Diamond Core Drills: Their Invention, Early Development, and Consequences for Mining and Quarrying

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During the late nineteenth century the world's output of manufactured goods increased exponentially, supplying a demand from a rapidly increasing and ever wealthier population. This boom was fuelled by an explosion in the output of fuel and raw materials which, astonishingly, ran ahead of demand and led to a gradual fall in prices. Thus, among metallic minerals, the global output of copper, lead, gold, and silver increased by two or three times in the last twenty years of the century, while their prices declined by ten per cent and sometimes much more.[1]

The causes of this avalanche of supply are well-known to mining historians—essentially new discoveries in new areas, new technologies to work lower grade and more complex ores, and better and cheaper transport facilities. All have been discussed in great detail in a wide ranging literature. However, there is one technology—arguably key to the introduction of all of the others—that has somehow been overlooked, probably because of its early simplicity and lack of notice in contemporary technical journals and mining manuals. It is one that first appeared in the third quarter of the century and created the opportunities for discovery and development that were seized in the last quarter. It has no specific name but will be referred to generically here as diamond core drilling.

By sinking small holes deep into the ground and recovering a cross-section core of the rock that they passed through, these devices provided opportunities for geologists and mining engineers to explore at depth without the need for driving slow and expensive shafts and tunnels. They were not the first devices for driving exploratory bore holes—a range of other drills had been used for many years and would continue to be used well into the future—but they went deeper, faster and were the first to produce a solid core that could be extracted and examined intact in the laboratory. As such, they provided a unique "telescope" for the prospector and established mine operator to investigate deeply underground.

Whereas, in the modern world, the camera has extended the reach of the human experience into distant space and the depths of the ocean—places which humans could not otherwise easily access—the core drill facilitated the exploration of solid rock. As such, it gave the mining industry the capacity to design the most efficient layout and development of its workings, to clarify potentially complex ownership issues and disputes, and to exploit the potentially productive knowledge of the emergent geological sciences.

In these ways, diamond core drilling provided the essential tool for finding and exploiting hidden, non-outcropping deposits and planning the optimum development of the lower-grade ores on which the industry has come increasingly to depend. It is notable that this "strategic," game-changing innovation, was a one-time advance. Nothing of similar consequence had preceded or has succeeded it. When today's scientists dispatched a mobile camera to explore the surface of the planet Mars, they equipped the "rover" with a compact diamond drill as the only viable device for exploring the sub-surface.

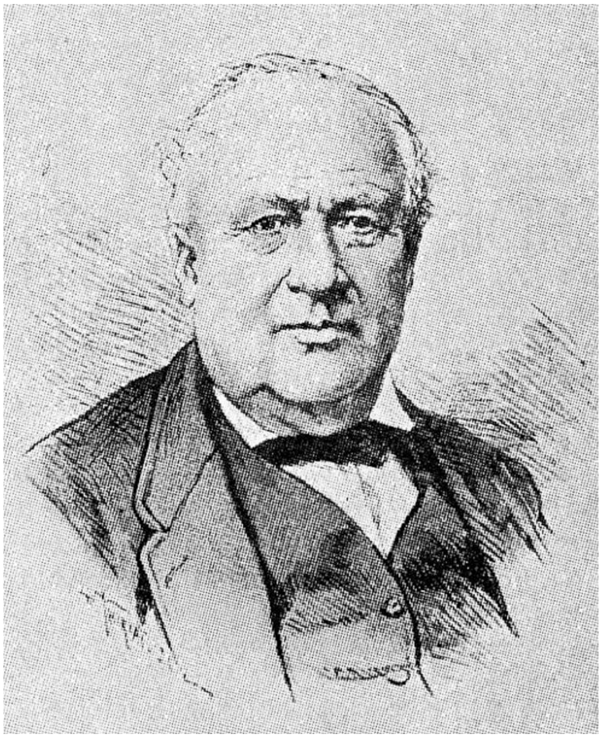
The process of technical change is often seen as involving three different, if not separate, stages—viz. invention, when an idea is first conceived and given physical form; innovation, when the device is given its first practical trials; and diffusion, when it begins to be widely taken up and starts to have an impact on the economy of an industry as a whole. This structure will be employed here in examining the evolution of diamond drills. Given the limitations of space, attention has been focused on the chronological introduction of the devices and their economic impact. Very little information has been provided on the details of their design and operation, though this can be found in the numerous sources cited.

