the current south face of the Spencer pit is as follows:

Rock Type	Thickness
Bentonitic overburden	10-15 ft
Bentonite (marker)	3½ in.
Shale	3½
Bentonite	¾
Shale	2¼
Bentonite A	5¼
Shale	¾
Bentonite	6½
Shale	¾
Bentonite	4
Shale	¾
Bentonite	4¼
Shale	1
Bentonite B	1
Shale	¾
Bentonite	5½
Shale	1
Bentonite	3
Shale	

The shale is black and fragmental and the bentonite is soft and light yellowish cream or grey. The yellow color, which is more intense along fracture and bedding planes, is due to the presence of jarosite, a hydrous iron-potassium sulphate, a product of weathering. Bentonite is recovered from six beds by Pembina Mountain Clays including horizon Bentonite A and the underlying bentonite beds listed above, with the exception of Bentonite B. Consequently, at this location, a total thickness of 28½ in. of bentonite is being recovered from six beds over a total thickness of 34½ in. The average thickness recovered is about 30 in. over a total thickness of about 40 in. A section of the south face is shown in Figure 11.

Pembina bentonite has been noted in many other outcrops in southern Manitoba along the Pembina Mountain escarpment and the Pembina River valley. It also outcrops intermittently along escarpments and valleys to the northwest and

has been noted as far northwest as Sawmill creek and north of Pelley, Sask., about 250 miles northwest of Babcock. In general, the outcrops of this formation noted in the northwest do not contain as great a concentration of bentonite as those in southern Manitoba.

Millwood bentonite also outcrops along the Pembina River and the Pembina Mountain escarpment, as well as in the Riding Mountain, Duck Mountain and Porcupine Mountain area. In the southern areas, this formation is more than 50 ft thick. The section exposed in Sec. 25, Tp. 4, Rge. 7, west of the principal meridian, immediately to the northwest of the Miami pit, comprises the upper 58 ft 11 in. of this member and consists completely of bentonite.

FIGURE 11
South face of Spencer pit showing the light-colored bentonite interbedded with shale.
The lowest recoverable bed is not visible.   Sample book is 6¾ in. long.

The following description of this section is quoted from Bannatyne (30):

Description	Feet	Inches	Sample
Top of butte; overburden; fragments of Odanah shale....	3	0	
Bentonitic shale, greenish grey; 3 bands of green waxy bentonite, 1″, 1″, and ½″ thick; 1″ purple-stained hard ironstone band 6′ 6″ from top	9	10	A
Bentonite, olive green, waxy, pure	0	7	B
Bentonitic shale, greenish grey; some minor iron staining; ½″ ironstone band at base	8	11	B
Bentonitic shale, grey, darker weathering than above sections; more iron stained and several bands of ironstone each ¾″ to 1″ thick	11	5	C
Bentonitic shale, grey; contains brown ironstone concretions, some stained purple	12	3	D
Bentonitic shale, grey; selenite crystals in upper part; scattered brown and purple ironstone concretions	12	11	E
Millwood beds, basal section; covered by slumped material .... over 10			
Total Over	68	11	

In several areas, a thin greenish buff bentonite bed has been observed in, or immediately above, the top of the Millwood formation. East of Brown in Sec. 18, Tp. 1, Rge. 5, this horizon is 10 in. thick and exhibits semiswelling properties.

Although the Millwood formation in the western part of the province has not been analyzed in detail, it is known to be highly bentonitic in several places.

Bentonite also occurs in relatively thin beds in the Boyne member of the Vermilion River formation and in the Favel, Ashville, and Swan River formations in western Manitoba.

More detailed descriptions of Manitoba bentonite deposits have been compiled recently by Bannatyne (30).

Ontario

The first noteworthy recording of bentonite in Ontario was made in 1930 by Maddox (39) who examined clay from a well two and a half miles southeast of Collingwood. This clay, identified as 'bentonite', was reported to be "possibly several feet thick" at a depth of about 320 ft, and probably from the upper part of the Black River limestone, Ordovician age.

Since then, narrow montmorillonite-bearing clay seams of Ordovician age have been noted and used as geological markers. These have been traced from the Medonte-Coboconk area of central Ontario to the Toronto area and to southwestern Ontario. Forman and Lake (40) analyzed samples of the three most important seams. They also investigated samples from Pennsylvania and neighboring states, namely the Tioga 'bentonite' of Devonian age and an Ordovician 'bentonite'. The Canadian samples, marked A, B and C were respectively from the lower Lowville formation, upper Black River group; upper Lowville formation, and lower Rockland formation, lower Trenton group. Samples A, B, and C were

45

found to be mixed-layer aggregates with illite predominating. The Tioga clay was determined to be illite with some montmorillonite, and the other United States sample was illite with a trace of montmorillonite. Consequently, these clays are not true bentonites.

To the writer's knowledge, no clay from Ontario has been positively identified as bentonite by conventional methods.

