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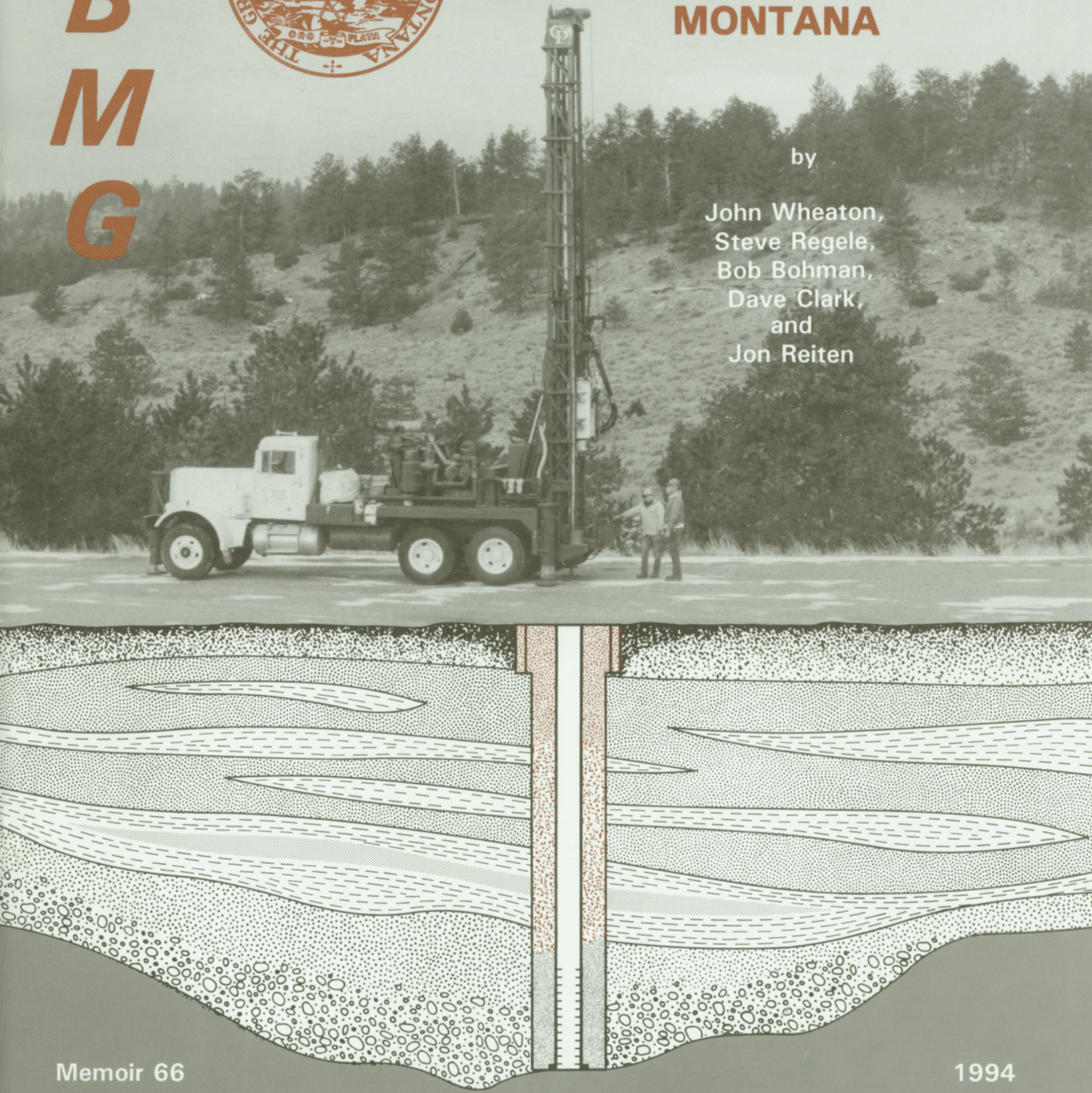

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Prepared in cooperation with
the Montana Department of
Natural Resources and Conservation

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Preface

State laws that govern drilling operations have changed to reflect growing concern for and awareness of ground water as a resource. In the 1970s and earlier, extensive coal, uranium and various other exploration drilling programs were carried out over vast areas of Montana. In most cases, the holes were left open except for a shallow surface plug. Water-level data now indicate that inter-aquifer mingling is occurring through some of these open holes (Van Voast and Reiten, 1988). Attention has thus been drawn to the need to effectively seal any hole that penetrates through or near an aquifer.

This study documents the efficiency and economics of different types of sealing materials. Data from a series of case studies address: 1) the effectiveness of selected grouts, 2) the limitations of different emplacement techniques, and 3) the comparative economics of application of different materials. Our goal is to suggest effective, reasonable and enforceable hole-plugging strategies that ensure environmental protection.

Appreciation for funding is extended to the Montana Department of Natural Resources and Conservation Resource Indemnity Trust Program, and to the Montana Department of State Lands Coal and Uranium Bureau. Access for field trials was granted by the following land owners and is gratefully acknowledged: Decker Coal Mining Company, Lawrence Cary, Clyde Finley, Bob and Kathy Bleeker, and the Montana Department of State Lands. Bentonite products were donated by Baroid Drilling Fluids, Inc., Wyo-Ben, Inc., and American Colloid Company. Reliable Exploration donated personnel and equipment for the seismic trials. A special thanks is extended to JoJean Lyford for dedication to the completion of the work and the quality of the collected data.

Several brands of bentonite products were used during the project. All of these were naturally occurring bentonite with no added chemicals. Although individual product names are not used in the main body of this publication, we recognize the need to list the products used by brand name. No endorsement of one brand over another is made or implied of the following: 1) Baroid Drilling Fluids, Inc., Roundup, Montana, Shur-Gel, Benseal; 2) Wyo-Ben, Inc, Billings, Montana, Enviroplug; 3) Geoloc, South Dakota; and 4) Quality Concrete, Billings, Montana, Portland Type I-II cement.

Additional data and case histories of the use of bentonite are presented in Regele and others (1993 b,c), and Wheaton and others (1993 a, b, c, d).

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Abstract

Proper grouting of boreholes and wells is the principle step in avoiding adverse impacts that may result from drilling activities. If drilled holes are not adequately plugged or if wells are improperly completed, water resources can be degraded or lost. Choosing the best grout involves balancing downhole conditions with grout characteristics and equipment needs. A range of materials and methods are used to plug boreholes and to seal the space between borehole walls and casings in wells. Six field and laboratory studies were utilized to examine selected grout characteristics of high-grade, pulverized bentonite, high-grade chip and granular bentonite, low-grade bentonite chips, and Portland cement. The characteristics examined were physical stability, hydraulic quality, emplacement methods, and economics of use.

In an unobstructed borehole, gravity-fed bentonite chips appear to provide the best seal, which is both hydrologically and physically strong compared to the other non-cement grouts. In an open borehole at depths of at least 2,000 feet, chips should be emplaceable without bridging if poured no faster than 1.5 to 2 minutes per 50-lb bag. Frequent sounding during grouting can detect possible bridging early enough to correct the problem. In some settings, low-grade bentonite can provide an adequate seal if it is properly screened for particle size.

If obstacles such as centralizers on well casing preclude the use of chips, then a high-solids slurry is an acceptable alternative for a flexible grout. [Mixing small batches is necessary to successfully pump this type of grout.] In holes at depths of about 400 feet, a 1¼-inch-diameter tremie and a progressing-cavity pump capable of at least 200 pounds per square inch of pressure is sufficient for bentonite slurries. Beyond 400 feet, a larger diameter tremie pipe is required for slurries of 5 to 6 percent or greater solids content by volume.

Certain types of water can react with the grout and weaken the seal. These effects, such as ion exchange reactions, are not always evident immediately but may take place over time. Careful attention should be directed both to the mixing water and to the chemistry of natural downhole waters before selecting a grout for long-term application.

In settings where ground motion is a concern, the grout should be a flexible-type material such as bentonite. Bentonite tends to re-establish a seal after it is disturbed, whereas rigid cement-based grouts do not reseal.

Neat-cement grout is the most expensive technique. Adding eight percent bentonite to the cement reduces the cost by about ten percent. Bentonite-slurry grouts are about 70 percent and high-grade bentonite chips are about 40 percent of the cost of neat cement. Low-grade bentonite chips are less expensive than high-grade chips, but the exact amount is difficult to determine because no commercial mines are currently selling low-grade products.

Introduction

Coal, oil, ground water, natural gas, and minerals are among the subsurface resources that are continually being developed in Montana. These resources are evaluated, in part, through drilling programs. For example, designs for coal mines are based on the results of drilling that identify the quantity and quality of the coal beds, overburden chemistry that may cause reclamation problems, and ground-water issues to be addressed by industry planners and regulators. Seismic shotholes are used to help identify geologic structures for potential oil and natural gas drilling locations. Ground water is both withdrawn and monitored by wells. Mineral resources are evaluated and developed, based at least in part, on drilling programs. Public works projects such as dams, bridges and large building designs also use boreholes to determine foundation strengths and weaknesses.

Drilling programs are an important part of resource development, and consequently, the economy. Ground water is vital to our way of life, thus protection and wise utilization of ground water is of paramount importance. Most drilling activities are now regulated in Montana. Water well and monitor well drillers must adhere to codes of the Board of Water Well Contractors.

Exploration drilling for metallic and non-metallic minerals, and coal and uranium-related drilling is regulated by the Montana Department of State Lands. Petroleum exploration, including seismic drilling, is regulated by the Oil and Gas Division of the Montana Department of Natural Resources and Conservation. Regulations that address drilling also address grouting and abandonment procedures and materials.

Purpose and scope

This report discusses grouting materials and grouting procedures, which are addressed through a series of laboratory experiments and field applications. Also presented are some environmental concerns and a description of the nature of bentonite.

Any drill hole provides the potential to adversely impact ground-water resources. Degradation can occur either through biological or chemical contamination, or through hydrostatic pressure loss. If holes are not adequately plugged when they no longer serve a useful purpose, or if production zones are not effectively sealed from all other zones, water and other natural resources can be degraded or lost and ground-water data can be invalidated. As shown in **Figure 1 (A-D)**, surface water can flow directly into an aquifer, water can move from one aquifer to another, and ground water can also discharge to the surface if the hydrostatic pressure is sufficient. This study addresses ways of protecting ground-water resources through proper grouting.

Where water flows from one aquifer to another, the loss, although not visible, can be substantial **(Figure 1B)**. This loss can be estimated mathematically since the rate of flow between two aquifers is controlled by the transmissivity of the aquifers and the vertical gradient between them. If a borehole is permanently left open, the rate of discharge from one aquifer will equal the rate of recharge to the other aquifer and the elevation of the potentiometric surfaces of both aquifers will be the same within the borehole.

The Thiem equation is used to calculate steady-state discharge rates from, or recharge to, a well (Driscoll, 1986). The Thiem equations for two aquifers in one borehole can be set equal to one another and solved simultaneously. For example, if the undisturbed vertical gradient between two aquifers is 45 feet, the transmissivity of the two aquifers is 3 feet squared per day and 25 feet squared per day. The radius of influence for both aquifers is about 5,000 feet and the borehole is 6 inches in diameter. The discharge rate is estimated to be about 0.4 gallons per minute, or about 600 gallons per day. For comparison, the average per capita domestic usage in America has been estimated at about 75 gallons per day (Fetter, 1980). Using this figure, it is estimated that a single, unplugged borehole in a typical eastern Montana setting could waste enough water to supply the needs of eight people.

The total number of holes drilled in any given area in any given year is difficult to estimate, since the holes are drilled for such a variety of reasons. Bond (1975) stated that more than 300,000 seismic shotholes were drilled in Montana between 1950 and 1970. More recently, in one area of southeastern Montana where coal-exploration drilling has been particularly intensive, more than 4,000 holes have been drilled in an area of about 20 square miles. Statewide, coal and uranium exploration drilling has probably exceeded 21,000 holes between 1974 and 1992.

The more holes drilled, the more opportunity there is for impact to the ground water. Once an impact occurs, the remediation of the impact can be time consuming, expensive, and in some cases, completely unachievable. The best mitigation of a ground-water impact is avoidance of the impact. Proper grouting of subsurface holes is a principle step in avoiding impacts.

For purposes of this report, grout is defined as an inorganic slurry or solid material, less permeable than the surrounding lithology, that is pumped or gravity fed into a borehole or well annulus to specific locations for the purposes of: 1) retarding the movement of water, and 2) physically stabilizing the hole. Grouting applications for boreholes include both the sealing of open holes and the sealing of annular spaces in wells around well casings. Grouting performs the following functions: 1) provides an effective hydrologic sealant in boreholes and annular spaces (prevents intermingling of aquifers, aquifer contamination, draining of aquifers, loss of hydrostatic pressure); 2) isolates production or monitored zones from all other zones in water and monitor wells; 3) prevents the escape of oil and natural gas; and 4) stabilizes the geologic formations to minimize ground-surface sub-

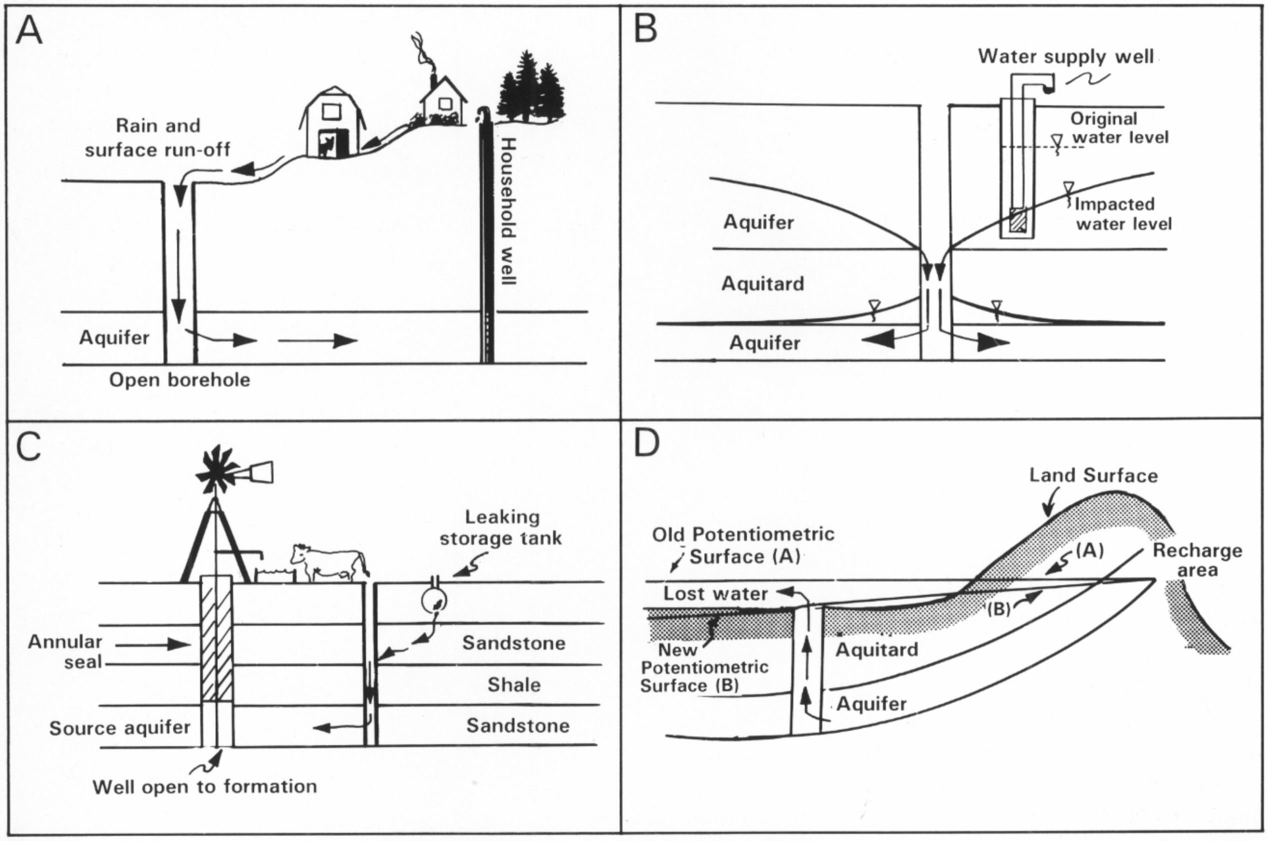


Figure 1—Ground-water supplies can be contaminated by surface-water infiltration (A). The water level in a shallow aquifer can be lowered to a nearly unusable level at a well by draining into the deeper aquifer (B). An aquifer can be degraded by mixing of ground water from a lower quality or contaminated aquifer (C). Water resources can be wasted and artesian pressure reduced by surface discharge from an open borehole (D).

sidence, such as where drilling has formed a large cavity at shallow depth.

Aspects of a material that determine its usability as a grout are: 1) stability of the seal, which is the ability to stand in the hole; 2) quality of the seal, which is the ability to block the flow of water, natural gas and contaminants through the subsurface spaces; 3) the ease with which it can be placed to the required depth in a borehole or annular space; and 4) economics.

The first concern is the stability of the seal, including the effect of chemical additives or *in situ* water quality and geochemistry on the performance of the grout. Physical strength of the seal is a direct measure of how well the material stays at the required location in a hole. A low-viscosity slurry may migrate into the surrounding formation, but chips will nearly always stand in a hole at the original fill level. Typically the higher the solids content, the greater the stability of the grout.

The second concern is the hydraulic quality of the seal that the grout provides. The principal role of a grout is to limit the movement of water, natural gas or contaminants in the hole that has been filled. The grout should retard this movement at least as well as the natural formation does, both through the grout itself and at the contact of the grout with the sides of the borehole. When hydrostatic pressure is applied against the seal, some amounts of fluid will move around or through it. Usually, with bentonite-based grouts, the higher the solids content, the better the hydraulic quality of the seal.

Flexibility is also an important characteristic which allows the grout to flow into cracks and irregular shapes in the hole, providing a uniform seal. In addition, a material that is flexible for a long period of time will be less affected by subsurface motion or changes in the shape of a borehole.

The third concern is the method of emplacing the grout. Two methods are available to place a grout at the desired position in the subsurface space. The grout can be pumped through a tremie pipe which discharges near the bottom of the hole, or if applied in a dry state, the grout can be gravity fed by pouring from the ground surface at a slow, controlled rate into the borehole or annular space. Emplacement factors include: the maximum depth to which chips can be gravity fed, and the maximum length of tremie pipe through which a viscous slurry can be pumped.

The fourth concern is the economics of grouting techniques, which include grout material, the equipment used to emplace the grout, and the labor cost. There are also indirect costs that are difficult to assess because they vary with site and job conditions. If the grout pumping equipment is a part of the drill rig, drilling cannot progress at additional sites while grouting is underway. If a grout column settles, equipment will need to be mobilized to add material to the top.

A wide variety of grout materials and grouting methods are presently used to plug boreholes and to seal the space between a borehole wall and well casings. Grout materials include: bentonite slurries (a mixture of bentonite and water); dry bentonite in powder, granular, pellet or chip form; drill cuttings (generally restricted to clay cuttings); cement (generally a mixture of dry Portland cement and water); concrete (a mixture of Portland cement, water and sand or gravel); other inorganic materials and various combinations of the above materials. Of these materials, bentonite in its various forms is probably the most often used.

Bentonite is a naturally occurring clay, and so there is some variation in the material. The terms high grade and low grade are used in this report to describe the quality of bentonite. The term high-grade bentonite is used here to describe bentonite that is commercially available through well drilling supply sources. The term low-grade bentonite is used here to describe bentonite that does not meet common drilling industry standards.

High-grade bentonite consists primarily of sodium montmorillonite with varying percentages of calcium montmorillonite plus minor constituents. Ion-exchange reactions between sodium montmorillonite and calcium, in either make-up or formation water, can produce calcium montmorillonite. Since sodium and calcium montmorillonites have different hydration characteristics, both varieties must be considered.

Some bentonite products use synthetic polymers to inhibit swelling and viscosity, thus making the slurry more pumpable. The polymers used for this type of application (polyacrylates and polyacrylamides) are very resistant to bacterial attack, unlike some natural biopolymers like xanthan and guar gums. However, few of these polymers have been approved for water well use because their eventual bacterial degradation can produce undesirable by-products.