Invention

Identifying the inventor of the diamond drill is not straightforward. It is usually attributed to Rodolphe Leschot.[2] Little is known of his life other than that he was a French railway engineer born in Switzerland of a long-established watch-making family and educated at the Ecole Centrale in Paris.[3] It was while working for Vatalia, Picard and Sons, engineers on the construction of the Mont Cenis Frejus Railway Tunnel, that he became aware of a pressing need for the mechanisation of drilling if projects of that kind were to be completed in any reasonable time.[4]

This was far from a unique insight, with many other inventors already working on the problem and many new designs shortly to be trialled in that tunnel and elsewhere. For his own solution, Rodolphe turned to his father, Georges-Auguste Leschot.[5] He is far better known, having worked for more than twenty years as the technical director of the famous Vacheron and Constantin watch-making business in Switzerland and having taken a major role in the development of antimagnetic improvements to tourbillon escapements.

Georges-Auguste Leschot (1800-84) was a highly skilled tool maker and designer of complex mechanisms, having had an early working relationship with Pierre Jacquet Droz, a famous automaton maker.[6] George Leschot is particularly well-known for his construction of the pantograph reduction milling machine, which allowed for the precise duplication of standardised interchangeable parts for watch movements and threatened to revolutionise the watch making industry.[7] However, it is said to have been his private interest in the basic mechanisms developed by the ancients—particularly the Egyptian bow-driven hollow rotary drill[8]—that provided the actual intellectual context within which the new drilling machine was conceived and which also suggested the use of rough stones or diamonds



Georges-Auguste Leschot
From: C. Dietzschold, Der Cornelius Nepos der Uhrmacher *(Krems an der Donau: C. Dietzschold, 1911), 47.*

rather than steel for the cutting edge. Certainly after Georges-Auguste Leschot died in Paris, on 4 February 1884, the *Engineering and Mining Journal* confidently credited him in an obituary as "the inventor of the Diamond Drill."[9]