Quebec

In 1946 Russell (41) described the bentonites in Member 7, lower Grande Grève formation of the Gaspé limestone series, Lower Devonian age. He noted at least twelve bentonite beds exposed at Cap Gaspé at the top of Forillon peninsula. The four thickest beds occupy the following positions stratigraphically above the base of Member 7: 8.0 to 12.4; 56.0 to 57.4; 157 to 158.4 and 162 to 163.8 ft. The base of Member 7 is near the bottom of the cliff at Cap Gaspé and the general dip is 24°SW. Thin seams of bentonite have also been reported from other parts of the Forillon peninsula. Smith et al. (42) found these clays to be largely mixed-layer minerals with illite and montmorillonite structures in random interstratification, along with quartz and feldspar. A number of minor mineral constituents are also present. Although insufficient data have been reported to determine whether this clay falls into the bentonite category, there is the possibility that it contains insufficient minerals of the montmorillonite group to be classified as such.

EXPLORATION

Very little exploration for bentonite has been undertaken in Canada and, until about 1960, not much was warranted. However, the situation has changed with the growth of Canada's requirements.

Compared with exploration for other commodities, bentonite exploration is simple and inexpensive because of the rock's stratigraphic occurrence and the current requirement for a surface or near-surface deposit. However, the laboratory testing that complements exploration is normally complex, and is necessary to determine potential uses.

Because about 94 per cent of Canada's consumption is of the swelling variety, and because the sole producer of the bleaching type is already capable of supplying a much larger Canadian market with a high-quality material, exploration should be confined to the search for swelling bentonite. Besides, much good-quality bentonite for bleaching is known to be available in the Pembina Mountain area of southern Manitoba. Further, the trend in Canada is towards increasing the requirements for the swelling type to about 97 per cent of total consumption. Semiswelling bentonite may share this market to a small extent.

Without performing swelling tests, it is difficult and usually impossible to determine in the field whether a bentonite is of the swelling or semiswelling type. Usually the nonswelling variety is off-white or light buff, whereas swelling bentonite is greenish buff in the undried state. Clays with greater swelling capacities produce a more pronounced mud-cracked, or popcorn, outcrop surface in dry

weather. Depending on the type of exploration program, it is usually preferable to test bentonites at least for their swelling properties before dismissing them as being of no further interest.

In view of current conditions of easily available, adequate sources of supply from the Untied States, a bentonite deposit, to be operated economically should be easily accessible to rail or water transportation and be at or near surface for easy exploitation. Depending on accessibility and depth of overburden, the minimum mineable thickness for a swelling bentonite deposit is in the order of 3 ft. Pembina Mountain Clays recovers nonswelling bentonite from six separate beds over a total mineable thickness of about 30 in. Overburden more than 25 ft deep has been removed commercially.

Exploration should first be directed towards formations known to contain swelling or high-quality semiswelling bentonite. To date, the largest swelling and high-quality semiswelling deposits have been found in the Edmonton formation in Alberta. In British Columbia, Tertiary deposits near Princeton, and in Saskatchewan, the Ravenscrag formation, are of interest. The Millwood formation is the most promising horizon in Manitoba for this type. In particular, the bed at or immediately above the Millwood should be explored. In the few places where it has been noted, it occurs as a thin horizon, but possibly greater thicknesses can be found. The remainder of the Millwood formation comprising mainly a large thickness of bentonite, also warrants further attention not only because of its large size, but also because it is closer than many main sources to the principal non-well-drilling markets in both Canada and the United States. Transportation to these markets is a major item in the cost of bentonite. Manitoba is closer than Wyoming to the main Canadian market and to a large United States market area.

Bentonite exploration is basically a matter of recognizing and discovering favorable stratigraphic horizons and prospecting and sampling these when warranted. Before production, promising deposits require thorough sampling by the removal of auger or core samples. Bentonite deposits normally vary at least slightly in quality both vertically and laterally. Detailed sampling followed by laboratory testing therefore are essential to determine the quality of a deposit. Test drilling for exploration purposes is often done at intervals of 100 ft or more and that for development is normally carried out on a 50- to 100-ft grid.

MINING AND BENEFICIATION AT CURRENT OPERATIONS

Mining methods are governed by the distribution of the various bentonite grades in a deposit, whereas beneficiation or mill methods depend on the end uses of the products.

Mining is carried out by the stripping method, and though relatively inexpensive, requires strict supervision to ensure quality control. As a rule, bentonite deposits cannot be worked efficiently in wet weather or when they are wet, because of their very slippery nature and the resulting insufficient traction for conventional equipment. Well-drained Canadian bentonite deposits are worked during periods of dry, warm weather, whereas poorly drained deposits are usually mined in cold

weather. Consequently, Canadian operators recover and stockpile as much bentonite as possible during dry warm periods or in cold weather.