It has been common practice to describe grouting materials in terms of percent (by weight) of solids entrained in the slurry. For grouts developed for plugging or sealing purposes, it is more appropriate to express percent solids by volume, since the purpose of the grout is to fill a void. This avoids confusion with oil drilling applications, where muds are often weighted by additives such as barite. Where the term "percent solids" is used in this report, it is an expression of a volumetric percentage.

Choosing the best grout for a given situation involves considering the hole geology and geometry, local and regional hydrogeology, the grout material types that are available, and the emplacement equipment. Slurries must be pumped through a tremie to ensure that they are at the correct depth in the hole. Chips, however, are not pumpable and so are limited to gravity feeding. Recently developed pneumatic systems provide some possibility that dry material will be emplaceable in boreholes and wells by means other than gravity feeding.

Bentonite (sodium montmorillonite) grouts are the central focus of this report, although cement was included for comparison. Bentonite can swell to 12 or more times its dry volume, thereby conforming to at least some irregularities in borehole walls. It is possible for bentonite to hydrate and swell, desiccate, rehydrate and swell an infinite number of times. Bentonite seals are also flexible, and may reseal if the initial seal is disrupted.

There are some limitations, however, on the performance of bentonite grouts. Slurries of bentonite can flow into fractures or porous formations leaving an empty borehole and thereby providing no seal. The ability of bentonite to rehydrate and swell can be altered or inhibited by certain contaminants. Low pH values and high calcium concentrations in the make-up or formation water can adversely affect the performance of a bentonite grout (Regele and others, 1993a). Chemistry of the post-emplacement, downhole environment can also adversely affect the long-term stability of bentonite.

Many questions exist regarding the effectiveness of different types of grout materials and the use of bentonite grouts in various borehole water chemistry, geochemistry, and hydrologic settings. Slurries have been observed to settle with time, leaving a subsurface void. The degree to which settling occurs and the effects on the hydrologic system have been difficult to determine. Adequacy of chips for grouting applications, and whether they must be high-grade bentonite to perform well have also been subjects of some speculation.

A specific challenge in grout applications is the stemming of seismic shotholes. Stemming is the process of backfilling shotholes in order to keep the shot energy focused downward, rather than blowing out away from the target formations. In a shothole, the stemming material is the grout, and it provides protection for the adjacent aquifers. Seismic exploration is a standard method for determining the existence and location of buried geologic structures. Shock waves are generated by detonating explosives in shotholes. Due to velocity differences caused by variations in rock density, the time required for shock waves to return to the ground surface can be used to compute the depths to geologic strata. Along a seismic line, shotholes are spaced from a few hundred feet to several thousand feet apart, depending on the target depth and the degree of precision desired. Many miles of seismic line are often required to develop a geologic interpretation.

In Montana, seismic shotholes are required to be stemmed before they are shot (Montana Department of Natural Resources and Conservation, 1992). The stemming material must provide physical support for the walls of the shothole. It also acts as a flow barrier from the time of stemming to long after the shot has been fired. The sealant must function in simple settings, as well as in very complicated hydrogeologic settings. If not ejected by the shot, the stemming material is also the abandonment medium for the hole, and the seismic crew need only attend to surface reclamation after the shot.

Nature and occurrence of bentonite

Bentonite is a naturally occurring clay rock, formed by the alteration of volcanic ash. Its mineralogical characteristics have given bentonite a number of unusual chemical and physical qualities. For this reason, bentonite has seen a wide range of uses during the late 19th and early 20th centuries. Among the early applications were uses in the cosmetic industry, and for bleaching/absorbent usage in both animal feed and wool processing (as fullers earth).

Cosmetic and bleaching/absorbent usage continues to the present day. Since World War II, additional uses of bentonite have been in iron-ore pelletizing, foundry sand bonding, ditch and pond sealing, and as a drilling mud. Adsorbent granules, especially pet litter, have become a major use with nearly a million tons per year being exported to Europe (Richard B. Berg, Personal Communication, 1993). In addition to these applications, bentonite has been used in face brick, refining catalysts, Portland cement, fertilizer, pottery glaze, glass, gypsum products, paint, pharmaceuticals, pesticides, paper, vitrified pipe and roofing tile (Beatty, 1976).

Reduced activities in the oil drilling and steel industries during the past decade have drastically reduced the demand for bentonite. More recent applications, however, have included slurry-stabilized excavation, environmental remediation, well completion, and drill-hole abandonment.

Mineralogy

Bentonite consists primarily of smectite group minerals. Less abundant constituents may include clay minerals like illite, kaolinite and chlorite, as well as calcite, gypsum, zeolites, and hydrous opaline silica species. Residual primary igneous minerals such as quartz, feldspars and biotite are also common.

The principal member of the smectite group is the mineral montmorillonite, which gives bentonite the characteristic physical and chemical qualities that make it commercially useful. Some discussion of the properties of montmorillonite is essential to an understanding of the physical properties of bentonite.

Montmorillonite is a member of the phyllosilicate (sheet silicate) family. Montmorillonite is the aluminum-rich, dioctahedral member of the smectite group. Within the phyllosilicates, the smectite group of minerals has a unit cell with a three-layer configuration consisting of an octahedral alumina (gibbsite) layer at the center, bounded by two tetrahedral silica layers **(Figures 2, 3).** In the unhydrated state, the montmorillonite unit cell has a c-axis spacing (perpendicular to layers) of about 9.6Å (Grim, 1968).

The generalized formula for the smectite group is expressed as $Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$. The actual composition, however, always deviates from the ideal formula because of cation substitution within the gibbsite layer. This lattice substitution may include magnesium, iron and sometimes zinc for aluminum in the octahedral layer, and aluminum for silicon in the tetrahedral layers. The type and extent of this substitution divides the smectite group into two subdivisions (dioctahedral and trioctahedral), and at least five species.

The substitution of divalent for trivalent cations within the octahedral layer creates a net negative charge on the lattice. In the species montmorillonite, this charge deficiency causes the adsorption of additional cations such as Na^{+1} and Ca^{+2} onto the surface of the lattice, in what are called inter-cell exchange positions **(Figure 2).** Because the individual cells of montmorillonite are only loosely attracted to one another, water or other molecules can also penetrate between the cells.

The low inter-cell attraction means that individual montmorillonite particles can desegregate to near unit-cell dimensions, resulting in a very small particle size (10Å) when in suspension in the direction perpendicular to the layers. This provides a very large surface area, estimated at 800 square meters per gram of montmorillonite, being available for the adsorption of cations and water (Grim, 1968; Berg, 1969).

The extremely small particle size, the negative charge imbalance, and the resulting inter-cell adsorption of cations and water give montmorillonite three important qualities: the remarkable ability to swell when wetted, a thixotropic behavior in the gel state, and a propensity for cation exchange between cations in solution and those adsorbed onto the surface of the mineral.

Hydration and swelling

The ability of montmorillonite to swell upon wetting is greatly assisted by its relatively weak inter-cell attraction. Water or other molecules can easily penetrate between the individual particles. While there is considerable discussion as to the state of the inter-cell water, detailed discussion is beyond the scope of this paper.

The swelling behavior of montmorillonite in water depends upon which cation is present in the inter-cell position. Cations with weaker affinity for the surface are associated with limited particle aggregation and greater swelling. Strongly bound cations, usually the divalent and polyvalent ones, tend towards stronger particle aggregation and less swelling.

The principal cations considered here are calcium and sodium. Other cations such as potassium and magnesium may also be found in the inter-cell position. This discussion is limited to the behavior of calcium montmorillonite and sodium montmorillonite, and the potential effect of the ionic content on the nature of montmorillonite.

Calcium montmorillonite does not exist in Montana in mineable quantities; it is mined primarily in the southeastern part of the United States. Sodium montmorillonite is the principal constituent of bentonite that is used for drilling mud and most bentonite based borehole and annular-seal materials. Sodium montmorillonite is readily available from companies headquartered in Montana, Wyoming and Texas. Sodium montmorillonite does, however, become calcium montmorillonite in certain calcic settings where cation-exchange reactions can occur (Grim 1968). The physical characteristics of the two mineral species are very different from one another.

When calcium montmorillonite is initially wetted, the basic unit cell expands from a c-axis spacing of 9.6Å to about 15.5Å, representing two molecular layers of water **(Figure 3)**. This double-layer state is relatively stable for calcium montmorillonite under room conditions. It may adsorb some additional water, but its ability to do so decreases rather abruptly beyond the double layer. X-ray data suggest that at maximum hydration for calcium montmorillonites, water adsorption is restricted to about the 2-layer limit, an increase in volume of only about 50 percent over the dry state.

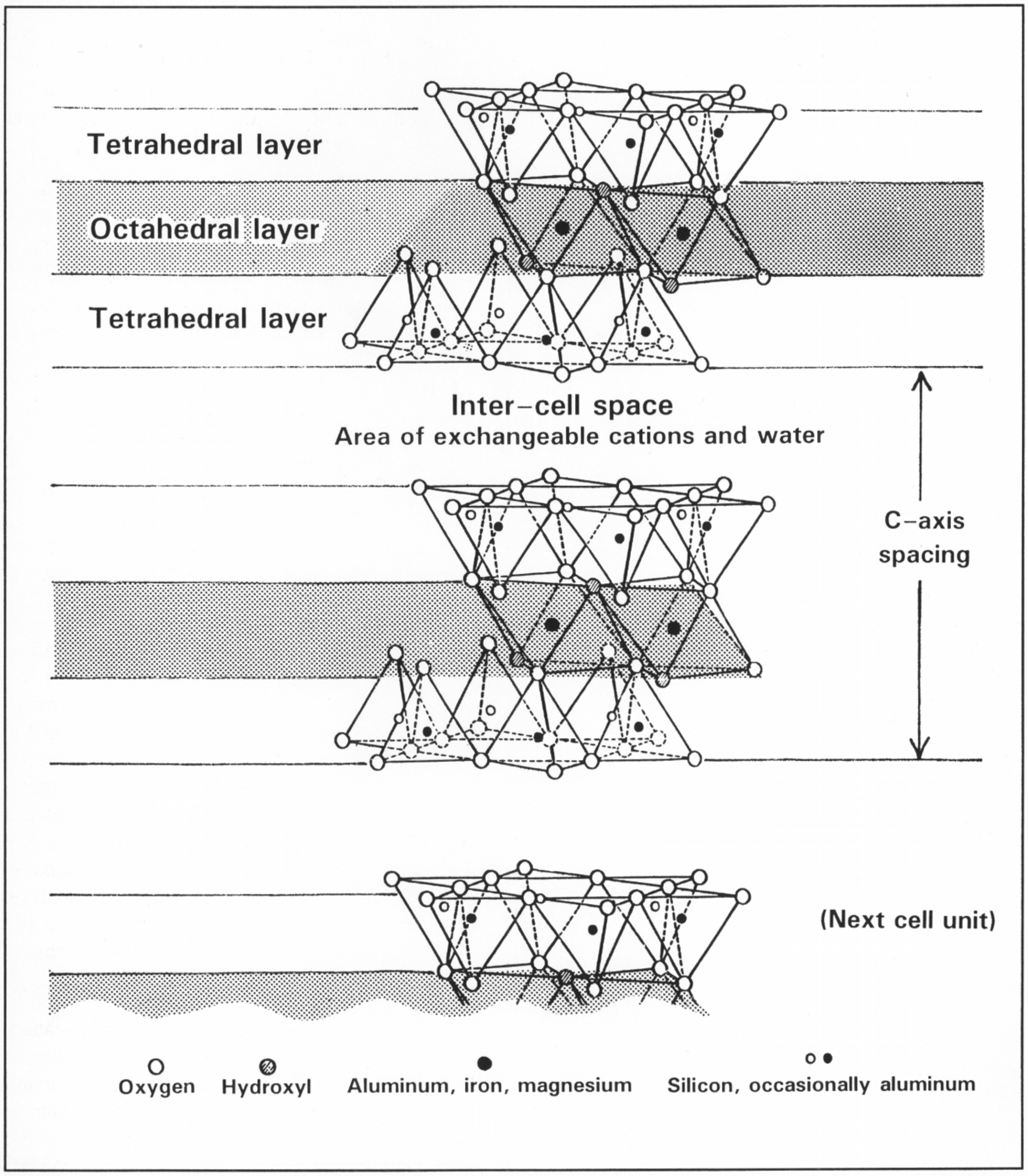


Figure 2—The structure of montmorillonite consists of three-layer stacks with a c-axis spacing of about 9.6 angstroms. The size along the other axis is limitless. For simplicity, the structure is shown as three-layered wafers here and in Figure 3. (*From* Grim, 1953; permission of McGraw-Hill, Inc.)

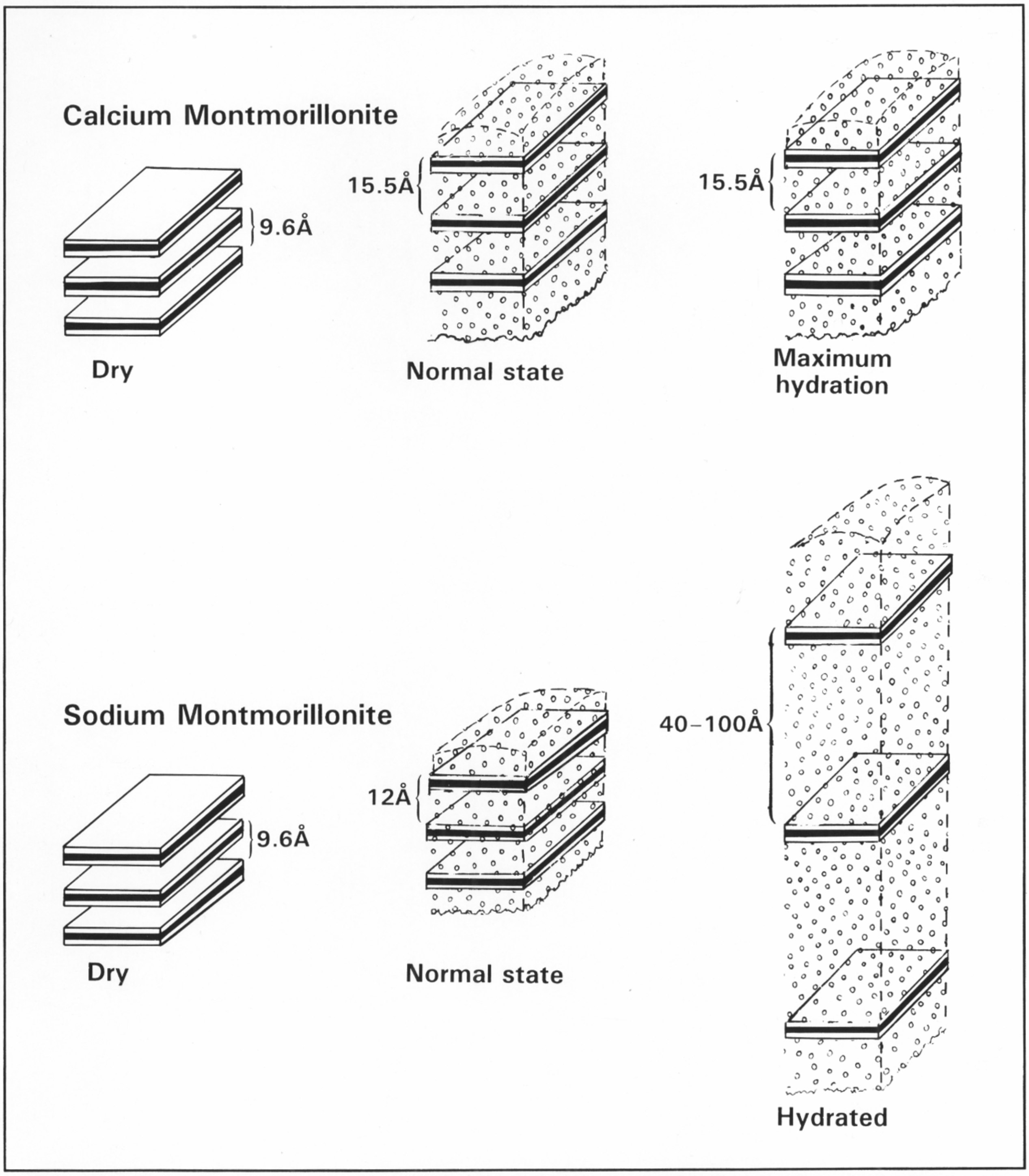


Figure 3—Layers of water molecules adsorb onto clay platelets or cells. Calcium montmorillonite takes on two layers of water in its normal state, while the sodic variety takes on only one. With the addition of more water, sodium montmorillonite continues to expand as a coherent gel, while the calcium species does not.

The unit cells of a hydrated calcium montmorillonite are not held far apart. Adding more water may temporarily disperse the cells, but they can settle by gravity or flocculate in response to electrostatic forces. With the hydration water limited to only about 5.0Å, cells can readily adhere to each other. As a result, calcium montmorillonites do not form the expanded, coherent gels which characterize the sodic variety.

The normal state of sodium montmorillonite involves only a single layer of water, and has a c-axis spacing of about 2Å **(Figure 3)**. It will further hydrate to a 2-layer state (15.5Å) at 50 or 60 percent humidity. Sodium montmorillonite does not, however, exhibit the sharp swelling limit of the calcic variety (Grim, 1968). It will swell up to twelve times its dry volume upon wetting.

Sodium montmorillonite is capable of maintaining a stable gel at inter-cell separations of from 40Å to 100Å (Grim, 1968). The strength of the gel state should diminish with distance from the particle surface and eventually be readily overcome by thermal or mechanical energy. A dispersed suspension of sodium montmorillonite exhibits thixotropic behavior. While at rest the suspensions form a coherent gel. An initial application of energy is required to break up this cohesiveness. Once agitated, the cells can remain disoriented and the suspension can flow freely under lower levels of energy.

The extensive swelling and the mechanical qualities of the gel are the reasons for the principal commercial applications of sodium bentonite in the drilling industry. A relatively small volume of sodium bentonite can produce a large volume of a viscous gel with a low-solids content. The thixotropic property of the gel allows bentonite muds to be pumped freely, but retain cuttings in suspension when circulation is stopped. In addition, the low permeability of the gel or slurry ($<10^{-5}$ ft/day) has created applications where fluid retention or exclusion is important, as in water well completion and borehole abandonment.

Ion exchange

The core molecular structure of montmorillonite is relatively stable. The cations that control the hydration, however, are not strongly bonded to the unit cell, and are easily replaced or displaced by other cations or compounds. These cations can alter the mechanical qualities of a bentonite suspension. A detailed discussion of ion exchange is presented in Grim (1968). Quantitative prediction is difficult because ion exchange is affected by a number of factors. Grim (1968) provides the following generalized observations:

- Ca^{+2} and Mg^{+2} and K^{+1} will replace Na^{+1}.
- Replacement is favored by higher concentrations in solution.
- With the same valence, ions of higher atomic number and larger radius will replace smaller ions.
- The replaceability of a given cation can be affected by the presence of various anions in solution.
- Ion exchange may take place in the presence of relatively little water between clay minerals and inorganic materials.

The ion exchange capability of montmorillonite is the greatest of all sheet silicates, except vermiculite. Regardless of their original composition, montmorillonite suspensions are highly susceptible to ion exchange. This is especially true of sodium montmorillonite in the presence of calcium or magnesium.

Hydration and mechanical behavior are, in turn, highly dependent upon the nature of the adsorbed cation, and can be altered by cation exchange. Grouting materials that contain montmorillonite, such as bentonite, need to be evaluated with this in mind. Possible interactions between chemistry of the bentonite and the chemistry of the mixing water, as well as the chemistry of the end-use environment, must be considered when evaluating the proposed application of bentonite where long-term stability is desired.

Organic compounds

Montmorillonite long has been known for its ability to adsorb a range of organic molecules (Grim, 1968). The adsorption of some organic compounds can displace exchangeable cations, reduce the ability of a montmorillonite to adsorb water, and change its physical characteristics. Some of these changes are irreversible (Hasenpatt and others, 1989). Because of this, the presence of organic chemicals in the environment of emplacement needs to be carefully considered.