Because of different basic end uses, bentonite produced in Alberta is processed in a different manner from that currently produced in Manitoba. Beneficiation for the usual swelling bentonite applications is not complex, but that for bleaching clays is an involved, partly chemical, process. To obtain particular properties in a semi-swelling bentonite, additives may be introduced during milling.

Magcobar Mining Company, Limited

This company, a subsidiary of the Magnet Cove Barium Corporation, started operating its $400,000 processing plant, beside the Camrose-Alliance line of Canadian National Railways, at Rosalind, Alberta in March, 1959. The main bentonite deposit is about nine miles south of Rosalind along the south side of the Battle River valley in Sec. 31, Tp. 42, Rge. 17, west of the 4th meridian.

Overburden from this deposit, usually from 15 to 25 ft thick, is removed and transported into the valley by bulldozers, front-end loaders, trucks and other earth-moving equipment. The deposit is then further sampled in detail by auger holes. After laboratory testing of the samples, strip and open-cut mining are undertaken by dragline. Bentonite is recovered by carefully keeping the various qualities separate. It is trucked to the plant and spread evenly over the flat top of the appropriate stockpile. Each stockpile contains the raw material necessary for a specific type of end-use. Stockpiles are usually sampled by vertical auger holes. At this stage, the clay contains about 30 to 40 per cent moisture. However, it undergoes air drying to about 26 per cent moisture in the stockpile.

The clay is recovered from stockpiles in vertical scoops by a front-end loader to ensure uniform blending and quality. It is reduced to minus 2 in. by a slicer and then conveyed to a 60-ft gas-fired rotary dryer. Although the dryer temperature ranges from about 800° C at the inlet to 100° to 200° C at the outlet, this crucial operation is carefully controlled so that the bentonite reaches a maximum temperature of only about 120° C. This reduces the moisture content to about 10 per cent without decreasing the swelling properties.

The dried product is collected in a bin and fed to a Raymond high-side roller mill equipped with a flash dryer. The milled product is removed by a Whizzer air separator to a cyclone and discharged to a storage bin. The products, usually 8

Bentonite products shipped from Magcobar Mining Co. Ltd., and their principal uses.

Product	Principal Current Application
Arrowhead A	Stock-feed pelletizing
Arrowhead B	Stock-feed pelletizing
Arrowhead M	Well drilling
Auto-Bond	Foundry
Beaver-Bond	Foundry
Flameout	Fire retardant
Kwik Thik	Seismic testing
Magcogel	Well drilling
Magcogel #5	Well drilling

to 10 per cent plus 200 mesh in particle size, have moisture contents varying from 5 to 9 per cent, depending on the specific application. Most of the production is bagged in 100-lb bags. Plant capacity is 10 tons of product an hour.

Most of the production is used in well drilling.

Baroid of Canada, Ltd.

Baroid of Canada, Ltd., a subsidiary of National Lead Company, Baroid Division, began operating a well-equipped bentonite processing plant at Onoway, Alberta, in January, 1960. This company owns and controls leases on deposits about 12 miles northwest of Onoway and is currently operating pits in the northwest quarter, Sec. 7, Tp. 56, Rge. 2, west of the 5th meridian.

The deposits are initially sampled by auger holes on centres of 25 ft or greater. To facilitate traction during mining, these low-lying deposits generally are worked only after the November freeze-up. Overburden, averaging 6 to 7 ft thick, is stripped off by earth movers. The bentonite is ripped, and recovered by means of a scraper and a front-end loader and then transported by trucks to stockpiles at the plant. The clay is spread evenly over the stockpiles and sampled when required. It contains from 45 to 50 per cent moisture but loses some of this moisture during the summer months while stockpiled.

For processing, bentonite is removed from stockpiles in vertical scoops by a front-end loader and transferred to a hopper. From there it passes through a slicer and is then fed to a gas-fired rotary dryer. The temperature in the hot zone of the dryer is about 480° C and the bentonite is kept at less than 150° C at all times. Two passes are required to reduce the high moisture content to 6 to 9 per cent. The dried clay is conveyed to a Williams high-side roller mill equipped with an air separator. Here it is reduced to about 90 per cent minus 200 mesh. When required, additives are also fed to the pulverizer. The plant is well equipped with dust collectors in series with the dryer and pulverizer. Rated output is 6 tons an hour and most of the output is marketed in bags.

Baroid of Canada markets bentonite under the following trade-names and principally for the uses cited:

Product	Principal Current Application
Albertabond	Foundry
Aquagel	Well drilling
Can-Gel	Well drilling

The bulk of this plant's output is sold for use in well drilling but some is marketed for foundry use and stock- and foundry-feed pelletizing.

Pembina Mountain Clays Ltd.