Occurrences of bentonite in Montana

Sodium montmorillonite is the primary constituent of the bentonite that is of economic importance in Montana. Bentonite occurs throughout a large portion of the State and is believed to be derived from *in situ* alteration of volcanic ash deposits. The major bentonite occurrences are in Late Cretaceous to mid-Tertiary age sediments associated with major volcanic events. The oldest bentonite beds occur in the Lower Cretaceous Colorado Group, Niobrara, Frontier, Belle Fourche, Mowry, and Thermopolis formations, and in the Vaughn and Bootlegger members of the Blackleaf Formation in northwestern Montana (Berg, 1969). Bentonite is also found in the Upper Cretaceous Bearpaw and Claggett shales, and in the lower Tertiary Fort Union and Climbing Arrow formations (Berg, 1969).

Although bentonite is found throughout much of Montana, reliable estimates of the total reserves remain confidential. In addition, the definition of what constitutes a reserve depends upon the proposed end use for the product. Bentonite for bonding foundry sand, for example, is evaluated according to specifications of the American Foundrymens Society (1963), as well as the specific needs of individual foundries (Grim, 1968). Bentonite for drilling mud applications, however, is defined by a different set of standards governed by the American Petroleum Institute (API). Considering the variety of end-uses for swelling bentonites listed by Beattie (1976), a comprehensive estimate of reserves would be an extremely difficult task.

Bentonite production in Montana

Reliable production figures for Montana bentonite are similarly difficult to estimate. Local bentonite deposits have reportedly been mined since the 1930s, primarily for lining irrigation ditches. Sahinen (1963) mentioned mining of bentonite in two localities in Silver Bow County and one in Choteau County, and noted that good-quality bentonite had been produced in Carter County. Listings by Lawson (1973, 1983) and Minarik and McCulloch (1992) provide the following information:

1971: Seven pits listed in Carter, Phillips, Rosebud, Treasure and Valley counties; three active, two exhausted, and two under development; production figures withheld.

1981: Four pits listed in Carter, Phillips, and Valley counties; one active (Carter County); no production figures.

1991: Production in Carter County 362,635 tons.

Annual reports filed with the Montana Department of State Lands show that the Bentonite Corporation produced 35,984 tons during its 1992 permit year, while American Colloid Company reported mining 2,481,649 tons from 4 pits during a similar period (Mark Carlstrom, Personal Communication, 1993).

Grades of bentonite

Currently, most commercial bentonite used in Montana is produced from Wyoming and South Dakota mines. Ample supplies of bentonite exist in Montana (Berg, 1969), but the quality of the material is considered to be lower than the material available in other areas, particularly Wyoming. However, as noted above, the quality control guidelines are based on end-uses, such as drilling fluids.

For bentonite that is used in annular and borehole sealing applications, several properties are tested, in some cases by American Society for Testing Materials (ASTM) or API methods. Specific properties include: 1) the ability of the material to adsorb water and increase in volume, or swell (no current ASTM or API method available); 2) the plate water adsorption rate, or the quantity of water that the bentonite will adsorb; 3) the fluid loss or the amount of water that can be forced out of the bentonite at a specific pressure; 4) the responsiveness of the bentonite to the addition of treating chemicals such as soda ash (no current API or ASTM method available); 5) the sand content (greater than 200-mesh sieve) of the bentonite; and 6) the number of barrels of drilling mud at specific viscosity (15 centipoise) yielded when one ton of bentonite is added to water (extrapolated from API viscosity test results) (Bob Stichman, Personal Communication, 1993).

Grouting materials

Bentonite grouting materials that were studied include: 1) high-grade, commercial, powdered, sodium bentonite (smaller than 200 mesh, or 0.0029 inches); 2) high-grade, commercial, granular, sodium bentonite (8-20 mesh or 0.033

to 0.093 inches); 3) high-grade, commercial, chip sodium bentonite (⅜ and ¾-inch); and 4) low-grade bentonite (unscreened).

The high-grade bentonite used was mined near Lovell, Wyoming from the Cretaceous Frontier, Belle Fourche, Mowry and Newcastle formations near Colony, Wyoming. According to the manufacturer's specifications, this material contained no additives, had a free swell that exceeded 18 cubic centimeters in 2 hours for a 2-gram sample, had a pH of between 6 and 11 standard units, a hydraulic conductivity of less than 10^{-5} ft/day, and a sand (200 mesh) content of less than 15 percent. Tests on 5 samples from the purchased lot showed a sand content of between 14.4 and 19.3 percent by weight, and an average of 16.7 percent, and a free swell of between 21 to 34 cubic centimeters for 2 grams.

The low-grade bentonite had been sorted during mining and left at a mine pit in the northwest quarter of section 10, Township 8 south, Range 24 east near Bridger, Montana. The bentonite beds occur in the Cretaceous Frontier Formation, and had been handled by scrapers and bucket front-end loaders, but had not been screened. The piles of unsorted shale and bentonite chips ranged from several inches in width to fine powder.

The low-grade material closely resembles the gray-brown shales described by Berg (1969), rather than the high-quality, yellowish-colored bentonite. Based on visual field observations, this material was expected to represent very low-quality grades. This was verified by a 200-mesh wet sieve analysis and by free-swelling tests. By weight, 10 samples contained between 8.7 and 54.5 percent sand, with an average sand content of 15.1 percent. The free swell measured for 5 samples was between 10 and 11 cubic centimeters for a 2-gram sample.

Berg (1969, p. 22) collected samples from the high-grade portions of this same bed about two miles to the northwest of the pit mentioned above, and described the beds as . . . *yellowish-gray to grayish-yellow and light greenish-gray to light olive-gray with black to dark-brown fissile shale and grayish-brown shale.* Berg (1969) also identified ironstone concretions, selenite crystals, plagioclase, K-feldspar, partly altered glass, calcite, quartz, biotite, and zeolites. Of the samples collected, none met API standards for commercial bentonite. Tests were made on standard drilling-fluid properties including yield, viscosity, water loss, filter cake, and sand content. All samples contained less than 10 percent sand (230-mesh sieve or 0.0024 inches) except one which contained 10.1 percent sand.

Laboratory evaluation of grouting materials and procedures

A series of four laboratory-style experiments were performed to test physical characteristics of bentonite and cement-based grouts, and emplacement techniques. Grouting materials must be physically stable so that voids do not develop in or above the grout column. The physical stabilities of bentonite grouts were measured in shallow borehole trials. Grouts must retard the movement of water through the borehole or annular space. The effectiveness of materials to seal against borehole walls and well casing, the ability to resist the development of cracks, and to reseal cracks that do develop, were tested in laboratory tub trials.

In order for a grout to be effective, it must be feasible to place the grout at the desired depth in the well or borehole. Dry-chip grouts are emplaced by gravity feeding, which allows the chips to fall to the bottom of the borehole. Experiments using gravity feeding were conducted to determine if a maximum effective depth could be estimated for this method of emplacement, and to measure the effects on fall velocities of chip sizes, duration of exposure to water, and material types. Fluid grouts (slurries) are emplaced by pumping through a tremie pipe. To investigate the performance of different types of pumps and to determine the maximum pumpable distances for slurries containing high- and low-solids contents, a series of field pumping trials were performed (Regele and others, 1993 b, c; Wheaton and others, 1993 a, b, c, d).

Grout column stability

The performance of a grout is largely dependent on its ability to remain physically stable once it is emplaced, rather than settle below the intended fill level. The stability of two slurries and three dry bentonite grouts emplaced in dry holes drilled in substrates with various porosities was therefore documented (Regele and others, 1993c).

Holes, 6 inches in diameter, were drilled to approximate depths of 25 feet in 3 different geological settings. Holes were drilled in clinker (rocks that have been baked by *in situ* burning of coal and then fractured by collapse) of the Tongue River Member of the Fort Union Formation at the Decker mine near Decker, Montana; sandstone of the Eagle Formation northeast of Billings, Montana; and in shale of the Colorado Group south of Billings. These sites were chosen to approximate respective worst, middle, and best-case drilling and hole abandonment conditions typically found in eastern Montana.

The physical stabilities of the dry-chip bentonite grouts were similar regardless of lithology. In all tested lithologies, over a period of about nine months, each of these grouts either remained stationary at the installed level or rose slightly because of swelling of the bentonite.

The slurry grouts (1.9–5.7% solids by volume) settled in all lithologies, although settling rates varied in response to slurry densities and rock-pore sizes. In the clinker holes, the lower-solids-content slurry stabilized at only about 10 percent of the original column height. The least settling was found in the sandstone boreholes where the higher solids slurry stabilized at about 90 percent of the original column height. In the other boreholes and with the two slurry types, the stabilized column heights fell between these two extremes.

Physical strength of grouts

A good grouting material must be able to form a seal with the borehole wall and with the well casing (if present), and to block the flow of water around or through the grout column. The grout must also resist separation or cracking from the effects of pressure. In replicated laboratory tub trials the comparative ability of the seals formed by the following seven grouts to withstand hydrostatic pressure was analyzed: 1) neat Portland cement; 2) cement plus 8 percent bentonite; 3) 9.0 lb/gal bentonite slurry; 4) 10.2 lb/gal bentonite slurry; 5) high-grade bentonite chips; 6) low-grade bentonite chips; and 7) a mixture of 75 percent gravel and 25 percent bentonite chips. The grouts were mixed with and tested using nine different water-quality types. These water qualities were chosen to represent extremes of water types found in Montana. The water-quality types were: 1) Billings city water (the control or reference water type); 2) three types of acidic water; 3) highly alkaline water; 4) two different, high concentrations of calcium; 5) high concentration of sodium; and 6) high concentration of sulfate (Regele and others, 1993b).

Cement-based grouts withstood the greatest hydrostatic pressures and also had the greater strengths. Of the bentonite-based grouts, the best seals were provided by high-grade bentonite chips **(Figure 4)**, although these withstood only about 5 to 15 percent of the pressure held by cement or cement/bentonite grouts. Overall, low-grade chips and 10.2 lb/gal slurry grout withstood about 70 percent of the pressure withstood by the high-grade chips. The 9.0 lb/gal slurry and the gravel/bentonite mixture withstood about 50 percent of the pressure of the high-grade chips.

The strongest cement-based grouts were those that were mixed with water containing a high concentration of calcium. The Billings city water produced the weakest cement grout. In general, the lower the pH of the water, the lower the pressure withstood by all grouts. The high-grade bentonite chips and the 10.2 lb/gal slurry were the grouts that showed the highest sensitivity to water quality. The 10.2 lb/gal and 9.0 lb/gal slurries showed significant losses of volume when mixed using high-calcium water, possibly because of cation exchange reactions and subsequent flocculation. Generally, the strongest bentonite grouts were those that were mixed with water containing a high concentration of sulfate, sodium, or unaltered Billings city water. Low pH water produced the weakest bentonite-based grouts.

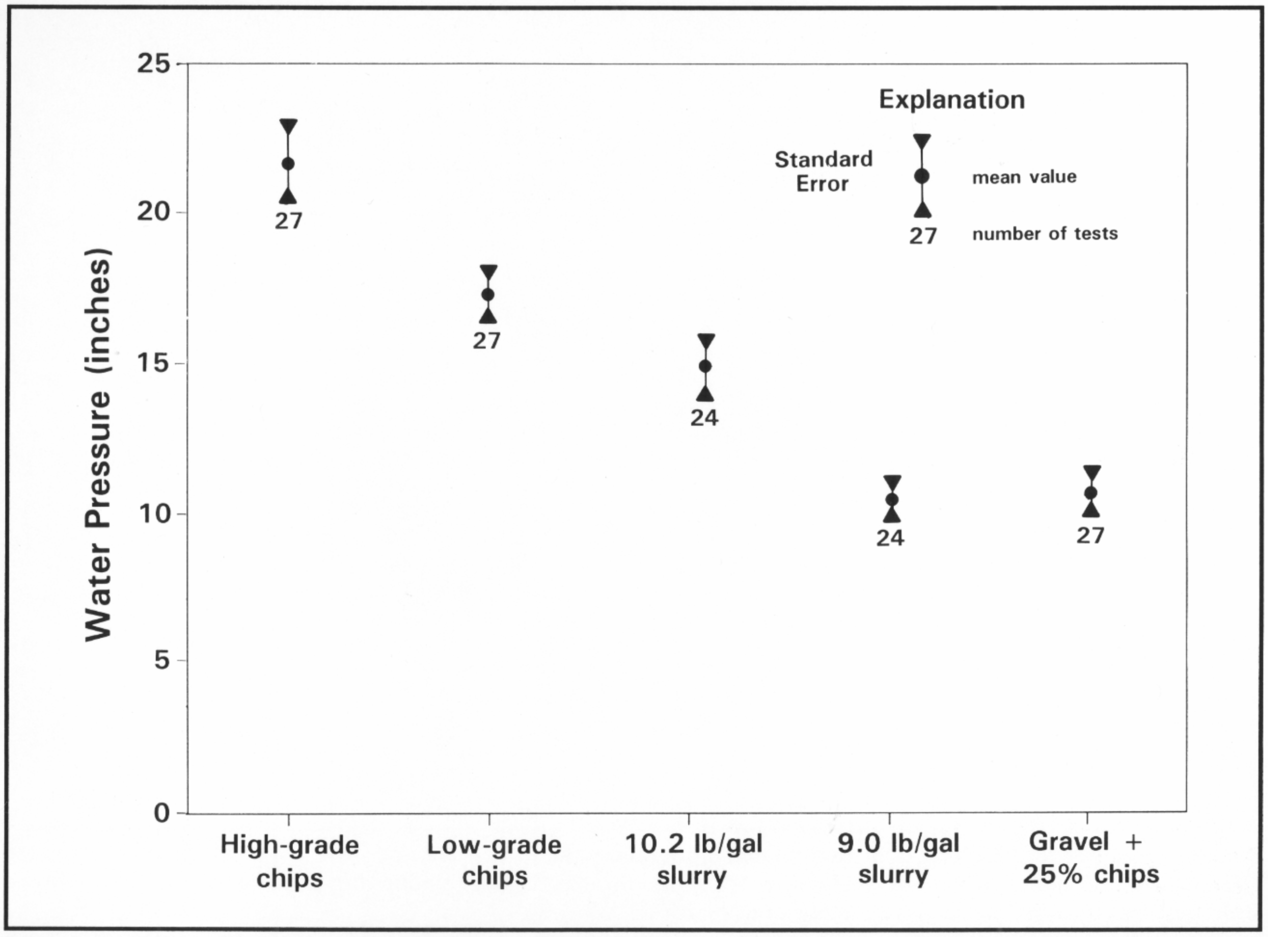


Figure 4—In laboratory tub trials, all of the bentonite-based grouts withstood far less pressure than did the cement-based grouts (which are not shown). Generally, among the bentonite-based grouts, the higher the content of bentonite in the grout, the stronger the seal.

Further tests compared the abilities of grouts to reseal by inducing failure of the initial seal, allowing it to set for one month, then subjecting it to a second application of pressure to induce a second failure of the seal (Regele and others, 1993b). The bentonite grouts provided poorer initial seals than did cement or cement/bentonite grouts, but provided significantly better secondary seals.

Emplacement by gravity

Gravity feeding of chips into an annulus or borehole is the simplest grouting technique, however, the success of the method is dependent to a large degree on factors that are effected by the fall velocities of the chips. Chips falling at different velocities may tend to bridge more easily due to collisions. Since exposure to water causes bentonite chips to hydrate and lose velocity, they may eventually reach a depth where they stop falling and form a bridge.

Physical characteristics of high- and low-grade bentonite chips and gravel chips were compared to fall velocity in a series of gravity-feeding trials (Wheaton and others, 1993a). Several concerns were addressed including whether the uniformity of chip sizes poured at one time is important to avoid bridging; whether different types of material can be poured together; and how water adsorption by bentonite chips during emplacement affects the fall velocity. Bentonite and gravel chips were dropped into a clear plastic tube and timed as they fell through a column of water. Most of the chips were allowed to hydrate before being dropped in order to simulate the time-dependent water

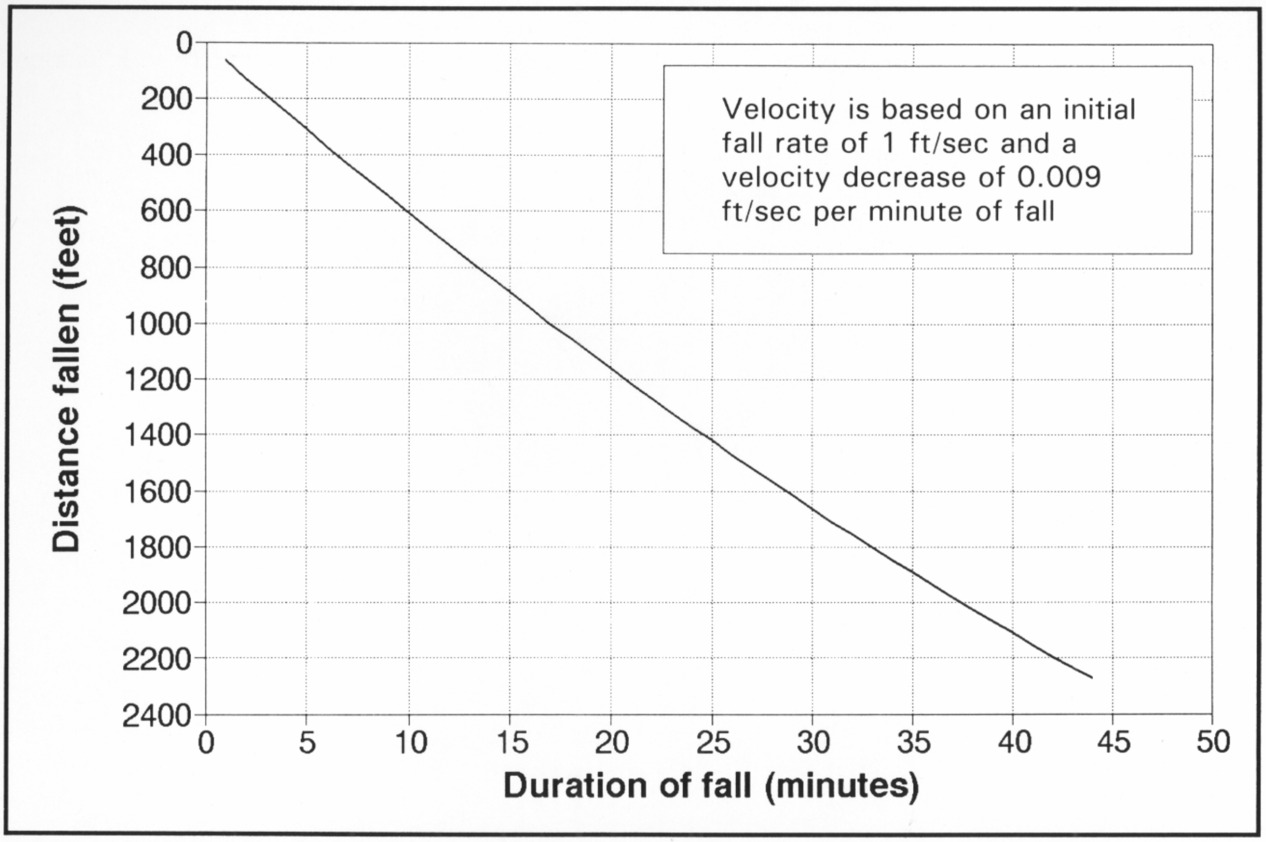


Figure 5—As bentonite chips hydrate and swell, the decrease in density and increase in surface area causes the chips to fall at a slower rate. This produces a slight curve in the relationship between the distance that a chip falls through water and the duration of the fall.

adsorption that occurs as chips fall through the water column in a borehole or annulus.

Gravel fell the fastest (0.6–2.9 ft/sec) with an average rate of 1.6 ft/sec; high-grade and low-grade bentonite chips had indistinguishable fall velocities averaging about 1.0 ft/sec. Smaller size chips have more surface area per unit weight, and therefore a greater resistance to falling. The tests confirmed that as the smallest dimension (or the overall size) decreases the velocity tends to decrease.

Hydration slows the fall velocity of bentonite chips in water at a rate of about 0.009 ft/sec per minute of fall. The chips had an initial fall velocity of just under 1 ft/sec, and after 44 minutes of exposure to water, had decreased to about 0.6 ft/sec. As a chip adsorbs water, its density decreases, becoming closer to that of water. The surface area increases as the chip swells, increasing the ratio of surface area to weight. The result is that the fall velocity of the chip decreases with increasing exposure to water. Adjusting the average fall rate for the effects of hydration, by reducing the velocity 0.009 ft/sec per minute of fall, produces a relationship that has a slight curve **(Figure 5)**. After a period of 44 minutes, an average chip had fallen the equivalent of nearly 2,300 feet. The graph **(Figure 5)** is a curve showing decreasing velocity, and indicates that a maximum depth probably exists for gravity emplacement of bentonite chips, at which bridge formation is virtually assured. However, the data do not indicate what that depth might be.