This company produces natural, nonswelling bentonite from a plant at Morden, Manitoba, and activated bentonite from a plant at Winnipeg. When incorporated in 1940, Pembina Mountain Clays Ltd. began exploiting the Spencer

deposit in Sec. 31 and 32, Tp. 3, Rge. 6, west of the principal meridian. From 1954 to 1960 it mined the Miami deposit in Sec. 26, Tp. 4, Rge. 7. Its current mining operations are mainly at the Spencer deposit, 11 miles by road northeast of Morden. Mining is seasonal and is undertaken during warm, dry weather.

An area is outlined for mining by careful drill-sampling and laboratory testing. Then the 10 to 30 ft of overburden is removed by bulldozer to expose the top or marker, bentonite bed. Smaller tractors, equipped with scrapers, carefully remove the remaining foot or so of clay and shale down to the top of the upper mineable bentonite bed. Each of the six mineable bentonite beds and the interbedded shale is recovered separately and in the same manner. Each bed is relatively thin, with the six recoverable beds representing a total thickness of about 40 in. However, by closely supervising its mechanized mining operation, the company recovers a high-quality bentonite.

Each bed is scraped into windrows by the small tractors and conveyed thence by a self-propelled loader into trucks. The bentonite is hauled to a stockpile at the company's Morden plant, but the interstratified waste is removed to a disposal area. This crude bentonite contains up to 45 per cent moisture at the pit but is commonly air-dried in the stockpile to 35 to 40 per cent.

At the Morden plant, which is adjacent to a Canadian Pacific Railway line, the crude clay is dried and crushed at the rate of 4 tons/hr. Bentonite is scraped into a grizzly and, after falling into a hopper, is conveyed to a bin inside the plant. From there it is fed to a dispersion dryer heated by a coal-fired furnace where the moisture is reduced to about 20 per cent. The final particle size is less than ¼ in. The clay is blown into a cyclone and then conveyed to a storage area to await shipment by rail to the Winnipeg plant. Some bentonite is further dried, reduced in size by a hammer mill, and sold in bags for use at foundries, in insecticides, in pelletizing animal and poultry feeds, and occasionally for decolorizing fats, tallows, and mineral oils.

These products, which vary in particle size from about 80 to 90 per cent minus 200 mesh, are listed below:

Product	Principal Current Application
Filtaclay 75	Feed pelletizing
Pembond	Foundry

The company produces activated clay from its Winnipeg plant. Bentonite is leached by dilute sulphuric acid and washed, filtered, dried, pulverized and bagged. The process is mainly a chemical one and requires close control and a substantial number of processing stages.

Various grades of activated bentonite are produced at the plant and sold under the trade names Pembina Mineral Oil Clay and Pembina Vegetable Oil Clay. The former is used essentially for bleaching mineral lubricating oils and waxes, for re-refining used lubricating oils, and occasionally for decolorizing animal fats and tallows. The principal use of the latter is to decolorize such vegetable oils as linseed, soyabean and rapeseed and to decolorize animal fats, tallows and beeswax.

50

Carol Pellet Company

In May, 1963, Carol Pellet Company commenced milling imported bentonite at its new plant at Labrador City, Labrador. The product is used captively in the pelletizing of iron-ore concentrates.

The feed consists of partly crushed and dried bentonite about minus 2 in. in size. It is simultaneously dried and ground in a Raymond roller mill equipped with an oil-burning furnace. The product contains about 8 per cent moisture and is approximately 80 per cent minus 325 mesh. It is air-conveyed to a cyclone for storage or used directly in the pelletizing plant. Production is about 20 tons/hr.

RESERVES AND RESOURCES

Operators do not customarily develop or determine in detail large reserves of bentonite. In general, they usually explore and outline sufficient bentonite for up to 10 years' operation and then thoroughly test and develop a two or three years' supply. Consequently, because Canada's production is relatively small, only small, thoroughly defined reserves appear in estimates.

To date, Magcobar Mining Company has estimated reserves of 2.3 million tons of swelling bentonite in the Rosalind, Alberta, area. Estimated reserves at part of the Onoway swelling bentonite deposits of Baroid of Canada may be about 300,000 tons. The reserves of Pembina Mountain Clays nonswelling clay are not known although the productive horizon underlies large areas of southern and south-western Mantioba. Subbentonites occur in abundance particularly in many parts of Alberta, Saskatchewan and Manitoba. They generally contain a high proportion of montmorillonite-group minerals and minor impurities.

Sufficient Canadian reserves of swelling and nonswelling bentonite are available to meet this country's current requirements of the domestic product for at least several decades. Two of the principal bentonite markets in Canada are the foundry and iron-ore pelletizing industries. Part of the former is supplied by a domestic product, whereas the latter is wholly supplied by imports. Although the use of Canadian bentonite in foundries will increase in proportionately greater amounts than that of the imported type, bentonite reserves will scarcely be affected in the long term. The rate by which currently outlined reserves could be depleted by an iron-ore pelletizing market is unknown but would depend on the extent to which the clay is accepted by this industry.