Emplacement by pumps

The pump pressures required to overcome pipe-friction loss for different types and weights of grout using both a diaphragm and a progressing-cavity pump were documented to determine empirically the maximum length of pipe through which a given slurry could be pumped. Bentonite slurries of 8.6 lb/gal through

10.2 lb/gal, cement slurries and cement-plus-bentonite slurries were pumped (Wheaton and others, 1993b).

Pumps and tremie pipes are used to place fluid grouts at desired depths in subsurface voids. The tremie pipe is set so that the discharge end is very close to the bottom of the borehole, or in a well, just above the sandpack. Between batches of grout the tremie is shortened, effectively raising the discharge end of the pipe. The pipe is raised such that the bottom of the pipe is always lower than the top of the grout plug. In this manner the pump forces the grout into place from the bottom of the hole to the top. Bridging is not normally considered to be a problem when emplacing slurry grouts, however, it should be noted that in a pumping trial using a clear plastic tube as a simulated borehole, a bridge did develop while a high-solids-content grout was being discharged through a tremie.

Several different types of pumps are commonly used for grouting, including piston, rubber-tooth-gear, diaphragm, and progressing-cavity pumps. Most drill rigs use piston pumps to circulate drilling fluids. These are sometimes used for grouting, but they cannot move fluids with high viscosity. Additionally, dry bentonite granules or chips will be sheared and begin hydrating while passing through the pump, thus increasing the viscosity. For these reasons, piston pumps are not considered practical or desirable for grouting.

Rubber-tooth-gear pumps are sometimes suggested for grouting applications. Wear on tooth faces and in bearings was excessive in one model tested using commercial bentonite products, and therefore it was not considered practical for general purpose grouting. It did, however, pump an 8.9 lb/gal slurry through about 100 feet of plastic pipe. With enough care, rubber-tooth-gear pumps may have a role in small grouting jobs.

Diaphragm pumps and progressing-cavity pumps are both popular for pumping thick slurries such as cement or bentonite. In this study the progressing-cavity pump performed better than did the diaphragm pump (Wheaton and Regele, 1993b). A fully hydrated and homogeneous 8.6 lb/gal slurry pumped easily at 25 psi through 500 feet of 1¼-inch pipe with 440 feet of water in the borehole. The pressure gradient for the 8.6 lb/gal slurry at a discharge rate of 60 gpm was 0.3 psi/ft. The 8.8 lb/gal slurry reacted very unpredictably to pumping vertically through 480 feet of standing water and is probably limited to less than 300 feet of tremie for dependable application using a pump capable of at least 200 psi. The pressure gradient for the 8.8 lb/gal slurry at discharge rates that ranged from 3 gpm to 60 gpm averaged about 0.5 psi/ft. The 9.3 lb/gal high-solids slurry contained a high percentage of dry bentonite, which did not greatly increase either the viscosity or the friction loss during pumping. Working quickly with small batches improves the performance of the slurry. The high-solids slurry can be used with confidence up to about 400 feet, with water standing in the borehole using a pump pressure of about 220 psi. The pressure gradient for the 9.3 lb/gal slurry at a discharge rate that ranged from 26 gpm to 65 gpm was about 0.3 psi/ft. However, in addition to the 0.3 psi/ft, an additional 100 psi was required to start the slurry moving. It is not apparent if this is related to the thixotropic behavior of the slurry, or to a restriction that may have developed in the pipe.

Cement-based slurries were tested in horizontal trials rather than in boreholes. The results indicated that the pressure gradient for neat cement and cement-plus-eight-percent-bentonite are both about the same as for the low-solids bentonite slurry (0.3 psi/ft).

The pump pressure required to place a slurry with a given solids content in a borehole is dependent on the degree of hydration of the solids, as well as the length and diameter of the pipe used; also, the Ca^{+2}:Na^{+1} ratio in the bentonite product will affect the viscosity of the slurry. Different brand products, and even products mined by the same company but from different areas, may respond differently to a limited degree.

Field evaluations of grouts in hole-plugging problems

In order to field test the results of the four laboratory trials, two sets of field applications of grouts were implemented. One test involved drilling and plugging four 500-foot-deep boreholes. The other test was stemming (filling) of seismic shotholes with low-grade and high-grade bentonite (Wheaton and others, 1993 c,d).

Plugging of 500-foot-deep holes

Four holes were drilled to a depth of about 500 feet and plugged in order to test emplacement methods and grout column stability. No bentonite or drilling foam was used during the drilling process. The boreholes were drilled in the Upper Cretaceous Judith River Formation, although at locations that were several miles apart. Borehole geology and notes on water-bearing units are available in Wheaton and others (1993c). Generally, the holes included shales and well-cemented sandstones. Between 356 and 483 feet of water stood in all holes during plugging. The bentonite treatments were added through the column of water, and the holes were filled from bottom to top. The holes were plugged with high-grade bentonite chips (HP-1), 9.3 lb/gal bentonite slurry (HP-2), 8.8 lb/gal bentonite slurry (HP-3), and 8.6 lb/gal bentonite slurry (HP-4).

Hydrogeologic setting and methods

Dry chip bentonite

Borehole HP-1 was drilled to a depth of 505 feet. The bedrock consisted of fine-grained sandstone, siltstone and shale. Sandstone made up 49 percent of the borehole lithology, whereas the siltstone and shale accounted for 23 and 28 percent, respectively (Wheaton and others, 1993c).

Water from HP-1 was dominated by sodium and bicarbonate ions and had a dissolved solids content of 813 mg/L **(Table 1)**. The pH was 8.6, and the temperature in the formation was 11.6^{o}C. Water production from the open borehole was less than 1 gallon per minute. The static water level was 22.5 feet below ground surface. The results of a caliper log were used to calculate the borehole volume, which was 774 gallons (103 cubic feet).

Borehole HP-1 was plugged from bottom to top using high-grade, commercial bentonite chips. For this hole, two sizes of chips (¾-inch and ⅜-inch) were used. A total of 130, 50-pound bags, or about 104 cubic feet of chips were used to plug HP-1. The chips were gravity fed through the 382-foot column of water. Because of the simplicity of the feeding method, it was easily accomplished by one person.

To control the pouring rate, the chips were poured through two types of structures. The first method was a simple PVC funnel with reducers on the end to provide choices of hole size **(Figure 6)**. The outlet hole sizes were chosen based on chip size and time per bag. After several practice pours, the rate per bag could be held fairly constant. However, some bridging occurred in the funnel when the chips were poured too fast. The best results with the funnel were achieved using ⅜ inch chips and a 1½-inch diameter outlet. The funnel is not a commercially available product, but was constructed using a combination of common polyvinyl chloride (PVC) fittings and pipe.

The second method of controlling the pour rate of the chips was the use of a chip slide constructed of plywood **(Figure 6)**. The outlet opening was controlled by two wooden 2x6s that were hinged to allow adjustment and held in place by clamps. The slide was built in such a manner that the angle of the tray could be adjusted until the angle of repose of the particular batch of chips was achieved. The best results were with a 1-inch opening, with the slide set 40 degrees above horizontal and using ⅜-inch chips. With these settings, the pour rate was very even and dependable.

High-solids bentonite slurry

Borehole HP-2 was drilled to a depth of 502 feet. The bedrock consisted of shale, fine-grained sandstone, and some siltstone. Shale made up 61 percent of the lithology and sandstone and siltstone made up 23 percent and 2 percent, respectively, (Wheaton and others, 1993c).

The water from HP-2 was dominated by sodium and bicarbonate ions and had a dissolved-

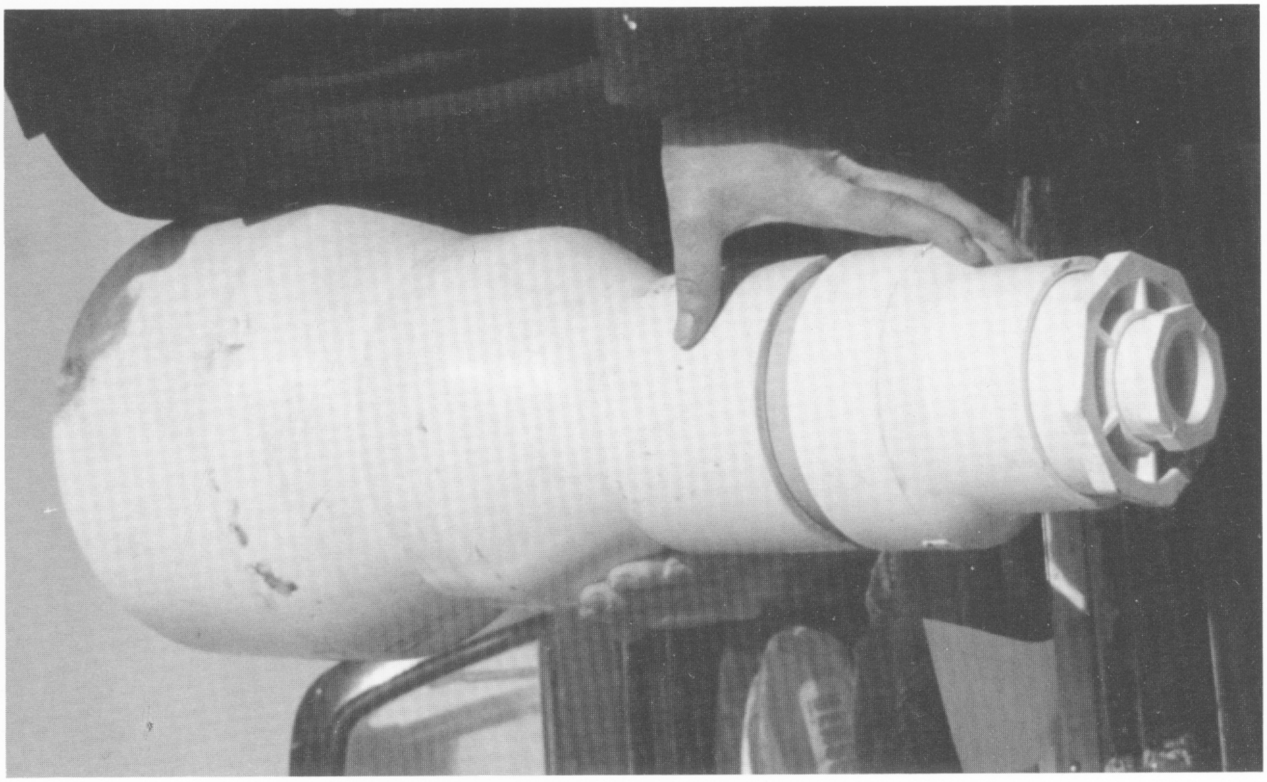


Figure 6—Two types of pour-rate control apparatus were used. The PVC funnel (top) performed acceptably with ⅜-inch chips, but occasionally bridged. The wooden chip tray (bottom) provided maximum flexibility with different chip sizes.

Table 1—Results of water-quality analyses for 500-foot-deep boreholes and water used to mix slurries.[1]

Formation Water

Source	Lab Number	Location	Date Sampled	Total Depth (feet)	Water Level (feet)	Field pH	Field Temperature (°C)	Field Conductance (μmhos/cm)
HP-01	92Q0014	02S21E08ACDA	01/29/92	505	102.3	8.6	11.6	1300
HP-02	92Q0015	04S21E12CAAC	01/07/92	502	36.9	8.7	7.7	1030
HP-03	92Q0016	04S21E12DBBA	01/10/92	515	32.0	8.1[†]		6870[†]
HP-04	92Q0017	04S22E07CBCA	01/24/92	502	58.0	8.0[†]	11.0	2160

Source	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Total Dissolved Solids (mg/L)
HP-01	11	3	290	2	469	0	64	196	810
HP-02	9	6	229	2	411	41	14	90	610
HP-03	29	7	1670	3	589	0	42	3150	5200
HP-04	62	27	459	4	1075	0	19	339	1450

Slurry Preparation Water

Source	Lab Number	Location	Date Sampled	Field pH	Field Temperature (°C)	Field Conductance (μmhos/cm)
Rock Creek	92Q0019	04S22E14DDBC	01/24/92	7.6	0.4	250

Source	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Total Dissolved Solids (mg/L)
Rock Creek	146	69	138	2	332	0.0	23	648	1200

[†]Laboratory values
[1]All analyses were performed at the MBMG laboratory, Butte.

Table 2—Slurry-mixing ratios for plugging 500-foot-deep boreholes.[1]

Grout Type	Mud weight (lbs/gal)	Water (gal)	Powdered Bentonite (pounds)	Granular Bentonite (pounds)	Percent solids by volume
High-solids bentonite slurry for 500-ft borehole (HP-2)	9.3	60	50	50	8.0
Medium-solids bentonite slurry for 500-ft borehole (HP-3)	8.8	55	50	0	3.8
Low-solids bentonite slurry for 500-ft borehole (HP-4)	8.6	150	100	0	2.1

[1]All bentonite products were high-grade commercial materials containing predominantly sodium montmorillonite.

solids content of 605 mg/L. The pH was 8.7, and the temperature was 7.7°C **(Table 1)**.

The static water level in HP-2 was 36.9 feet below ground surface. Water production from the open borehole was about 18 gallons per minute. The results of a caliper log were used to calculate the hole volume, which was 706 gallons (94 cubic feet). HP-2 was plugged from bottom to top with 595 gallons of high-solids, high-grade bentonite slurry with a weight of 9.3 lbs/gal. Chemical analysis of a sample of the Rock Creek water used for make-up is shown in **Table 1**. The calculated dissolved-solids content of the make-up water was 1,200 mg/L; dominant ions were calcium, sodium and sulfate. The pH was 7.6 and the temperature was 0.4°C.

Slurries that were mixed with 100 gallons of water and 100 pounds each of powdered and granular bentonite were too viscous to be pumped and were discarded. The final slurry mixture contained 60 gallons of water and 50 pounds of each bentonite product. Details and mixing ratios for the slurries are listed in **Table 2**. During the pumping process, the slurry contained granular bentonite that was not yet hydrated.

Medium-solids bentonite slurry

Borehole HP-3 was drilled to a depth of 515 feet. The bedrock consisted of shale, fine-grained sandstone, and some siltstone. Shale comprised 49 percent of the borehole lithology, sandstone was 38 percent and siltstone was 11 percent (Wheaton and others, 1993c).

The water from HP-3 was dominated by sodium and sulfate ions, and had a dissolved solids content of 5,200 mg/L. The pH measured at the laboratory was 8.1 **(Table 1)**. The static water level in HP-3 was 32 feet below ground surface. Water production from the borehole was about five gallons per minute. The results of a caliper log were used to calculate the hole volume, which was 634 gallons (85 cubic feet).

HP-3 was plugged from bottom to top with 625 gallons of medium-solids-content, high-grade bentonite slurry with a weight of 8.8 lbs/gal. The slurry was a mixture of 55 gallons of make-up water and 50 pounds of powdered bentonite **(Table 2)**. The make-up water was the same as used at HP-2 **(Table 1)**.

Low-solids bentonite slurry

Borehole HP-4 was drilled to a depth of 502 feet. The bedrock consisted of shale, fine-grained sandstone, and some siltstone. Shale made up 58 percent of the borehole lithology, sandstone 28 percent and siltstone 2 percent (Wheaton and others, 1993c).

The water from HP-4 was dominated by sodium and bicarbonate ions and had a calculated dissolved solids content of 1,450 mg/L **(Table 1)**. The pH was 8.0 and the temperature was 11.0°C. The static water level in HP-4 was 58.0 feet below ground surface. Water production from the hole was about five gallons per minute. The results of a caliper log were used to calculate the hole volume, which was 594 gallons (79 cubic feet).

HP-4 was plugged from bottom to top with 768 gallons of low-solids-content, high-grade bentonite slurry that weighed 8.6 lbs/gal. The slurry was a mixture of 150 gallons of makeup water and 100 pounds of powdered bentonite. The make-up water was the same as that used at HP-2 and HP-3 **(Table 1)**.

Results of the 500-foot borehole plugging tests

Generally, the higher solids contents of the grout materials were reflected in less settling in the columns. The actual mixing ratios and percent solids by volume for the slurry grouts are listed in **Table 2**. [The chip bentonite was added in dry form, and therefore is not included in **Table 2**.] Dry chip bentonite has a porosity similar to gravel, and has a solids content of about 80 percent. A 50-pound bag fills a void volume of about 0.8 cubic feet.

Depths from ground surface to the top of the bentonite plugs were measured over a period of nine months at each of the four sites. The rates of settling of the grout columns with respect to time are shown in **Figures 7-10**. During that time the top of the bentonite-chip plug in hole HP-1 dropped 0.3 feet **(Figure 7)**. The top of the plug was dry throughout the monitoring period. The three types of slurry grouts were all made from the same type of 200-mesh bentonite, with the exception that the 9.3 lb/gal slurry also contained 8 to 20 mesh granular bentonite **(Table 2)**. The top of the 9.3 lb/gal bentonite plug in hole HP-2 dropped about 1.5 feet very rapidly **(Figure 8)**. During the remainder of the test, the plug dropped very slowly an additional 0.25 feet. The top of the 8.8 lb/gal bentonite plug in hole HP-3 dropped about 10 feet very rapidly **(Figure 9)**. During the remainder of the test, the depth to the top of the plug stayed within about a 1-foot range, at between 10 and 11 feet below ground surface. The top of the 8.6 lb/gal bentonite plug in hole HP-4 dropped more than 207 feet over a period of one month **(Figure 10)**. During the remainder of the test, the depth to the top of the plug increased slightly to about 209 feet below ground surface.

The solids content of the grout mixtures and the borehole lithology determined the rate at which the grouts settled in the boreholes. The chips did not settle, and the low-solids (8.6 lb/gal) slurry settled more than 200 feet over a period of about 6 months, which was about 42 percent of the original column height. There is an inverse correlation between the solids content of the grout, and the amount of settling of the grout column. However, the amount of settling with the 8.6 lb/gal grout is far greater than the other grouts. Particularly surprising is the difference between the 8.6 lb/gal and 8.8 lb/gal grouts. The volumetric solids contents for the 2 grouts were 2.1 percent and 3.8 percent, while the settling of the grout columns reached 42 percent and 2 percent, respectively. Both grouts were made from the same commercial product. The borehole lithologies are similar at HP-3 and HP-4 since they were drilled in the same section of the Judith River Formation and were located less than one mile apart. The amount of shale at the two holes was 50 percent at HP-3 and 60 percent at HP-4.

There are three possible explanations for the observed differences in settling rates. The first is that ion exchange reactions could have caused the bentonite gel in HP-4 to flocculate. As discussed previously, if the sodium ions in the inter-cell position are replaced by calcium, the maximum potential swelling decreases several times. The formation water **(Table 1)** at HP-4 contains a higher calcium concentration than at HP-3, however, the difference does not seem significant enough to cause the difference in settling rates.

The second possibility is that the slurry in HP-4 flowed away from the borehole, either through porosity in the sandstones or through fractures. Primary porosity is not likely to explain the difference in grout performance between the holes. Fractures, though not detected during drilling, could have been intercepted by HP-4.

The third possibility is that a separation developed in the grout column at HP-3. The lower part of the column may have settled at a rate that is more comparable to HP-4, but the top settled at a slower rate. Differences in settling within a single grout column could occur due to heterogeneities in the grout, or because of differences in the borehole wall.