LABORATORY INVESTIGATION

Numerous methods of laboratory investigation are available for bentonite. This section describes some of the more common tests. Within limits, these tests may be varied to meet particular applications. It must be realized that such laboratory procedures are only guides in determining the quality of a bentonite for an industrial use. The actual application of a clay in an industrial process is ultimately necessary to determine its suitability.

51

The following discussion is based on the assumption that the bentonite has been milled and partly dried.

Mineralogical—Standard X-ray methods are the only direct means of determining the approximate proportion of montmorillonite-group minerals and of other minerals or impurities in a bentonite. This analysis may not indicate the type of bentonite but it will indicate what impurities are present and whether they occur in amounts that could adversely affect the quality. Standard X-ray diffraction and X-ray powder photography analyses may be used. Various treatments such as ethylene glycol saturation, acid leaching, and heat treatment may be employed prior to X-ray analysis.

Chemical Analysis—Chemical analyses are rarely made except for bentonite used in the food industry or for decolorizing purposes. For these applications, the following constituents are determined: total acidity in terms of sulphuric acid, silica, alumina, ferrous and ferric oxides, titania, magnesia, calcium oxide, sodium oxide, potassium oxide, arsenic, lead, zinc, copper and free sulphur.

Drying—Owing to the relatively large amount of water that can be absorbed by bentonite, the clay should be dried before most test work to ensure accurate and comparative results. The temperature should be 100° to 105° C and the period of drying would depend on the size of sample.

Moisture—Knowledge of the free-moisture content is important because it affects handling and the actual amount of bentonite in a sample. Because of bentonite's hygroscopic nature, its natural moisture content is high. Moisture may be determined by calculating the total loss in weight of about 100 grams of material at a temperature of 100° C for a minimum of four hours.

Differential Thermal Analysis—This test is used to assist in the identification of clay minerals and in determining thermal properties. It is a comparative method and requires substantiation by other tests, particularly those relating to mineral identification. Differential thermal analysis consists of determining the temperature differences, on heating, between a reference sample and the clay sample. The resulting graph of relative endothermic and exothermic reactions is compared with standard graphs.

Particle-size Distribution—This test is normally carried out by the producer rather than by the consumer. It consists of the standard Ro-Tap method with screening carried out for 30 minutes or, for coarse bentonite, for a shorter period. The bentonite must be dried and cooled before testing. For more accurate results, particularly when comparing a number of finely divided samples, the Alpine air jet sieve is of great assistance.

Sand Content—Knowledge of the sand content is desired for muds used in well drilling. One hundred grams of dried bentonite are added to 1,000 ml of distilled water and vigorously stirred by a high-speed mixer for 10 minutes. After standing for two hours, the mixture is again stirred for 5 minutes and wet-screened with a 200-mesh sieve. The oversize is washed on the screen with a water spray, dried, and weighed. The per cent oversize (plus 200 mesh) is regarded as the sand content.

Surface Area—Although more direct tests are normally made, specific surface-area measurements may be employed as one of the means of measuring the adsorptive power of bentonite. Preferred methods of determining surface area are the Lea and Nurse, or the Goldstick methods using nitrogen as the gaseous medium.

Swelling—The swelling test is a rapid, easy and fairly accurate method of determining an important bentonite property. Two grams of dried bentonite are added in 0.1-gram lots to a 100-ml glass graduate filled with distilled water. Each addition is made as soon as the previous one has settled and the volume of gel is recorded one hour after the last portion has been added.

Colloidal Content—This test is a simple and useful method for indicating the relative proportion of sodium-based montmorillonite in a sample. It indicates the quantity of gel that can be produced from a given amount of sample. Ten grams of clay are mixed for 20 minutes with 500 ml of distilled water and the mixture poured into a glass graduate and allowed to settle for 24 hours. After decantation, the residue is dried and weighed. The weight loss in per cent represents the colloidal fraction.

Rate of Stabilization—The period required for bentonite to reach stability under the conditions imposed is herein designated as the 'rate of stabilization'. This period is directly proportional to the immiscibility of bentonite and a liquid, and to the rate of adsorption and absorption of this liquid by the clay. It is an extremely important consideration in industrial application, particularly, for example, where maximum viscosity or maximum strength is required in the short period of a few minutes. Because it may be important to know at any time the yield, gel strength, yield value, and apparent and plastic viscosity, the tests for these properties are commonly conducted at various intervals or at the end of one specific interval. For instance, the gel strength attained in a few minutes has a direct bearing on the effectiveness of a bentonite in pelletizing or in foundries, but is of no consequence in well drilling. The rate of stabilization is one aspect that is commonly overlooked during preliminary testing but its effect becomes evident when strength tests are performed.

Apparent Viscosity—Apparent viscosity is the ratio between the shearing stress applied to a fluid and the rate of shear that is produced. It represents the resistance of a fluid to change in shape or motion. This property is important in most of the applications for swelling bentonite. Viscosity tests indicate the maximum viscosity that can be obtained with a given amount of bentonite. They are also used to determine the percentage of bentonite required to produce a fluid of a desired viscosity for any aging period. Apparent viscosity may be measured by various instruments but the Stormer or Fann V-G meter viscometer is most commonly used. The details of operating these instruments are not described here.