In order for a grout or abandonment plug to be effective either hydrologically or physically, it

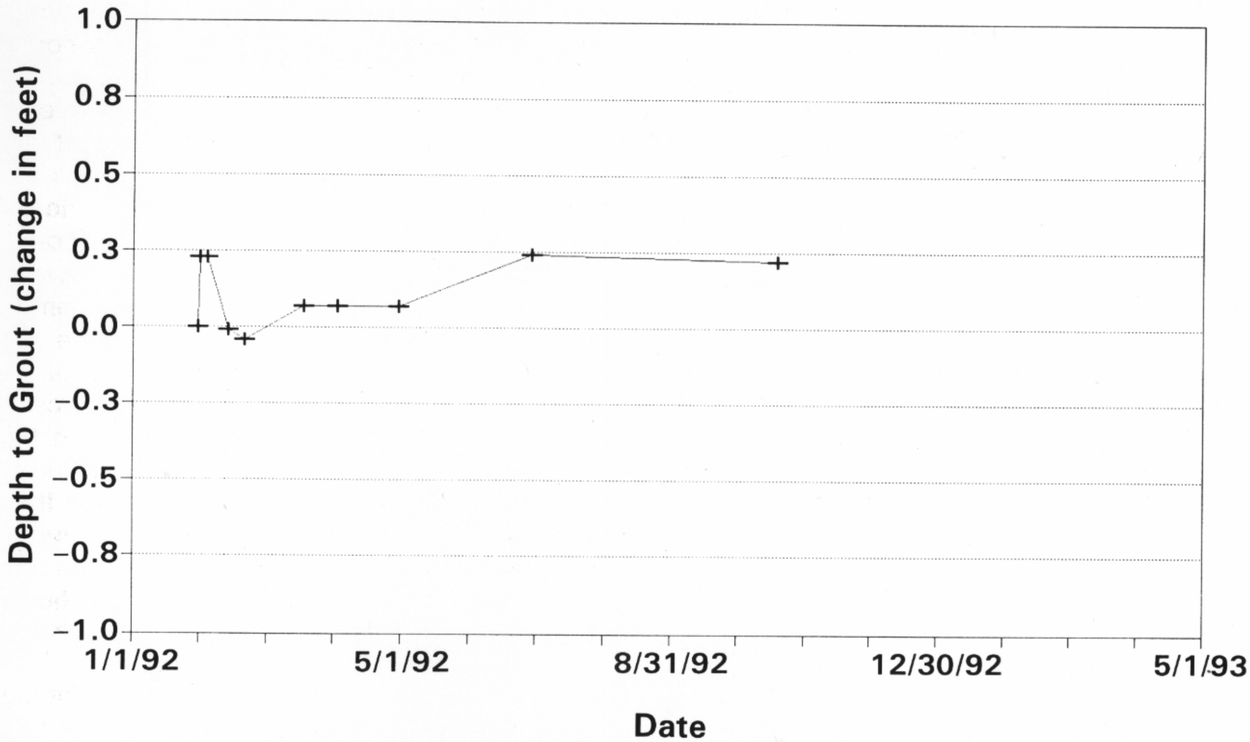


Figure 7— The depth to the top of the bentonite-chip grout remained fairly stable within a range of 0.3 feet in 500-foot borehole HP-1.

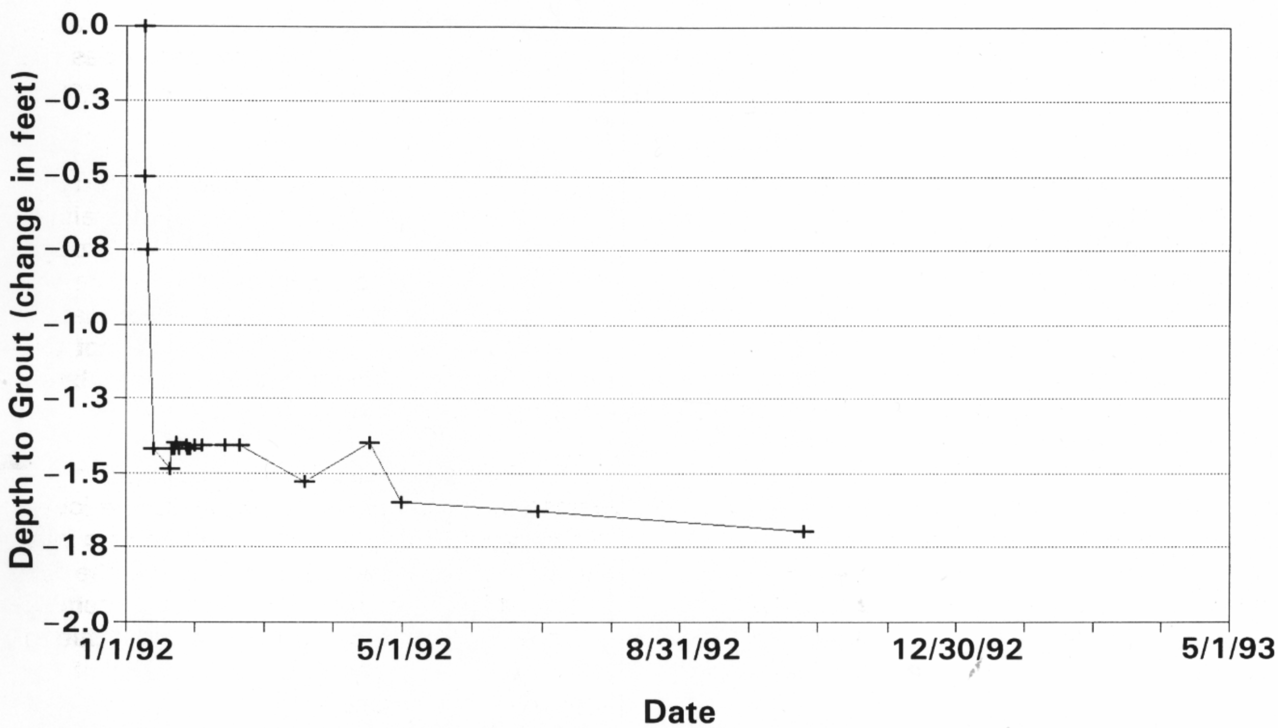


Figure 8—The 9.3 lb/gal slurry grout declined 1.5 feet rapidly, then slowly settled an additional 0.25 feet in 500-foot borehole HP-2.

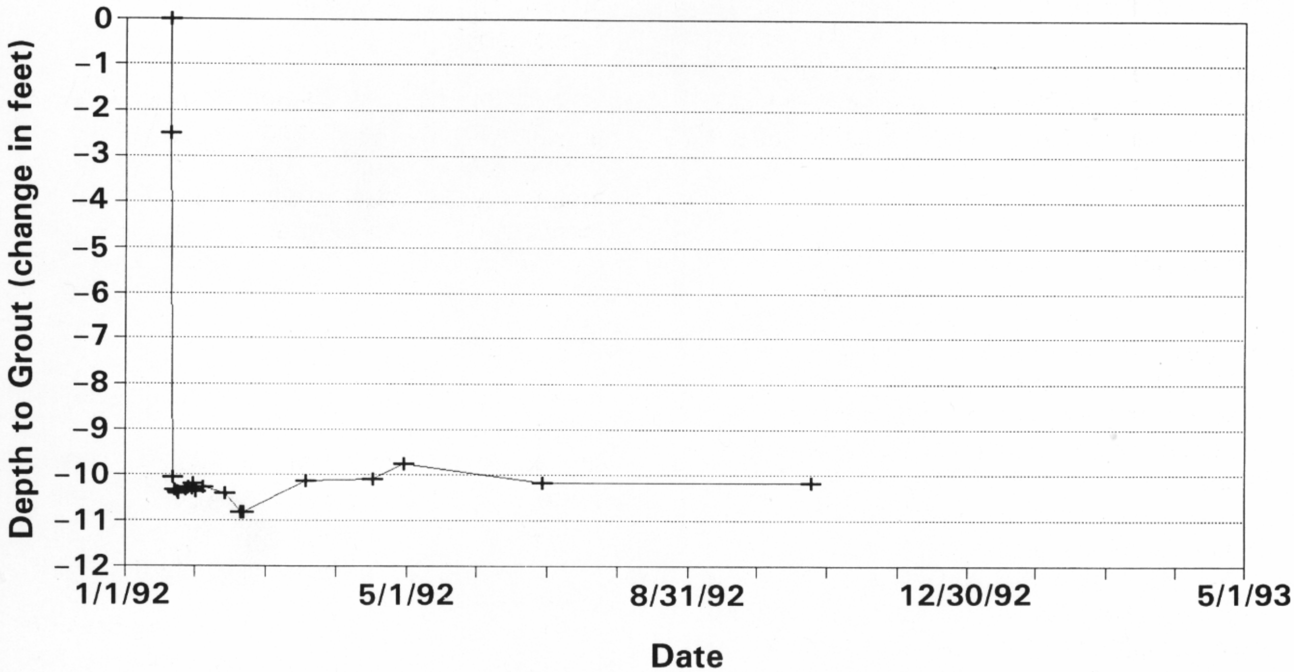


Figure 9—The 8.8 lb/gal slurry grout declined about 10 feet, then remained fairly stable within a 1-foot range in 500-foot borehole HP-3.

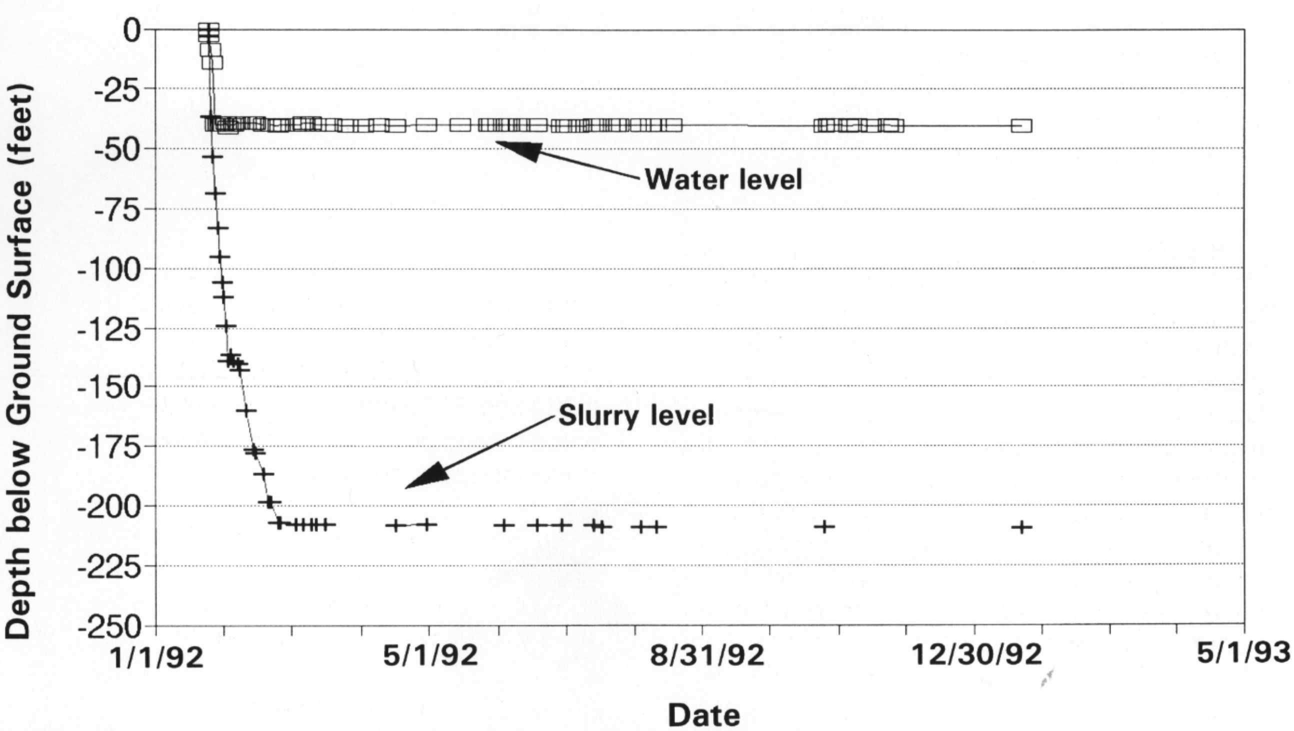


Figure 10—The 8.6 lb/gal slurry grout declined more than 207 feet within 1 month, then slowly declined an additional 2 feet in 500-foot borehole HP-4.

must remain in the desired portion of the hole. Results of the 500-foot-hole plugging trials indicate that a high-solids slurry (> 9 lb/gal) or chips can provide physically stable plugs. Slurries must be checked and retopped after settling has occurred. Settling may continue for as little as a few days or for more than six months.

Plugging of seismic shotholes

Tests of stemming materials were conducted in eight seismic shotholes. At each site, one monitor well was completed in each of two water-bearing sandstone units adjacent to the shotholes. Due to an apparent failed annular seal in one monitor well, the hydrologic data from that site were not considered valid. The effectiveness of the stemming material was documented at four high-grade and three low-grade bentonite-stemmed shotholes. Additional details and lithologic descriptions of the seismic stemming tests may be found in Wheaton and others, (1993d).

Hydrogeologic setting for seismic tests

The site chosen for shothole stemming tests was in Stillwater County, in south-central Montana along the flood plain and terraces of Hensley Creek, about 5 miles northeast of Columbus. The local geology consisted of interbedded sandstones and shales of the Judith River Formation overlain by unconsolidated gravel, sand and silt deposits **(Figure 11)**.

A partially-saturated gravel aquifer and two shallow water-bearing sandstones separated by low-permeability shales of the Judith River Formation were penetrated by drilling. The shallow gravel and the upper sandstone are one hydrologic unit; however, the deeper sandstone is hydrologically separate. Static water levels for the shallower sandstone are shown in **Figure 11**. Water levels in the deeper sandstone did not reach static levels at all sites during the study duration, and therefore are not included in the figure; however, there was a downward gradient from the shallower aquifer to the deeper aquifer. The surface water in Hensley Creek was at a higher elevation than the water table in the shallow sandstone aquifer. Water-level changes at four monitor wells are shown in **Figures 12–15**. Monitoring activities that could have impacted water levels included drilling, development work, purging and sample collection, slug testing and shot detonations.

The upper sandstone was yellowish-brown to gray, fine to medium grained. The sandstone was probably weathered, and aquifer porosity was probably a combination of weather-enhanced primary and secondary-fracture porosity. The shallow sandstone water was under unconfined to semiconfined conditions. Slug tests performed at monitor wells indicated that hydraulic conductivity in the shallow aquifer ranged from 10^{-2} ft/day to 63 ft/day. Water in the shallow aquifer had a temperature of 9.0°C to 10.0°C. The pH ranged from 7.2 to 7.5 and the specific conductance was 1,770 to 2,900 µmhos/cm. Results of laboratory analyses indicated that in terms of percent milliequivalent per liter (percent meq/L), the water in the shallow aquifer was dominated by nearly equal amounts of calcium, sodium and magnesium cations. The dominant anion was sulfate, and the calculated dissolved-solids concentration was 1,690 mg/L.

The deeper sandstone was gray, fine to medium grained. Porosity in the deeper aquifer was due almost entirely to fractures. Water in the deeper sandstone was under confined conditions. Hydraulic conductivity in the deeper aquifer ranged from 3×10^{-4} ft/day to 4×10^{-1} ft/day. For comparison, the hydraulic conductivity of high-grade bentonite is reported to be less than 10^{-5} ft/day. Because the recovery times after sampling and development in the deeper aquifer are extremely long, slug test results may be erroneously high and may reflect local effects of drilling and development. In the deeper sandstone, the water temperature was 9.5°C; the pH ranged from 8.1 to 8.9 and the specific conductance was between 1,120 and 2,470 µmhos/cm. The water was dominated by sodium and bicarbonate ions and had a dissolved-solids concentration of 744 mg/L.

Eight, 5⅛-inch seismic shotholes were drilled to a depth of 75 feet, loaded with 10 pounds of explosives and stemmed. Holes 2, 4, 6 and 8 were stemmed with low-grade bentonite chips; holes 1, 3, 5, and 7 were stemmed with high-grade bentonite chips **(Figure 11)**. The calculated shothole volume was 10.7 cubic feet. All of the holes (excepting shothole 6) were plugged with between 11.2 and 12.4 cubic feet of stemming

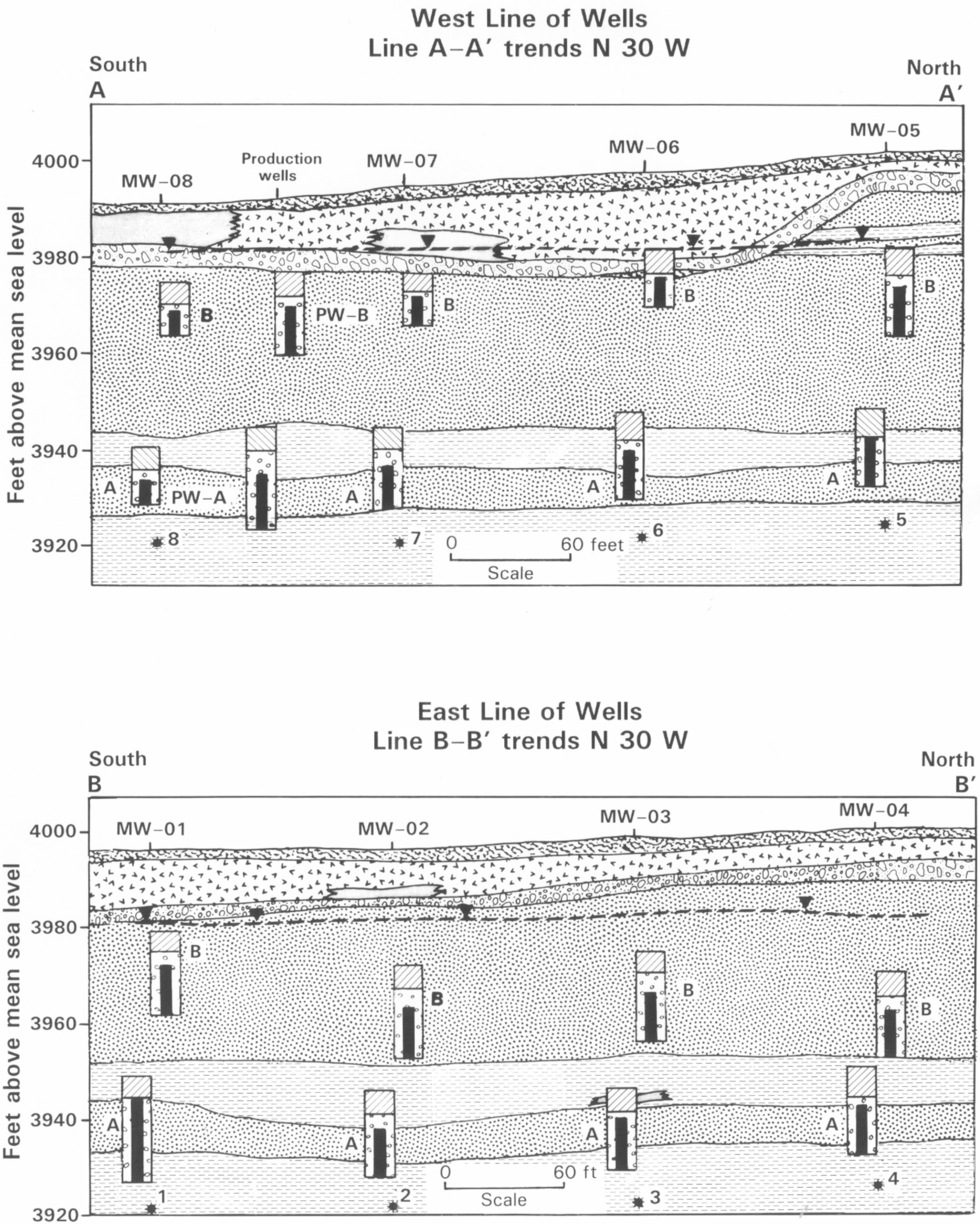
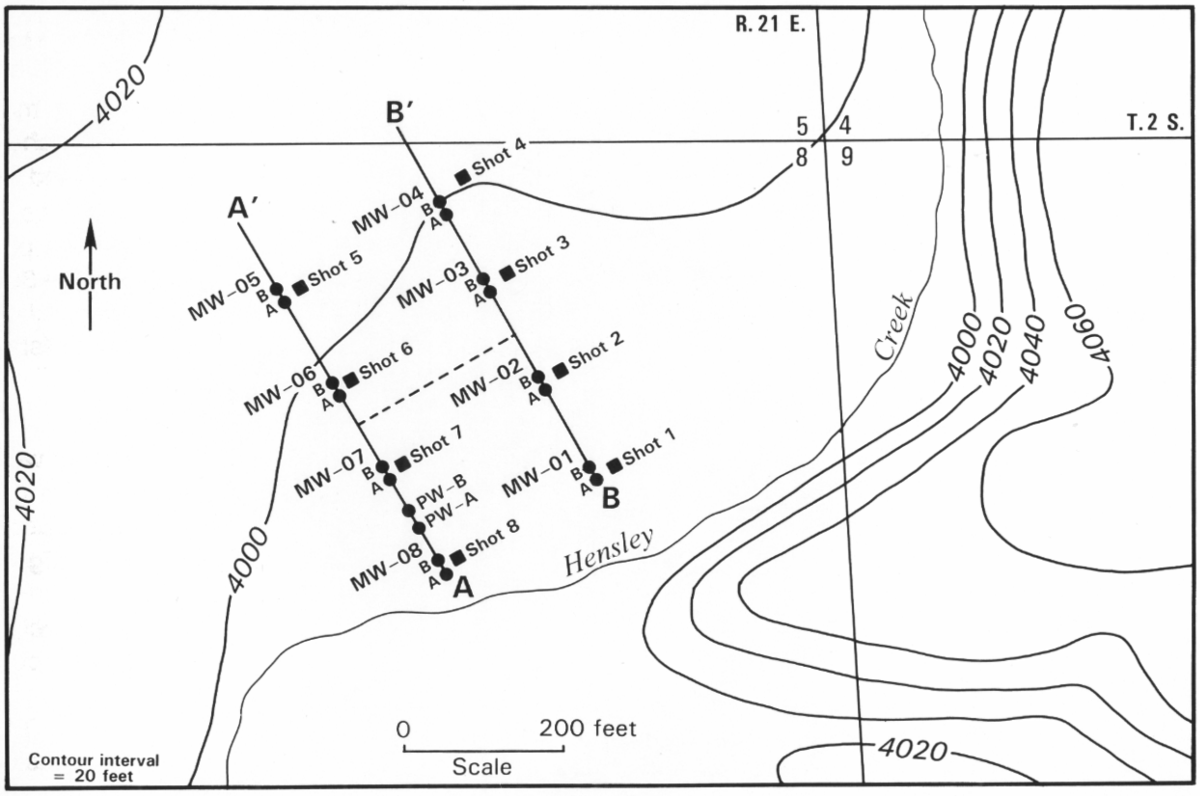


Figure 11—The seismic test site contained a shallow gravel aquifer and two sandstone aquifers in the Judith River Formation. The tests consisted of two seismic transects with four shotholes each and eight monitor wells.