Plastic Viscosity—Plastic viscosity is the ratio of the shearing stress minus the yield stress to the rate of shear. This property can also be measured by the Stormer or Fann viscometer and is of assistance in determining the characteristics of a swelling bentonite. With a Fann viscometer, plastic viscosity is equivalent to the difference between readings at 600 and 300 rpm.

53

Yield—Yield is the number of barrels of mud having an apparent viscosity of 15 centipoises that can be produced from one ton of clay. It is used mainly by the well-drilling industry to indicate the maximum viscosity that a definite amount of clay can produce and thus to determine the economics in using a particular clay. The yield of a clay may be determined with a Stormer or Fann viscometer. It is converted to barrels from a determination of the percentage of clay required to obtain a viscosity of 15 centipoises.

Yield Value—The yield value is the minimum shearing force that can create flow. It is closely related to the coefficient of thixotropy and is regarded by some as a direct measure of the plasticity of a material. This value is measured after a designated period by a viscometer and is equivalent to the difference between the reading at 300 rpm and the plastic viscosity.

Gel Strength—Gel strength is proportional to the shearing force required to disturb the thixotropy of a gel. This property varies directly with thixotropic strength and is commonly determined with viscometers for various periods. It is determined mainly for well-drilling purposes but is of importance for some other uses, particularly where bonding and pumping are involved.

Wall Building—Wall-building or filtration tests are used by the well-drilling industry to determine the relative thickness of solids deposited on well walls and also to indicate the relative fluid loss. This test involves the use of a standard filter press normally at a pressure of 100 lb/sq in. for 30 minutes. For oil-base muds, pressures up to 1,000 lb/sq in. are used.

Hydrogen-ion Concentration—Commonly, swelling bentonites are employed in aqueous mixtures having a pH, or hydrogen-ion concentration, of 6 or more. For some purposes, a pH of more than 12 is required. The pH influences the properties of bentonite, particularly its thixotropic or bonding properties. This property may be determined for a given clay-water mixture by using a glass-electrode pH meter.

Liquid Limit—The liquid limit is an expression of the bonding property of bentonite. It is the minimum weight per cent of moisture that will cause a bentonite-water mixture to flow when jarred in a prescribed manner. This property varies directly with the thixotropism of a mixture and is most commonly used in testing bentonite for foundry purposes. Plastic limit and plasticity index, which are related to the liquid limit, may also be determined but are not discussed further.

Compressive, Shear and Tensile Strength and Deformation (Foundry)—In foundries, green compressive, shear and tensile strengths as well as green deformation and dry compressive strength of sand-clay molding mixtures are extremely important. These properties are determined by mixing the various proportions of bentonite and water with standard molding sand and comparing the results with standard mixtures. The bentonite and sand are mixed dry and then wet for definite periods and finally formed into cylindrical specimens 2 in. in diameter and 2 in. high. These specimens are then tested for strength and deformation. The green compressive strength is the maximum compressive stress that the green specimen can sustain as determined with the use of a standard compressive apparatus. The dry compressive strength is obtained in the same manner by drying at 105° to

110° C. Shear strength is the maximum compressive strength resulting from the application of a load to diametrically opposite halves of the two plane specimen surfaces. Green tensile strength is determined by a different apparatus which subjects the specimen to tensile stress. Deformation is tested by employing a compression apparatus equipped with a deformation arm.

Iron-ore-pellet Strength Tests—These tests include green drop; green, dry, and fired compressive strength and deformation; and tumble determinations on iron-ore pellets. The former involves dropping each of ten freshly formed pellets a distance of 18 in. on to a steel plate until it breaks. The drop number is the average number of drops before breaking. Green, dry and fired compressive strengths may be measured with a standard foundry compression apparatus equipped for pellets or with a specially designed pellet tester. Pellets are dried at 105° to 110° C for dry testing, and heated to about 1,290° C and then cooled for fired-strength determinations. One tumble test involves tumbling at 25-lb sample of plus 3-mesh pellets in an ASTM coke tumbler for 200 revolutions at 24 rpm. The percentage of product that is minus 3 mesh and plus 10 mesh after 3 minutes of screening on a Ro-Tap, is designated as the 'tumble index'.

The main problem in this test work is to consistently produce pellets that are uniform in quality. This is accomplished by a complex and delicate process of producing 'seed' pellets from the concentrate, feeding them to a rotating rubber aircraft tire, and then adding a pre-mixed, moist, mixture of concentrate and bentonite.

Decolorization—Decolorizing or bleaching tests are normally made on artificially activated clays, although naturally active clays are sometimes investigated. Test procedures vary with the consumer and also with the type of fluid to be bleached. For mineral oils, one test involves heating and mixture of oil and 4 per cent bentonite to a temperature of 230° C in 15 minutes and then filtering the cooled product. The filtration time is noted and the filtrate transmittance measured with a colorimeter. Test results are compared with those determined for a standard bentonite.

Cation-exchange Capacity—Although this property can affect viscosity, it is not commonly required by most industries because more direct test methods are available. It is, however, an important property in evaluating bentonite for decolorization uses. Several methods may be employed. One involves the adsorption of methylene blue and the result is given as milliequivalents adsorbed per 100 grams of bentonite.

PROPERTIES OF SOME CANADIAN BENTONITES

A summary of the general properties of some Canadian bentonites is presented in this section. Detailed information on the properties of many Canadian bentonites will be made available in the near future. This will include results from research conducted at the Mines Branch during the last few years.

Canadian bentonite is being used for all main purposes except iron-ore pelletizing and steel-foundry use, although occasional small shipments have been made

to steel foundries. Canada's producers market bentonite for well drilling; iron foundries; decolorizing vegetable, mineral and animal oils, and other fluids; pelletizing poultry and animal feeds; plasticizing ceramic mixes; sealing reservoirs; suppressing forest fires; seismic testing; paints; and for cemeting oilwells. Other uses, such as deodorizing, will no doubt develop as the domestic producers continue their efforts to capture more of the Canadian market.

The following tables list a few of the properties, mainly of commercial domestic bentonites, to indicate the varieties that are available. These properties were determined by test procedures mentioned in the preceding section.

TABLE 9
X-Ray Diffraction Analyses of some Canadian Bentonites (43)

Sample		Major Crystalline Constituents	Intermediate Crystalline Constituents	Minor Crystalline Constituents
Alberta	1	montmorillonite	cristobalite	Quartz, hydrous mica, plagioclase, calcite
	2	montmorillonite	cristobalite	hydrous mica, quartz, plagioclase, calcite
	3	montmorillonite		plagioclase, cristobalite, quartz, calcite
	4	montmorillonite	cristobalite	plagioclase, quartz, calcite
Manitoba	1	montmorillonite		jarosite, quartz, potash, feldspar
	2	montmorillonite	quartz	calcite, potash, feldspar

TABLE 10
Properties of Some Canadian Swelling Bentonites

Sample	Swelling Index (ml)	Colloidal Content (%)	Yield, 25°C (bbl/ ton)	Initial Gel Strength, 6% slurry, 25°C (lb/100 sq ft)	Liquid Limit	Green Compressive Strength (psi)	Green Tensile Strength (oz/sq in.)	Dry Compressive Strength (psi)
1	23	77	97	14	—	—	—	—
2	24	73	105	10	—	—	—	—
3	15	55	48	1	—	—	—	—
4	18	78	111	10	—	—	—	—
5	16	81	105	1	632	10.2	26.0	104
6	13	64	60	1	337	11.4	27.8	95
7	22	73	59	1	578	11.1	32.4	139

TABLE 11
Properties of Some Canadian Nonswelling Bentonites

Sample	Swelling Index (ml)	Colloidal Content (%)	Yield, 25°C (bbl/ ton)	Initial Gel Strength, 6% slurry, 25°C (lb/100 sq ft)	Liquid Limit	Green Compressive Strength (psi)	Green Tensile Strength (oz/sq in.)	Dry Compressive Strength (psi)
8	3	9	18	9	137	14.1	34.6	51
9	6	4	21	9	133	13.0	34.8	84

After leaching with sulphuric acid for 1 hr—

	Filtering Time (min.)	Transmittance (%)
Sample 8	2.0	92
Sample 9	2.1	96

TECHNOLOGY AND POSSIBLE EFFECTS

Blast-furnace technology has advanced tremendously in the last five years and indications are that the technology of blast-furnace feed and operation will continue to increase notably in the near future. Current technology has provided a large new market for bentonite in this field but the requirements for bentonite per ton of iron-ore concentrate appear uncertain after the next decade. Bentonite is a chemical contaminant in iron-ore-concentrate pellets and, depending on the extent of application, adds about ¾ per cent more total impurity or about ½ per cent silica to the product. This represents considerable chemical contamination to an iron-ore concentrate containing only 2 or 3 per cent silica. Consequently, scientists will attempt to find methods for decreasing the proportion of bentonite.

Pellets can be produced without binders other than water, but to date the mechanics and economics involved appear unacceptable to the producers of natural iron-ore pellets. With better mixing and longer periods of contact with moisture, less bentonite could be used at some plants.