EXPLANATION

LITHOLOGIC DESCRIPTION

Topsoil, dark brown, clayey

Silty clay, yellowish brown, fine grained

Sand, yellowish brown, fine grained

Gravel, yellowish brown, sandstone fragments, silt and clay

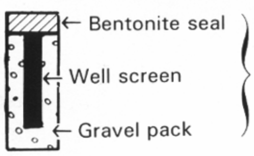
— Alluvial deposits

Sandstone, gray, yellowish brown at top, fine to medium grained

Shale, dark brown to dark gray, sand, silty, bentonite layers

— Judith River Formation

COMPLETION DESCRIPTION



All wells

Vertical exaggeration 1:4

5 — Shot hole, indicating location of charge

Hydrostatic water pressure of shallow aquifer

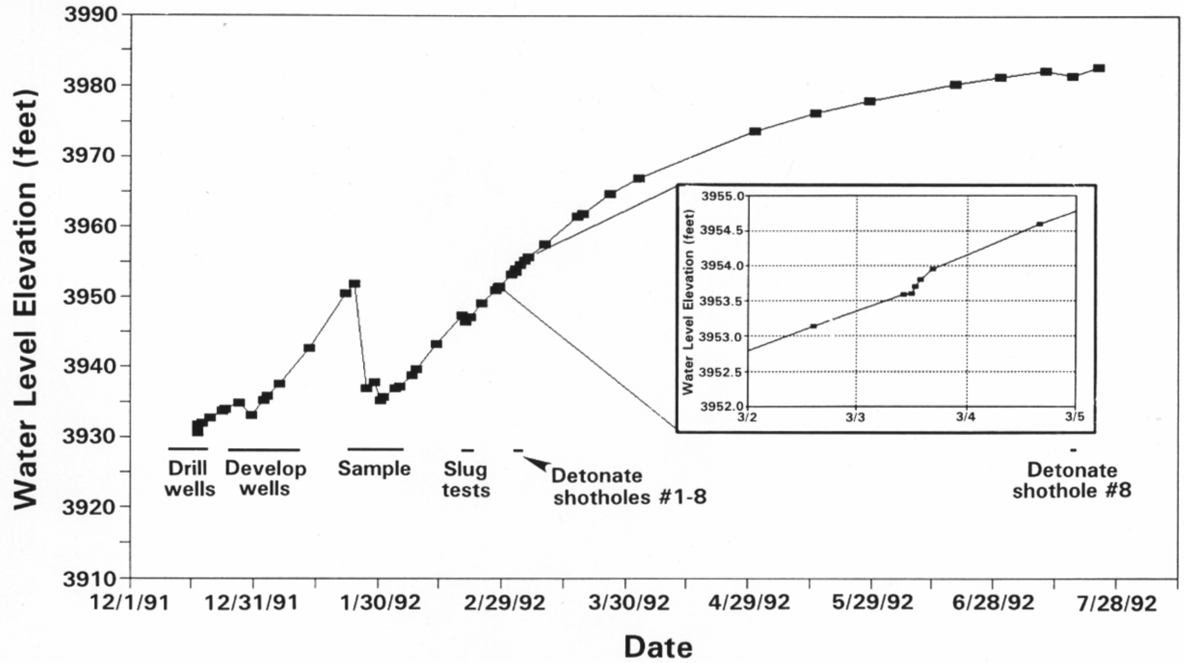


Figure 12—The water level in the deeper aquifer at the seismic test site near shothole 2 gradually increased. Shothole 2 was stemmed with low-grade bentonite. The inset graph shows the water level in the deeper aquifer during seismic blasting (shown at an expanded scale).

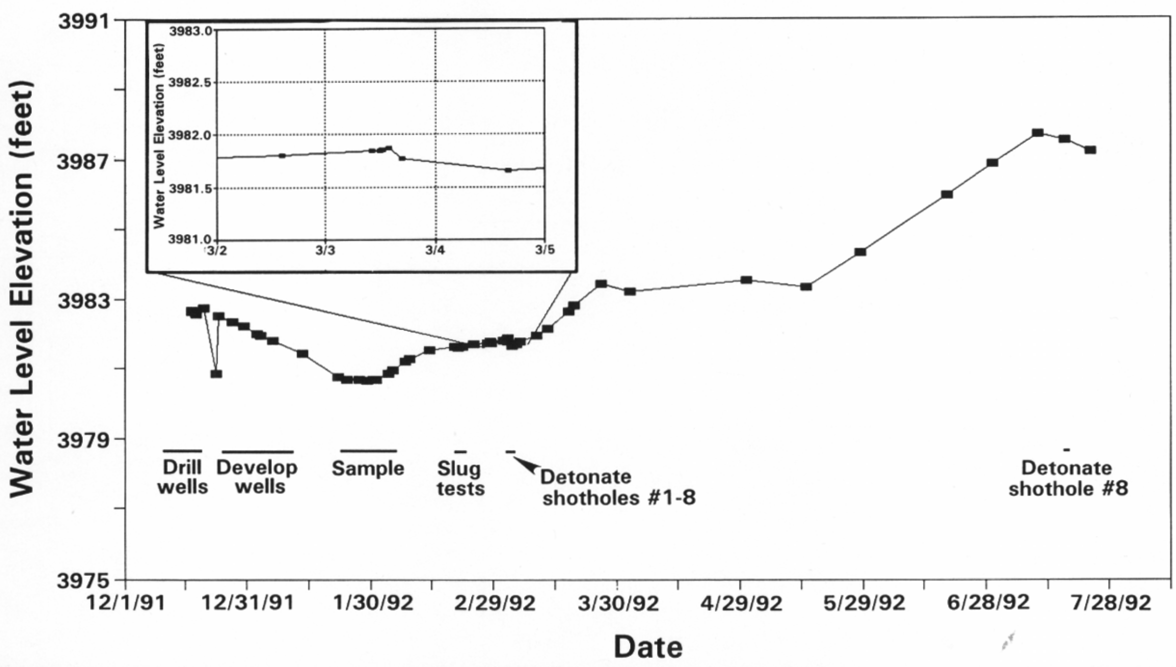


Figure 13—The water level in the shallower aquifer at the seismic test site near shothole 2 responded to seasonal variations. Shothole 2 was stemmed with low-grade bentonite. The inset graph shows the water level in the shallower aquifer during seismic blasting (shown at an expanded scale).

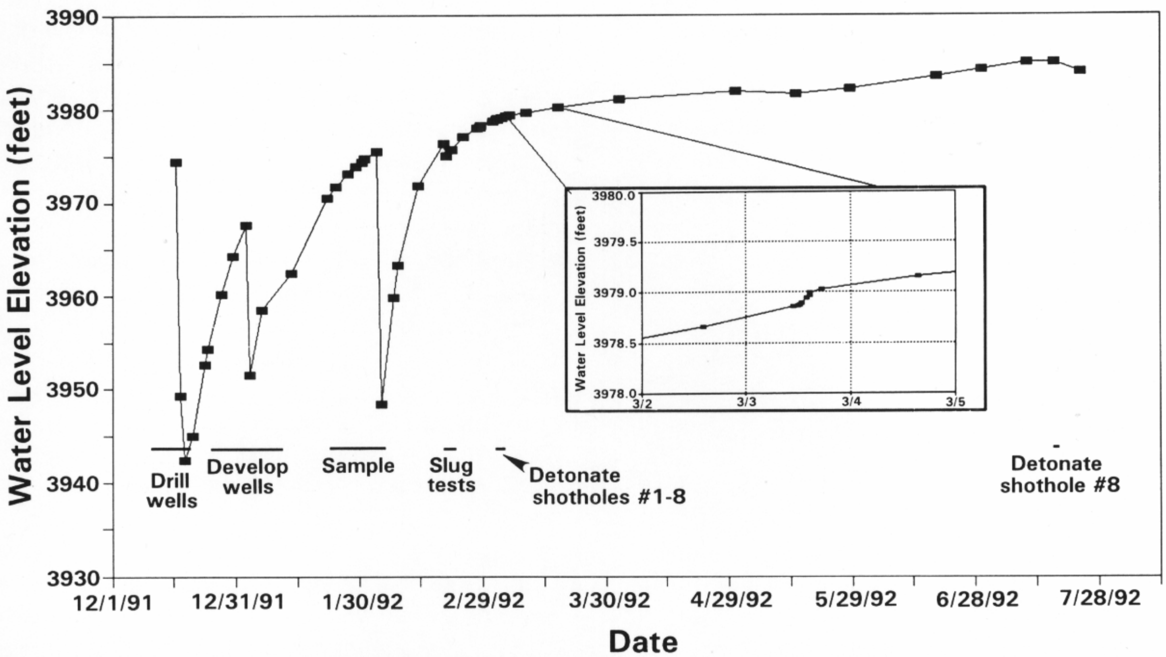


Figure 14—The water level in the deeper aquifer at the seismic test site near shothole 5 remained fairly stable after recovering from the effects of drilling and sampling activities. Shothole 5 was stemmed with high-grade bentonite. The inset graph shows the water level in the deeper aquifer during seismic blasting (shown at an expanded scale).

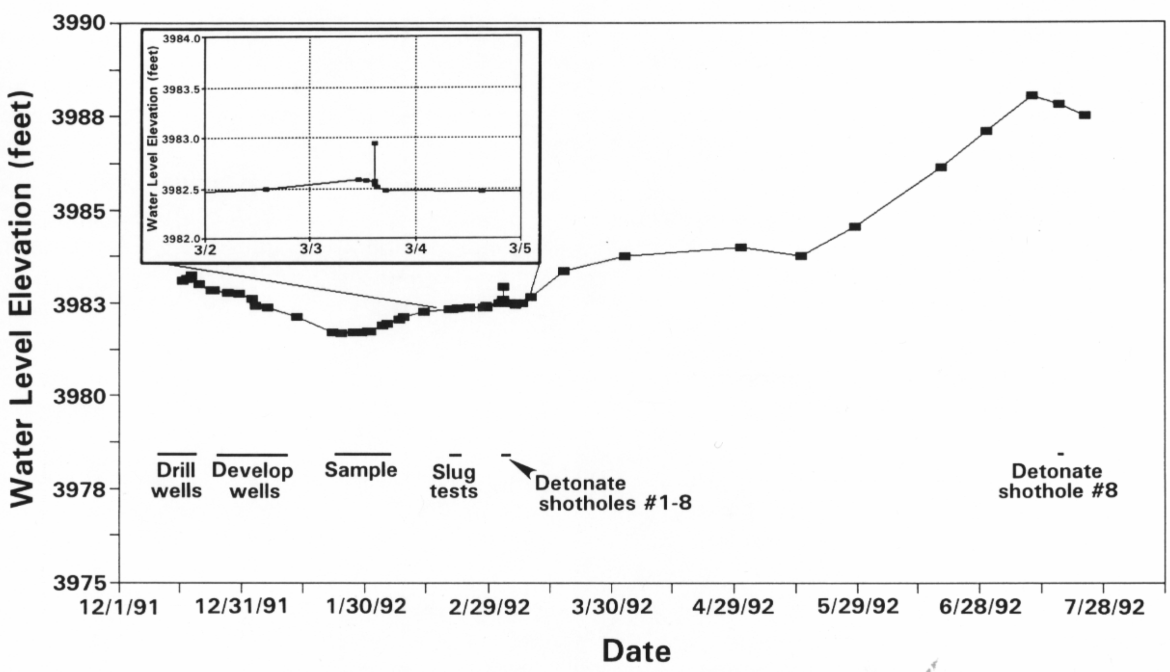


Figure 15—The water level in the shallower aquifer at the seismic test site near shothole 5 responded to seasonal variations. Shothole 5 was stemmed with high-grade bentonite. The inset graph shows the water level in the shallower aquifer during seismic blasting (shown at an expanded scale).

material. Shothole 6 was stemmed with 8.7 cubic feet of material, apparently due to bridging.

The high-grade bentonite was poured directly from 50-pound bags into holes at a rate of about one minute per bag. The low-grade bentonite was shoveled across a screen that had ½-inch openings. Chips that did not pass through the screen were poured into the shotholes at about the same rate as the high-grade chips. The stemmed holes were allowed to stabilize for several weeks before the shots were detonated.

Results of the shothole stemming applications

Both the physical stability and the hydraulic quality of the stemming and grouting materials were tested. An important measure of the physical stability of stemming material is how well it withstands ground motion such as the shock of seismic blasting. No attempt was made to record the seismic energy of the shots. Visual observations and photographs during the detonation show that significant motion of the stem occurred only at shothole 8. At this hole, loaded with low-grade bentonite, the entire column of stemming material, along with about 15 feet of steel surface casing, blew out of the hole with the shot. Shothole 8 was successfully stemmed a second time with high-grade bentonite, and is discussed later in this report.

The hydraulic quality of seals in the seismic shotholes was tested before and after the shots had been detonated. The hydrostatic pressures in the aquifers had been drawn down by the removal of water during the drilling and development of monitor wells and shotholes. If the well-annular seals and the shothole stemming seals were effective, the hydrostatic pressures in the aquifers should have eventually returned to the pre-drilling or undisturbed levels. Since no data can be gathered before drilling, the investigation of seal quality can only be made by identifying trends in the water-level data after drilling **(Figures 12–15)**. In the seven shotholes where valid hydrologic data were collected, water levels rose after drilling-related withdrawals, and the pressures in the two aquifers followed different trends, therefore the stem is assumed to have effectively separated the aquifers.

At all seven sites the aquifers recovered from drilling and later responded to development and sampling activities in a predictable manner. Short-term recovery trends were indicated in the deeper aquifer at several monitor sites where low-grade and high-grade bentonite chips were used. In general, more change and faster recovery was seen in the areas with higher hydraulic conductivity (southwestern part of study area). The extremely slow but consistent recovery of hydrostatic pressure in some wells such as in the deep aquifer at site 2 **(Figure 12)** indicates very low hydraulic conductivity and good seals, which did not allow communication between aquifers to hasten recharge. The data indicate that both high-grade and low-grade bentonite can provide adequate seals prior to a detonation.

Detonation in the shotholes that were stemmed with low-grade bentonite caused water-level responses that were very similar to those where the holes were stemmed with high-grade bentonite. The maximum change was 0.8 feet and most responses were short term. At shothole 2, which was stemmed with low-grade bentonite, an apparent communication developed between the aquifers **(Figures 12,13)**. The water level rose in the deep aquifer and dropped in the shallow aquifer. Within a few days, the effects of water-level fluctuation from blasting were covered by seasonal variations in water levels. A similar response was recorded at shothole 4 (Wheaton and others, 1993d).

Where shots were stemmed with high-grade bentonite, the water-level responses were generally short term and between 0.4 feet and 0.8 feet. For example, at site 5 which was stemmed with high-grade bentonite **(Figures 14, 15)**, the water level in the shallow aquifer dropped, and the level in the deeper aquifer rose in response to the detonation. The changes in hydrostatic pressure lasted at least one week and then became indistinguishable from the seasonal variations. The data indicate that communication developed between the aquifers at this site. Paths of communication could be either a failed seal or a blasting-induced fracture in the intervening aquitard. Time and pressure allowed the seals to re-establish, and the water-level trends now follow the aquifer-wide seasonal trends. Similar responses occurred at other shotholes stemmed with high-grade bentonite.

At shothole 8, which was stemmed with low-grade bentonite, the stemming material was blown out of the hole **(Figure 16)**. Water flowed

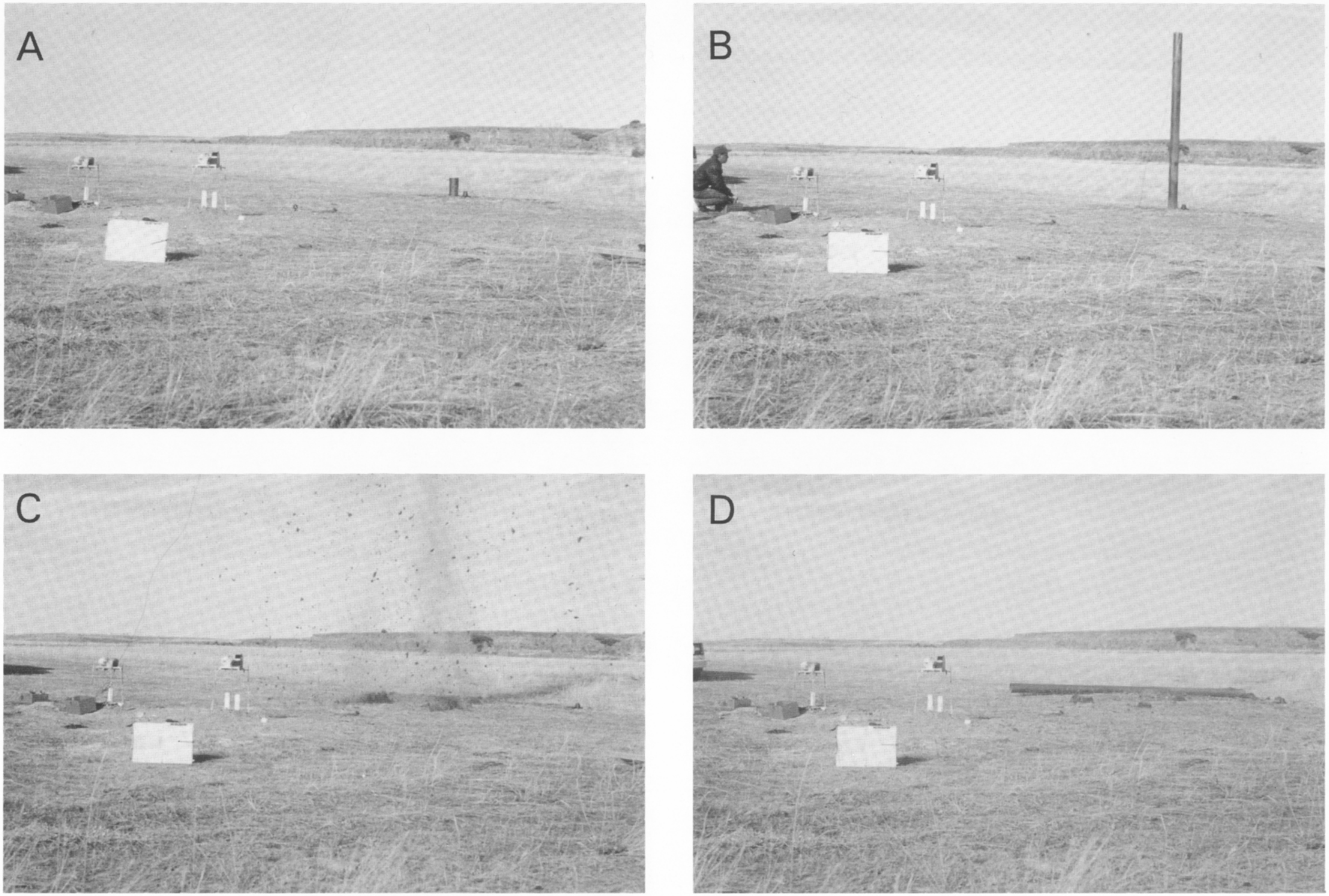


Figure 16—Shothole 8 was stemmed with low-grade bentonite chips (A). As the charge was detonated, the stemming material was completely ejected from the hole by the blast. Note the lead wire following the steel surface casing in frames (B) and (C). The stem material was scattered over a large area by the blast rather than forming a mound near the shothole (D).

out of a fracture in the shallow sandstone and quickly filled the shothole. The deeper sandstone showed a small, short-term impact to water level, but the water level in the shallow aquifer at shothole 8 showed only the near-instantaneous water-level rise and recovery due to the energy wave from the blast. The shothole was recharged, and stemmed with high-grade bentonite chips, and allowed to sit for several months. When the second charge in shothole 8 was detonated, no water-level impacts were detected during or after the shot except for short-term fluctuations at the deeper monitor well.

Water levels in both the shallow and deeper aquifers were monitored for five months after the shots were detonated. The data do not indicate communication through the shotholes between the aquifers, or surface water infiltration to the aquifers **(Figures 12–15)**. The vertical gradient continued to be downward. The shallow aquifer showed more seasonal variation in water level than did the deeper aquifer. Water levels in wells completed in areas of very low hydraulic conductivity in the deeper aquifer continued to recover at about the same rate as before the shots. Very little difference can be seen between high-grade and low-grade bentonite performance as a stemming material in this hydrogeologic setting.

Choosing the correct grout

The best grout for a particular situation should serve the desired purpose and be selected by considering the borehole or well, available grout materials, equipment, and project budget. The borehole size or well completion determine the work space that is available, in terms of depth and width. The water quality and lithology surrounding the borehole may limit the choices of material. The availability of grout materials and the characteristics of those materials must be compared to the purpose of the grout. The type of equipment that is available at a project site may also limit the choices of grout materials. Finally, although the grout must fulfill a given purpose, it also should be economical and legal to use.

The purpose of a grout is primarily determined by the hydrogeology and lithology surrounding the borehole. Grouting is intended to block the movement of water or other fluids, and to provide physical stability to geologic formations. In order to prevent the movement of water in the borehole or annulus, the grout must have a hydraulic conductivity that is less than that of the adjacent aquitards. The U.S. Environmental Protection Agency (1992) suggests that a grout have a hydraulic conductivity that is one to two orders of magnitude less than that of the surrounding formations. Any of the grouts tested in this study have low hydraulic conductivities with the exception of the gravel-plus-bentonite mixture. If the grout must withstand artesian pressure, then it must be both physically strong and have a low hydraulic conductivity. For a physically strong grout, the best choice might be bentonite chips, or in the case of high pressure, cement. If the grout is intended mainly to provide physical stability for a borehole or well casing, such as above the saturated zone, then the material choice will be based mainly on physical strength. Any of the high-solids materials could provide this function.

Due to emplacement limitations, the depth and diameter of the borehole may limit the choice of grout materials. If the depth exceeds 400 feet, then the types of high-solids slurries and pumps that were tested should not be used (Wheaton and Regele, 1993b). In an unobstructed borehole, gravity-fed bentonite chips may be the best choice. Based on results in the gravity-feeding trials (Wheaton and others, 1993a) and in 500-foot-borehole HP-1, chips should fall without bridging if poured at a steady and slow rate in a water-filled, open borehole (4–6-inch diameter) up to depths of at least 2,000 feet. The manufacturer's recommendation of pouring at a rate of 1 to 2 minutes per 50-pound bag appears to be an acceptable guideline.

When grouting the annulus of a well, it is important that the grouting material completely surround the casing. Contact between casing and sidewall can create areas (dead spots) where little or no sealant is emplaced. Casing centralizers have been recommended to avoid this problem

(Driscoll, 1986). Such centralizers can, however, act as obstacles or bridging points in a hole where chip bentonite is to be used. For this kind of application, the operator should take care to select centralizers whose design presents a minimal profile in the vertical direction. Also, the chip pour rate should probably be reduced and the frequency of sounding to the top of the plug during grouting should be increased.

High-solids slurry grouts should be seriously considered where obstacles such as casing centralizers exist in the borehole. In the shallow hole plugging trials, the chips did not move into the voids around the boreholes, however, the slurries did tend to flow. Even the higher-solids content slurries are capable of flowing to fill the available void size and shape. This should help avoid "dead spots" in the annular seal. The operator must decide on a project-specific basis between the benefits of slurry that may flow to fill the voids, versus a dry-chip grout that will be physically stronger.

The design of the grout column may allow for different grout applications at different depths. For example, on top of the sand pack in a well the grout must be designed so that it does not infiltrate the sand and interfere with the slotted interval of the casing. In the tub trials, the cement and the bentonite slurries all tended to infiltrate into the sand pack, with the cement infiltrating the farthest and most thoroughly. However, dry chips did not noticeably infiltrate the sand. Therefore, in well completions, bentonite chips are frequently placed directly on top of the sand. Above this seal, either chips, cement or a bentonite slurry may be desirable, depending on site conditions.

Different types of grouts can be used in the same hole, with some precautions. A grout with a high degree of physical stability (such as chips) should probably not be placed above a slurry, since the slurries will nearly always settle. Settling of the slurry may leave a void below the chips, since the chips would not tend to slide down the hole. The tendency of chips to become stationary, once emplaced, was seen in the seismic shotholes where the pressure generated by the explosives did not cause motion in the stem (excepting one hole). If grouts with differing physical strengths are to be used in the same hole, the lower-strength material should probably be placed above the higher-strength material.

Certain types of water can react with the grout material and weaken the seal. The quality of both the water used to mix the grout and the formation water that the grout will be in contact with must be considered when choosing a material type. In the tub trials, city water and water with a high-sodium concentration decreased the relative sealability of the cement grouts. Sulfate ions did not seem to strongly affect any of the grouts although sulfate is reported to interfere with the use of certain types of cement (Driscoll, 1986). The high-grade bentonite chip grout that was treated with city water and high sulfate and high-sodium water, exhibited an increase in sealability relative to other water types. The strength of the high-solids slurry grout was markedly decreased by both the high-sodium water and the high-pH water, which also was high in sodium. While the bentonite grouts and the cement grout tended to hold less pressure with decreasing pH, the degree of adverse influence on sealability was much greater for cement than for the bentonite grouts.

The affect of high-calcium water samples on the 9.0 lb/gal grouts and 10.2 lb/gal in the tub trials may illustrate the need to consider the chemistry of downhole water. These grouts each showed significant loss of volume within a few days of emplacement, and failed at unexpectedly low water pressures. This appears to be the result of cation exchange between the original sodium bentonite and the calcic water.

The cation-exchange reaction removes sodium ions from the inter-cell position in the montmorillonite and replaces them with calcium ions. The resulting calcium montmorillonite has physical characteristics that are greatly different from those of sodium montmorillonite, as discussed earlier in this report. The cation-exchange reaction is not reversible and the grout will flocculate and permanently lose volume, resulting in a partially filled borehole or annulus. In highly calcic settings it may be better to start with calcium montmorillonite, although this was not investigated during the project. Even though the hydraulic conductivity may be greater and strength may be less than that of sodium montmorillonite, the volume would be less likely to change after emplacement.

Special care is needed where grout may come into contact with certain organic compounds.

Grim (1968), and Hasenpatt and others (1989) discuss the ability of ring-structure and other hydrocarbons to displace cations in the exchange position and bond to the basal surface. In some cases, these effects are irreversible and can permanently impair the ability of the grout to carry out the function for which it was designed.

If the original seal of the grout is disturbed, as may happen along seismic lines or adjacent to mine-related blasting areas, then the ability of the grout to be flexible and to re-establish the seal is important. Therefore, where ground motion is a concern, bentonite is a better choice of grout material than rigid cement. Both in tub trial settings and in field tests of stemming material, the bentonite-chip grouts demonstrated an ability to re-establish a seal against test pressures that were not significantly different from the initial seal provided by these grouts. The cement and cement-plus-eight-percent-bentonite grouts did not re-establish a seal in the tub trials. These different responses to repeated pressure testing are attributed to the non-plastic type seal provided by cement grouts, as opposed to the flexible seal of the bentonite grouts.

Based on specific borehole conditions and project needs, the best grout material can be chosen. Each type of grouting material has its own advantages and disadvantages **(Table 3)**. Some materials may not be available at a specific project site. The type of equipment available may also limit the choice of grout materials.

The cost of grouting should be included in the original budget for every project. Whether the grouting is for hole abandonment or for annular seals, the costs must still be accounted for before the drilling begins. The most economical grouts are the materials that require the least equipment, such as the gravity-fed chips. Among the slurries, cement is more costly than bentonite. The economic considerations of choosing a grout are discussed later in this report.

In any hole grouted with a slurry, checks of the depth to the top of the plug are necessary in about a week and again several months after the plug is emplaced. Because of the cost that this entails (if a slurry grout is chosen) retopping needs to be considered during the planning stage of the project.

Mixing grouts

Manufacturer's instructions are written on most material packages that describe the intended uses and mixing guidelines for a particular product. Mud weights are frequently measured in the field using a calibrated balance. However, non-homogeneous mixtures and poor measuring methodologies can create misleading results. This was especially true in experiments with high-solids slurries, where mixing time was minimized and chips tended to settle to the bottom of the vat.

The approximate volume of slurry, mud weight and percent solids can be estimated using the graph in **Figure 17**, or by using the following formulas. These formulas use the densities of water, bentonite and cement, and convert those values to slurry density, volume and percent-solids content. The density conversion factors used in the equations are estimated average values. The unit for each variable is shown in parentheses.

$$\text{Volume of slurry (gal)} = \frac{\text{bentonite (lb)}}{\text{20.9 lb/gal}} + \frac{\text{cement (lb)}}{\text{26.3 lb/gal}} + \text{water (gal)}$$

$$\text{Mud weight of slurry (lb/gal)} = \frac{\text{bentonite (lb)} + \text{cement (lb)} + [\text{ water (gal)} \times \text{8.34 lb/gal}]}{\text{volume of slurry (gal)}}$$

$$\text{Percent solids by (volume)} = \frac{\text{bentonite (lb)}}{\text{20.9 lb/gal} \times \text{volume of slurry (gal)}} \times 100$$

$$\text{Percent solids (by weight)} = \frac{\text{bentonite (lb)}}{\text{slurry volume (gal)} \times \text{slurry mud weight lb/gal}} \times 100$$

Table 3—Advantages and disadvantages of different types of grouting materials.

Type	Advantages	Disadvantages
Bentonite chips	– Readily available – No pumping equipment needed, may be gravity fed; therefore less expensive than other grouts – High-solids content, rarely settles or shrinks – Swells to fill the void – Flexible seal – Very low hydraulic conductivity – Re-seals if disturbed – Does not contaminate water sample	– Flocculates in certain water chemistries – May bridge during installation leaving voids in the seal, especially in small or congested annular spaces in wells – Few methods of checking quality of seal
Bentonite slurry	– Readily available – Flexible seal – Low hydraulic conductivity – Probably re-seals if disturbed	– Settles after pumping, must be topped – Extra pumping and mixing equipment required – Flocculates in certain water chemistry – Very low physical strength – Few methods of checking quality of seal – Fairly expensive
Portland cement	– Readily available – Sets up solid – Possible to determine quality of seal using acoustic logs – High physical strength – Rigid	– Extra pumping equipment and clean-up required – Shrinks as it cures, may develop a micro-annulus – May affect water quality results in monitoring wells – Susceptible to degradation in low pH, high salt or high sulfate water – May flow into porous formations – Heat of hydration may damage non-metallic well casing. – Very expensive
Portland cement plus bentonite	– Readily available – Sets up solid – Possible to determine quality of the seal using acoustic logs – Less likely to shrink and form micro-annulus than Portland cement – Rigid	– Extra pumping equipment and clean-up required – May affect water-quality results in monitoring wells – Susceptible to degradation in low pH, high salt or high sulfate water – May crack after installation – Heat of hydration may damage non-metallic well-casing – Very expensive – May flow into porous formations
Drill Cuttings	– High-solids content – Readily available – Very inexpensive – Only requires hand tools	– May not form an adequate seal – May bridge during installation leaving voids in the seal – Cannot be checked – In certain situations, may cause water-quality problems

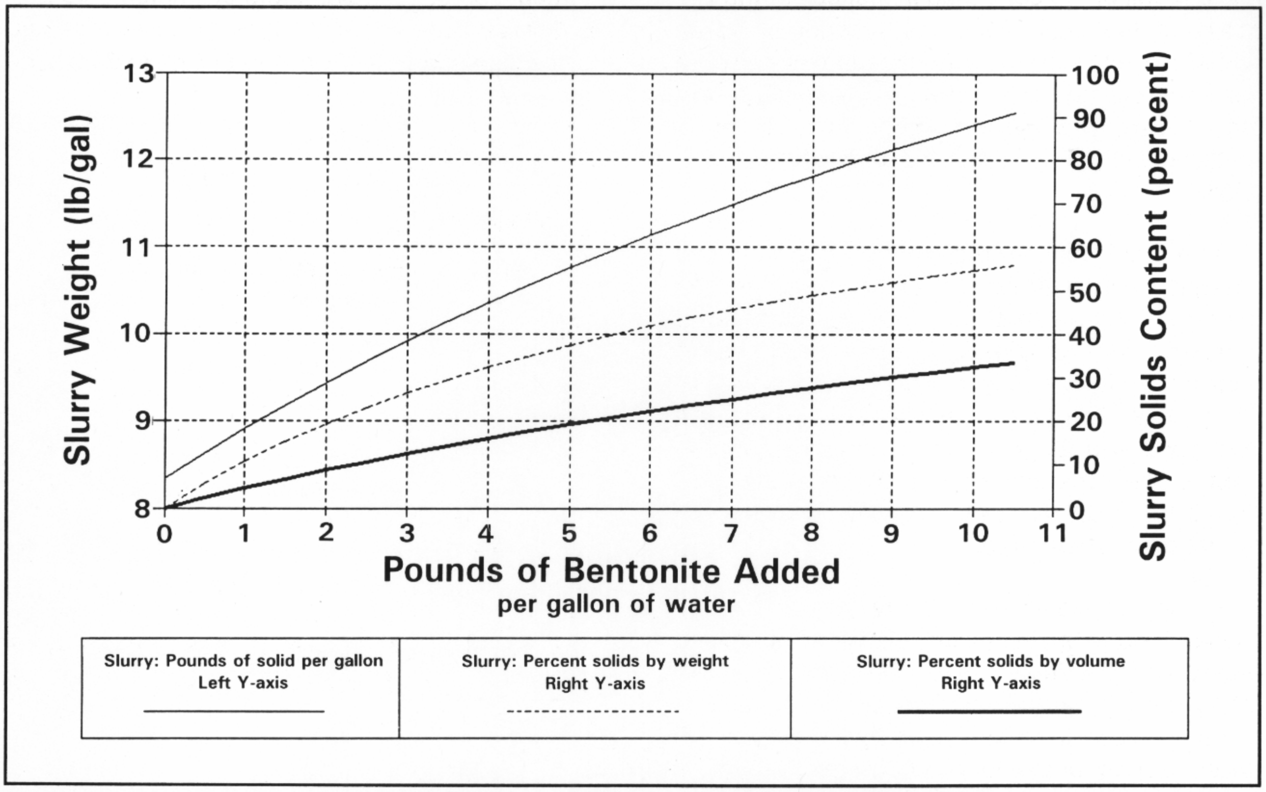


Figure 17—In order to estimate the amount of bentonite to add to each gallon of water for a given weight or solids-content slurry, choose the desired end point from the appropriate y-axis, move horizontally to the correct diagonal line, then move straight down and select the amount of bentonite needed. The type of bentonite used will not affect the results of the estimation, since the chart is based on average specific weights. For example, if a slurry with 20 percent solids by volume is desired, just over 5 pounds of bentonite must be added to each gallon of water. The bentonite can be powdered or granular (or a combination of the two), depending on the application.

The most effective bentonite slurries tested had dry bentonite suspended in the slurry when emplaced. The dry bentonite does not increase the viscosity of the slurry as much as does hydrated bentonite. Any dry bentonite emplaced in a saturated borehole will hydrate after emplacement, providing a high-percent-solids (by volume) slurry which had a relatively low viscosity during emplacement. It was found that a mixture of 60 gallons of water and 50 pounds of pulverized bentonite provides a good base. Stirring in 50 pounds of granular bentonite as the slurry is being pumped down the hole provides the dry material. The pulverized material forms a viscous slurry that suspends and carries the granular particles. In addition, the viscous slurry binds most of the water, reducing the tendency to hydrate the granules and provide more working time before the viscosity buildup of the dry material inhibits pumping. The use of this type of slurry does, however, require a certain amount of practice.

Emplacement of grout

Grouts can be emplaced by pumping (slurry grouts) or gravity feeding (dry grouts). A brief overview of pumping may help to explain some of the results of the pumping tests. The use of pumps to emplace grouts is limited by three factors. First, the fluid must be able to flow to the pump, whether by suction forces created by the pump, or by gravity flow from a hopper. Secondly, the fluid must be able to pass through the pump. The size of solids and the viscosity of the fluid must not be so great as to plug the pump. Furthermore, the pump must be able to overcome the friction loss of the fluid moving through the tremie pipe. Fluid viscosity is the controlling fluid characteristic in all factors.

Viscosity, or the resistance of a fluid to flow, is a measure of the fluid's resistance to shear stress. Viscosity is not a direct function of density.

It is a result of the combined influences of the viscosity of the base fluid, the amount of solids added per unit volume, attractive forces between the particles, and the ability of the solids to hydrate. Also, the more homogeneous a slurry (better mixing), the higher the viscosity (Driscoll, 1986).

The montmorillonite platelets have negative charges on the faces and positive charges on the edges. As the material is allowed to set, or if it moves slowly, the platelets align (face to edge) and viscosity increases. If the velocity of the fluid is increased (as happens when the fluid passes through a small pipe), the motion breaks down the alignment that exists between the charges on the platelets, and the viscosity at that point decreases.

For the above reasons, the response of a particular batch of bentonite slurry to pumping pressures, pipe length, and pipe diameter is not totally predictable, as was indicated by variations of pump pressures and discharge rates experienced during pumping trials. In general, more retention time during handling will allow the bentonite to hydrate more thoroughly and increase the viscosity. If mixing time is sufficient, the mixture becomes homogeneous and the viscosity reaches a maximum point, yet density and percent-solids content may not be particularly high. After mixing (if the batch is allowed to sit), alignment between charged platelets occurs and viscosity increases, with no increase in solids content.