Some bentonites closely approach their maximum effectiveness in a few hours or less when agitated in an aqueous slurry, but others require longer periods of contact with moisture. Thus, any dried bentonite (containing about 8 per cent moisture) added to a moist iron-ore concentrate is not going to immediately attain its maximum efficiency in the green state when roughly mixed for only a minute or so. Even if it were throughly mixed and dispersed in the concentrate, and depending on the period required for pelletizing, it is doubtful whether any dry, swelling bentonite would reach its maximum efficiency prior to, or during, the green-pellet formation. Consequently, to obtain the required results, the practice is to add dry bentonite, a chemical contaminant, in excess of that needed under ideal conditions. Bentonite could be used more efficiently in an aged slurry that has reached its maximum thixotropy, viscosity and gel strength before application. This would apply mainly to plants where bentonite is not required for the adsorption of excessive moisture. Better mixing facilities would also improve the effectiveness of this clay.

Thus, when the properties of bentonite are given more consideration, this

57

commodity will probably be used more efficiently with a net decrease in the proportion required per ton of concentrate. Then bentonite from more sources will have the opportunity to compete economically. This will apply particularly to some of the Canadian bentonites which generally require relatively longer periods in contact with water to reach maximum efficiency. With longer water-contact periods, a few Canadian bentonites possess gel and viscosity properties equivalent or superior to those required for the pelletizing of iron-ore concentrates. However, these are not the ultimate criteria for this application.

Other binders are possible substitutes for bentonite in iron-ore concentrate pellets. These include lime, limestone, coal, some sodium salts, asbestos fibres, starches, gums, lignin sulphonates, and synthetic organic compounds. Most of these, when used by themselves, are considered to be either too expensive or not sufficiently effective.

There is the distinct probability that less bentonite will be tolerated as a binder, in view of the inevitable production of self-fluxing pellets in at least some pellet plants having a cheap source of supply of high-quality lime or limestone.

Relatively recent technology in the use of various drilling fluids has initiated a minor trend towards the use of other media. Under some conditions, petroleum products and gases are used as substitutes for bentonite. Air, in particular, will replace aqueous-bentonite media to some extent in arctic and arid regions.

It is difficult for natural bentonite to compete as a catalyst against artificial catalysts and attapulgite. Artificial catalysts can be produced in a number of grades to suit most individual requirements. Both artificial catalysts and attapulgite can often be recovered for re-use more efficiently. The trend in the last decade has been towards increased use of artificial catalysts and other clay minerals.

OUTLOOK

In the immediate future, world bentonite consumption will increase notably, mainly because of the current trend towards increased demand for pellets of iron-ore concentrates for blast-furnace feed. As pelletizing technology advances, the amount of bentonite per unit of iron-ore concentrate required to produce suitable pellets will probably be reduced, at least to a minor extent. In Canada, only bentonite is being used for pelletizing natural iron ores and no substitute has seriously threatened this application. However, in the long term, the possibility exists that bentonite may be replaced, at least in part, by other binders.

Although substitutes for bentonite are being used in well drilling, for the immediate future clay consumption by this industry should remain at least as large as in the past. The use of substitutes will increase, but as yet there has been no significant threat to the bentonite industry.

The application of bentonite in foundry moldings should increase with a natural rise in demand. In adsorptive applications, however, other clays and artificial compounds are providing much competition.

Consequently, world outlook is for a noteworthy increase in bentonite consumption in the immediate future with the possibility that some of this increase

eventually will be absorbed as a result of more efficient usage and by increased use of substitute materials.

Canada has sufficient indicated reserves of swelling and nonswelling bentonite to meet this country's current requirements for the Canadian product for several decades. To date, Canadian bentonite has not been accepted by the steel-foundry and the iron-ore-pelletizing industries. Consequently, the quantity of reserves that would be available for these purposes is unknown.

The swelling type will be required for about 97 per cent of the Canadian bentonite market by the end of 1965. The trend towards the predominant use of swelling bentonite will continue in the foreseeable future. With the main market in eastern Canada, a high-quality swelling bentonite deposit in Manitoba would be of considerable interest.

Because the United States has large reserves of all common types of bentonite, the outlook for any appreciable increase in Canada's small export trade is poor. With recent new production of activated bentonite in the United States, it appears that Canada reached a near peak in the export of that commodity in 1961. However, the use of domestic bentonite in Canada will probably increase for foundry and well-drilling use at the expense of the imported clay.

The main market for bentonite in Canada will soon be for the pelletizing of iron-ore concentrates. In 1962 this market amounted to about 10,000 tons and by the end of 1965 it should be about 100,000 tons a year. The current trend is for the use of imported bentonite. In order to supply this market, Canadian producers will have to make a concentrated effort to find, process, and possibly beneficiate a clay to produce a product at least equal to clays in current use. To be suitable for this purpose, the prime prerequisite is quality, not cost.

To date, none of the few Canadian commercial swelling bentonites has been accepted for this type of pelletizing. The Mines Branch is currently investigating the quality of bentonites for this application, along with methods for improving quality by the use of additives. Mixing and aging methods will also be investigated in the anticipation that improved handling conditions will strengthen the position of Canadian bentonite in this major application.

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