The work space, which is the diameter of the borehole or the annular space between the borehole wall and well casing, restricts the equipment that can be used and therefore further restricts the number of material options available. The effect of the size of the work area can be seen in an example. In an 8-inch diameter borehole, with 4½-inch outside diameter casing, the annular space is 1¾ inches, and the tremie pipe size is limited to about 1¼-inch inside diameter. However, if a 2½-inch outside diameter (2-inch inside diameter) casing were used in the same size borehole, a 2-inch inside diameter tremie pipe could be used. Increasing the diameter of the pipe would reduce the velocity of the fluid plus decrease the friction loss. The amount of decrease in friction loss can be estimated analytically. Using the Darcy-Weisbach equation (Olson, 1966), a comparison of pipe diameters estimates a 40 percent reduction in friction loss by increasing the tremie pipe diameter from 1¼ inches to 2 inches.

$$Hf = \frac{\Delta \rho}{\gamma} = f\left(\frac{L}{D}\right)\frac{V^2}{2g}$$

Where:

Hf	Head loss due to friction
$\Delta \rho$	Change in pressure
γ	Specific weight of the fluid
f	Coefficient of friction
L	Length of pipe
D	Diameter of pipe
V	Velocity of fluid in pipe
g	Acceleration due to gravity

For the purpose of comparing the effects of only one variable in the equation (pipe diameter), all of the other variables can be set to a constant. The length of pipe, coefficient of friction for the particular type of pipe, and velocity of the fluid can be set equal to C.

$$Hf = C \times \frac{1}{D}$$

Increasing D from 1¼ to 2 would decrease Hf by about 40 percent. Since velocity is dependent on the pumping rate and the diameter of the pipe, it would decrease as the pipe diameter was increased, thus further decreasing the friction loss. Using the Darcy-Weisbach equation and setting all variables, except velocity, equal to a constant, to wit:

$$Hf = C \times V^2$$

If the discharge rate is the same in a 1¼-inch and a 2-inch diameter pipe, then the decrease in the friction coefficient is about 85 percent. This is due to the increase in the cross-sectional area of the larger pipe. In an application, however, the discharge rate is controlled in part by the friction loss of the pipe. Increasing the diameter of the pipe will cause the discharge rate of the pump to increase. The resulting increase in velocity would offset some of the advantages of the larger diameter pipe. However, a minimum of a 40 percent reduction in friction loss would still be realized by increasing the tremie pipe diameter from 1¼ inches to 2 inches. Therefore the estimated practical limit for using the tested bentonite slurries may be extended by increasing the diameter of the tremie pipe. In the pumping trials conducted during this project, the limit of pumping a higher-solids-content slurry using a 1¼-inch tremie pipe was about 400 feet. Had a 2-inch pipe been used, this limit may have been closer to 550 feet, based on the above calculations of friction loss. The decrease in friction loss would be reflected in a combination of increased potential depths of application, higher discharge rates for the pump, and lower pump pressure.

In the experiments, a 1¼-inch diameter steel tremie pipe was used, in conjunction with a progressing-cavity and a diaphragm pump. The progressing-cavity pump performed best in the pumping trials. It handled very viscous material with a high-solids content extremely well. Although the progressing-cavity pump did not transport the viscous medium-solids slurry as far as the diaphragm pump, it did perform at a much higher discharge rate. Even though some slurries were tested that were thick enough to plug it, clearing the progressing-cavity pump was fairly easy by disconnecting the discharge hose and circulating water.

The tests showed that emplacement of a high-solids slurry (> 9 lb/gal) is difficult, but physical stability is good. The high-solids slurries could not be effectively pumped farther than 250 feet in a 1¼-inch steel pipe using a progressing-cavity pump. Pumping of the high-solids slurry should be finished within about ten minutes after the start of mixing to avoid hydration of the dry bentonite. Individual batch sizes should be kept small (about 50–60 gal) to avoid excessive handling time. The granular material should be coarse enough to avoid fast hydration, yet small enough to pass easily through the pump. The 8- to 20-mesh size range worked very well. No restrictions should exist in the piping system. The pump and tremie line should be purged with water immediately after completion of each pumping batch to prevent plugging due to hydration of the granular bentonite. A cement mixer or paddle-type mixer may be suitable for stirring the batches.

Emplacement of an 8.8 lb/gal medium-solids slurry is not difficult, but physical stability is not as acceptable as other choices. The medium-solids slurries could not be effectively pumped farther than 250 feet in a 1¼-inch diameter steel pipe using a progressing-cavity pump. Using this type of slurry would require returning to the hole and topping the plug after a week, and again after several months of settling has occurred, based on the settling rates measured during the 500-foot plugging trials.

Emplacement of the lower-solids slurry is not difficult, but the physical stability is undesirable. The low-solids slurry was pumped to 500 feet in the pumping trials, however, the top of the 8.6 lb/gal grout plug dropped about 150 feet below the uppermost aquifer in 500-foot borehole HP-4. Using this type of slurry would require returning to the hole periodically and topping the plug several times as settling occurred.

Bridging is usually not a concern when emplacing slurries, as long as a tremie pipe is used, and the slurry is discharged from near the bottom of the hole and pumped until it discharges at ground surface. It should be noted, however, that a bridge did develop during one laboratory-type pumping test where a clear plastic tube was used as a borehole allowing visual inspection of the process. The bottom (discharge end) of the tremie was placed about three feet above the sandpack to allow room for the slurry to discharge. A bridge formed just below the tremie pipe, and the remaining slurry pumped out of the top of the tube without sealing the space below the bridge.

For materials that cannot be pumped through a tremie pipe, the alternative is gravity feeding. With gravity feeding from ground surface the main concern is bridging. Bridging prevents additional material from passing to the deeper parts of the hole, thus leaving voids in the borehole seal. Several factors influence bridge formation: fall velocity, material type, particle size, range of size, wall texture, hole alignment and hole size. Solid particles that become wet in a borehole can adhere to one another and to the sides of the borehole (or casing if present).

As measured in the velocity tube trials, fall velocity is controlled by chip size and shape, and material type. The viscosity of the fluid through which the chips fall would also have an influence on the fall rate. The effects of fine-powdered bentonite possibly increasing the borehole-water viscosity were not investigated. Pouring materials of different masses or pouring at an uneven rate can create congestion, thereby increasing the probability of bridging. Eventually some particles or lumps containing several chips may stick to the side of the hole, creating turbulence and forcing other chips to stick and worsen the problem.

Bentonite chips provide a seal that is both hydrologically and physically strong compared to other bentonite-based grouts. Based on test results, chips are the preferred grout material where subsurface space allows their use. However, they must be added at a steady pour rate that is no faster than 1.5 to 2 minutes per bag to minimize the chances of bridging. This pour rate is based on industry recommendations and visual observations and is a function of the number of chips per minute rather than pounds or bags per minute. It is particularly important that a slower pour rate per bag be maintained for smaller chips. A slow and steady pour rate allows the chips to be spaced farther apart as they fall, thus decreasing turbulence and collisions, and lessening the chances of bridging.

Pour rates probably should be reduced during plugging of deep boreholes as a precaution to decrease the chances of chip collisions and bridging. In a deep borehole the odds of a bridge forming are greater due to the fall distance, and the consequences of a bridge are much more severe due to the complications of correcting the problem at greater depths. Overall, the results of the gravity-feeding trials do not indicate a specific limitation of depth for the application of bentonite chips as a sealing material in smooth-sided, open boreholes. However, video surveys and caliper logs demonstrate that boreholes are not truly smooth or straight, rather they are often very rough, and may even have large cavities resulting from caving (Robert E. Crowder, Personal Communication, 1993).

The use of a device to control the pour rate is important when using dry grout material. The chip tray was the most satisfactory method tested during the shallow hole and 500-foot hole plugging trials. The chip tray not only allowed a steady rate of pour for the duration of work, it also made the work easier by allowing several bags to be loaded at a time and supporting the weight of the chips. The best results with the chip tray were with $3/8$-inch chips, with an outlet opening of $1 1/8$-inch and the slide angle set at 40 degrees above horizontal. Screening during application would further reduce bentonite dust entering the water column and building viscosity. Controlling the build-up of viscosity in the water column would increase confidence in the success of emplacing the sealing material to the desired depth.

Sounding the depth to the seal as the chips are emplaced is a vital step in the process to ensure that the seal is at the correct depth. When plugging an open borehole, the operator should interrupt the pour and measure the depth from ground surface to the top of the plug, preferably at least as often as after every 10 bags of chips. The measurement should then be compared to the calculated depth for the amount of material added to the hole. If a discrepancy is detected, for example if a bridge had developed, it would be caught early and might be corrected with a minimal amount of effort. This step is essential if the plugging process is to be successful. In limited spaces, especially in annular spaces around centralizers, the frequency of soundings should be increased, possibly to once every 50-pound bag (U.S. Environmental Protection Agency, 1992). While pouring chips during the 500-foot-borehole plugging trials, the depth soundings slowed the process about 2 to 3 minutes for each sounding.

One effective method of sounding during well completion involves placing a full-depth string of black butyl tubing in the space to be grouted by lightly taping it to the casing during installation. This tube is then withdrawn as the pour proceeds. A sounding device, such as a weighted steel tape can be lowered through the tube and used to constantly probe the top of the grout column. Bridging could be detected early and perhaps corrected. In a worst case, if a bridge develops that cannot be removed, the sounding tube may provide a pathway for pumping a slurry grout into the annulus below the bridge. [Extreme caution is advisable when lowering anything, such as a steel tape, into a well annulus or borehole.]

In some situations, bentonite-based or other highly viscous fluids are used in the drilling process. If the drilling fluids are not removed from the borehole, then the fall velocity of chips would be decreased, since fall velocity is dependent in part on the difference in density of the falling object and the medium through which it falls. This may increase the chance of a bridge forming if gravity-fed chips are used as a grout.

When chips are used as an annular seal, they must be poured with extreme care to avoid bridging at the casing centralizers. If centralizers are not used in deeper wells, chips should probably not be used because of the potential for bridging where the casing lays against the borehole. In very shallow wells, many of these problems are insignificant.

Economic considerations

Table 4 presents the average 1992 costs of materials and equipment used in this study. These materials and methods are commonly used in most hole-plugging and well-completion projects. Prices are based on averaged figures obtained from quotes from several sources. The number of crew members required and the time needed for each grout type was based on the results of this project.

The dry-material applications (gravity-fed materials) are significantly less expensive than the slurry applications **(Table 4)**. Bentonite chips, for example, are only 60 percent of the application cost of bentonite slurry, and about 45 percent the cost of the cement applications. The use of low-grade bentonite drops the cost to less than one-third the cost of the bentonite slurry, and just over 20 percent of cement grouts. The need for a drill-rig pump (or other suitable pumping equipment) and at least two laborers in the slurry applications, greatly increases the overall cost of the grouting method, as compared to dry-material applications. The drill rig is usually committed to a specific site during slurry grouting operations, and therefore, is unavailable for other drilling activities. When a hole is being grouted with dry material, the drill rig can be employed at a different site.

One other important consideration in the analysis of economic differences between dry, gravity-fed grouts and slurry grouts is the comparatively better performance of dry grouts over the long term. In numerous cases in Montana, including the shallow and 500-foot-borehole trials, it has been discovered that slurries can require considerable time to settle to a stable level in boreholes. These drops in slurry levels present problems regarding the possible long-term stability and the effectiveness of the grout.

It may be necessary in some cases to repeatedly monitor the slurry grout until a stable level has occurred, then revisit the site to top off or regrout the hole. The overall effectiveness of the types of grout material and the need to revisit sites were not included in the economic calculations on **Table 4**, but should be carefully considered. Revisiting (and often redrilling) a site with a drill rig and pump to properly regrout a slurried hole can easily increase the costs of grouting by two or more times the costs noted in **Table 4.**

In slurry applications, complicated field tests have been used in the past to ascertain the characteristics of the slurry mixture (filtrate volume, thickness of wall cake, mud weight, gel strength). The equipment, time and expertise necessary for conducting these tests is not always available and will add to the overall costs of using slurry grouts. The results of these tests are relevant to drilling fluids, but are probably unnecessary for most grouting applications.

There is also the legal/regulatory aspect of grout stability. Federal and state laws require that most boreholes be plugged or otherwise sealed to prevent inter-aquifer mixing, loss of water (or of other natural resources), and subsidence. Improper sealing of boreholes or wells may place a driller in non-compliance with the laws governing this activity. This can lead not only to the need for expensive regrouting, but to potential legal or regulatory problems or penalties.

Material for seismic stemming

The hydrogeology of the site chosen to study materials used in seismic stemming was complex. The ground water was controlled by a combination of low primary porosity and by fractures which form secondary porosity. Under the wide range of physical characteristics for the aquifers at this site, little difference in the sealability of the high-grade or low-grade bentonite could be determined.

At shotholes 2, 3, and 5, temporary inter-aquifer communication occurred as a result of blasting, however, there were no visible changes in the stems at ground surface. Two of the three shotholes were stemmed with high-grade bentonite, and one with low-grade bentonite. All three

Table 4—Economic considerations of grouting (1992 dollars).

	Bentonite Chips	Bentonite Powder (9-lb slurry)	Bentonite Granules (10-lb Slurry)	Low Grade Bentonite chips	75% Gravel plus 25% Bentonite	Neat Cement	Cement plus 8% Bentonite
Cost	$4.35	$7.75	$4.25	$40.00	$6.00	$7.50	$7.50
Unit size	50-lb bag	50-lb bag	50-lb bag	1 ton	50-lb bag	94-lb bag	94-lb bag
Comments	Delivered	Delivered	Delivered	Not Delivered	Delivered	Delivered	Delivered
Quantity/linear ft (6" hole)	1 bag/ 3 lin ft	1.5 gals/ 1 lin ft	1.5 gals/ 1 lin ft	50 lb/ 3 lin ft	1 bag/ 3 lin ft	1.5 gals/ 1 lin ft	1.5 gals/ 1 lin ft
Labor cost *	1 person @ $10.00/hr	$0.00*	$0.00*	1 person @ $10.00/hr	1 person @ $10.00/hr	$0.00*	$0.00*
Pumping rig cost *	$0.00*	$200.00/hr	$200.00/hr	$0.00*	$0.00*	$200.00/hr	$200.00/hr
Dry material needed lbs./500'x6" hole	7,700 lbs (154 bags)	1,100 lbs (22 bags)	1,500 lbs (30 bags)	8,000 lbs (4 tons)	7,700 lbs (154 bags)	8,500 lbs (91 bags)	4,900 lbs cement (52 bags)/200 lbs bentonite (4 bags)
Slurry material produced Units/ 500'x6" hole	n/a	750 gal	750 gal	n/a	n/a	750 gal	750 gal
Mixing ratio (lb/gal) water	n/a	50/35 gals	50/25 gals	n/a	n/a	94/5.2 gals	1200 lbs cement/ 100 lbs bentonite/ 120 gals water
Truck rental (5 yd cap)	$0.00	$0.00	$0.00	$150.00/day	$0.00	$0.00	$0.00
Truck rental (1 yd cap)	$65.00/day	$0.00	$0.00	$0.00	$65.00/day	$0.00	$0.00
Plugging time/ 500 ft hole	6 hrs	6 hrs	6 hrs	6 hrs	6 hrs	6 hrs	6 hrs
Total plugging price (500 ft hole)	$794.90	$1,370.50	$1,327.50	$370.00 **	$1,049.00	$1,882.50	$1,621.00

* Where drill rigs are used, labor is included.

** In a commercial size operation, additional costs include, but may not be limited to mine permitting, mining and reclamation.

shotholes were stemmed with a volume of bentonite that exceeded the calculated volume of the borehole.

In the three shotholes where inter-aquifer communication occurred, a seal was re-established within a few weeks and water levels later appeared to be responding to natural fluctuations. All other seismic-induced water-level fluctuations apparently resulted from the shock wave of energy acting on the aquifer and causing water levels to rise for short periods.

Three possible avenues for inter-aquifer communication exist: 1) leakage through the stem in the shot hole, 2) leakage through the annular seal of the monitor wells, most likely the deepest well at a site, and 3) leakage through fractures developed in the aquitard by the shots. In the stemming experiments, it was most likely that leakage occurred through the stem of the shothole or the annular seal of the monitor well. Because of the flexible nature of the bentonite, the grout or stem probably resealed.

At site 8, the low-grade stemming material was blown out of the shothole. This indicates that the swelling capabilities of the high-grade material may provide more resistance to movement of the grout. However, seismic crews have indicated that under normal field conditions, blowouts occur in about ten percent of the holes. Therefore, one blowout in eight holes is not unusual, though unexpected in controlled conditions where fines were screened out of the fill material and volumes were carefully measured.

If placed in the shothole properly, well-screened, low-grade bentonite appears to be a satisfactory stemming material. The use of high-grade bentonite may not be justified in every circumstance.

Future developments for bentonite

For drilling-related activities, bentonite grade has typically been determined by performance as a drilling mud. The characteristics that are needed for drilling fluid are the ability to build viscosity, barrel yield and plate-water adsorption. The most important quality is the ability to build viscosity in drilling mud in order to remove drill cuttings from the borehole. Consistency and thickness of wall cake are essential drilling-fluid properties measured in relation to fluid loss. The response of bentonite-based drilling mud to formation contaminants encountered during drilling, and the amount of abrasive sand and grit, as well as the pH, are also concerns.

A different set of standards is needed for grading bentonite that is used for grouting materials. For example, of the commonly measured drilling-fluid properties, only free swell is a factor to consider for grouting and for stemming seismic shotholes. Free swell determines how well the material fills the hole when emplaced, and how much friction it builds between the grout and the side walls of the hole. The friction should help hold a stem in place during the shot. Also, free swell would determine the ability of the material to heal fractures and adjust to ground motion.

Some measurement of shear strength of a partially hydrated chip sample would help evaluate seismic stemming material. The ability of the stem to withstand shearing during the shot would help reduce motion and subsequent voids in the stem.

The required hydraulic conductivity of an effective grout is dependent on site-specific aquitard and aquifer characteristics. It must be the same as (or less than) the least conductive aquitard in order to maintain the naturally occurring separation of aquifers.

The ability of a sample to be screened and shipped as uniform-sized chips may be the most important property of a chip-type grouting material. Some samples seem to break into small chips, even after passing across a screen. This produces material with large chips as well as fines. The fines are probably a major contributor to bridging problems, first by clumping together to form large chunks that block the fall of other chips, and second by increasing the viscosity of the water in the hole, and thus decreasing the fall rates of subsequent chips.

Bentonite balls showed an attractively narrow range of fall velocities (Wheaton and others, 1993a). There may be an application for a uniformly balled product for the abandonment of deeper, wet holes. Such a product, which is worthy of further study, could be produced from rough-crushed, unsorted ¼-inch (or less) bentonite, perhaps using rotary-table technology to decrease costs.

Producers of bentonite products are addressing the problem of emplacing high-solids-content, slurry-grout material to the correct depth with treated bentonite that hydrates slowly. The most common approach is to coat the bentonite particles with a polymer. The polymer coating inhibits the rate of hydration. When first mixed, the slurry has a relatively low viscosity, and a high-solids content. Full hydration occurs over a longer period of time, and allows the grout to eventually achieve full viscosity. One disadvantage is that polymers, which are organic molecules, tend to eventually break down. The National Sanitation Foundation has approved few of these products for water-well use. According to bentonite companies, new products will be on the market soon that will allow the advantages of high-solids and low initial viscosity, without the potential disadvantages of placing organic material in the subsurface (Dennis Johnson, Personal Communication, 1993).

Recently developed treated-bentonite grouts that are intended for high-solids-slurry application have been successfully pumped to depths of 1,800 feet in California (Bob Stichman, Personal Communication, 1993). These grouts, with a solids content of 30 percent by weight (about 15 percent by volume), were pumped through 1¼-inch tremie pipe with progressing cavity pumps.

The slurry grout that performed the best during our tests was a slurry mixed with powdered bentonite, water and chip bentonite. These types of mixtures are now being manufactured as single-bag products to eliminate measuring problems at the site. As bentonite products having a higher-solids content (both high-solids slurries and chip grouts) become easier to use and less expensive, their use will become more frequent and successful. This will be beneficial to ground-water resources because of the grouting advantages of bentonite over other materials.

Long-term stability of emplaced grouting material is of paramount importance in plugging and other remediation applications. Grouts must be capable of retaining the properties for which they were originally selected in the environment in which they were emplaced. Ion-exchange reactions with bentonite not only occur with formation water, but are reported to occur with formation lithology (Grim, 1968). A more rigorous protocol is needed for the evaluation of long-term chemical and physical stability of grouts. Furthermore, a more systematic means of evaluating the suitability of various grouting materials in different chemical environments needs to be developed. If possible, methods should be developed to quantitatively predict the long-term effect of cation exchange and other borehole-induced reactions on the qualities of grout.

Future work should lead to the development of a broader spectrum of bentonite-based products for plugging or remediation applications. High-grade sodium bentonite (in its various grinds) is often proclaimed as the best bentonite-based material for most plugging applications. The cement industry has, by comparison, produced eight classes of cement products for oil field applications. A better understanding of the long-term downhole stability of grouts could result in the development of a similar broad array of bentonite products that are better tailored to specific remediation purposes.

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