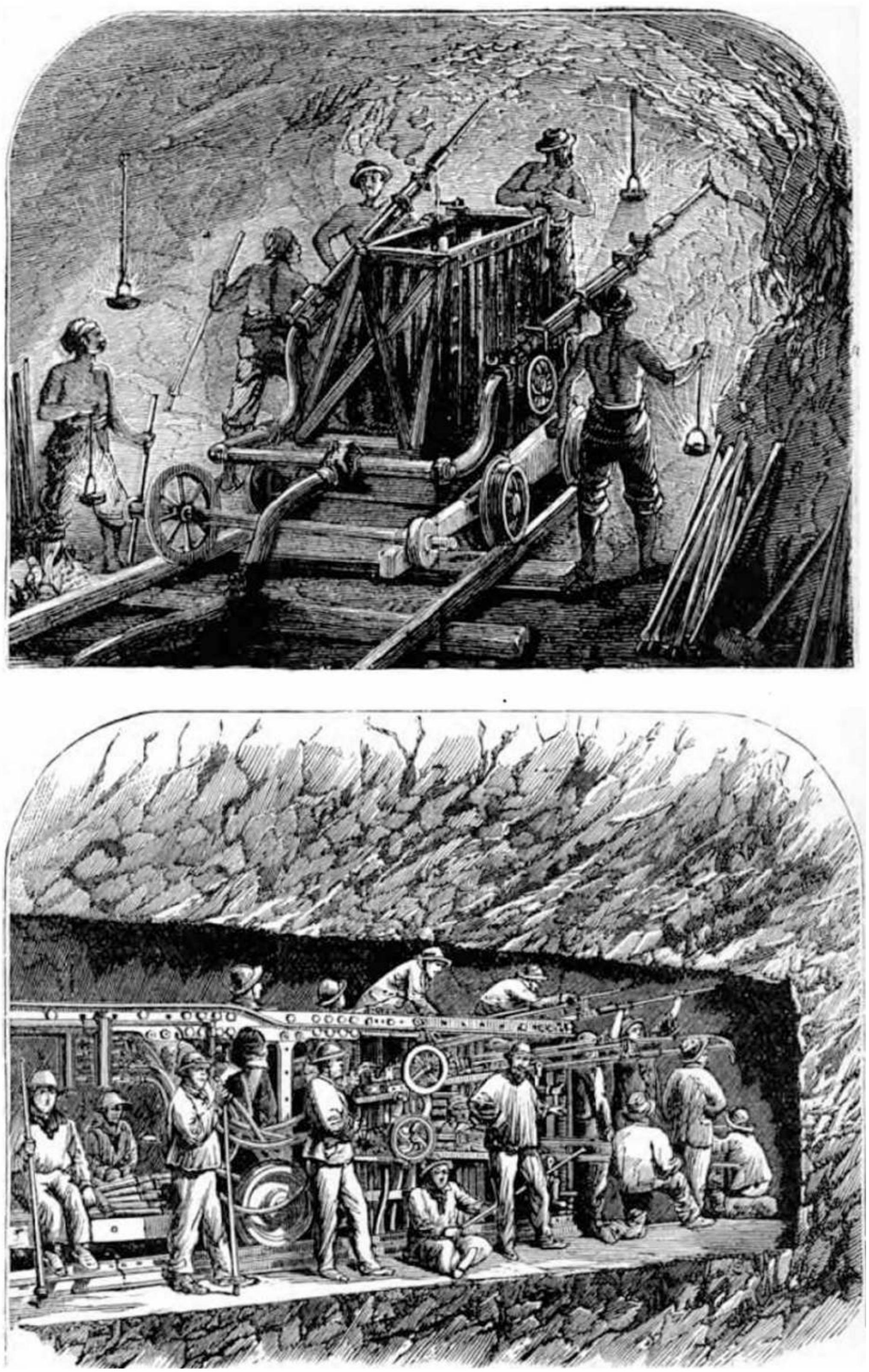
Having designed the machine, and with full-time commitments of their own in other spheres, the Leschots employed a skilled mechanic, Charles Sechehaye, to construct the first functional device in Geneva in June 1862. They patented it in several European countries shortly thereafter.[10] In brief, the drill consisted of a hollow rotating casing, or pipe, crowned with a bit mounting eight black diamonds. Water was pumped down the bore hole to flush out ground dust while a core of rock was captured inside the pipe, to be periodically withdrawn. All-in-all, it had taken the commercial perception of a practical engineer, the intellectual insight of a classically aware mechanical genius, and the practical skills of a working craftsman to deliver a new drilling machine that was totally different from any of the mechanical "impact" drills concurrently under-development.

Rodolphe Leschot appears to have carried out further development work on his machine with La Rochetolay and Perret in Paris; saw its trial in several other tunnelling projects, such the Saint Gothard and Tarare; and displayed it at the Paris Exhibition in 1867,[11] but he never put it into commercial production, apparently preferring to licence his patents instead.[12]

Innovation

As has been seen, the primary event in focusing Leschot's interest in developing his drill was the driving of the Mont Cenis Frejus Railway Tunnel in the Alps, between Mondane in France and Bardonecchia in Italy. Started in 1857, it was intended to be the world's longest, measuring almost eight miles between portals. Unfortunately the route and topography militated against the usual practice of driving multiple faces outwards from numerous airshafts, so the construction had to be undertaken laboriously from both ends. Using the hand-boring techniques then still in use, it was estimated that driving the tunnel might take up to forty years.

The need to find some method of mechanising and speeding up the process was clear. Various attempts had been made from the early nineteenth century to develop such machines, starting with Trevithick in the U.K., J.M. and J.N. Singer in the U.S., Schumann in Germany, and, by mid-century, Brunton, Pidding, Fontainmoreau, and many others had proposed various devices. By the late 1850s compressed air was emerging as the preferred motive power for the drills, since its exhaust also helped resolve the problem of ventilation at the working face. However, none of these machines were proving sufficiently manoeuvrable and reliable. Progress had to be made if the Mont Cenis and other urgent railway tunnel projects across Europe and the U.S. were to progress.



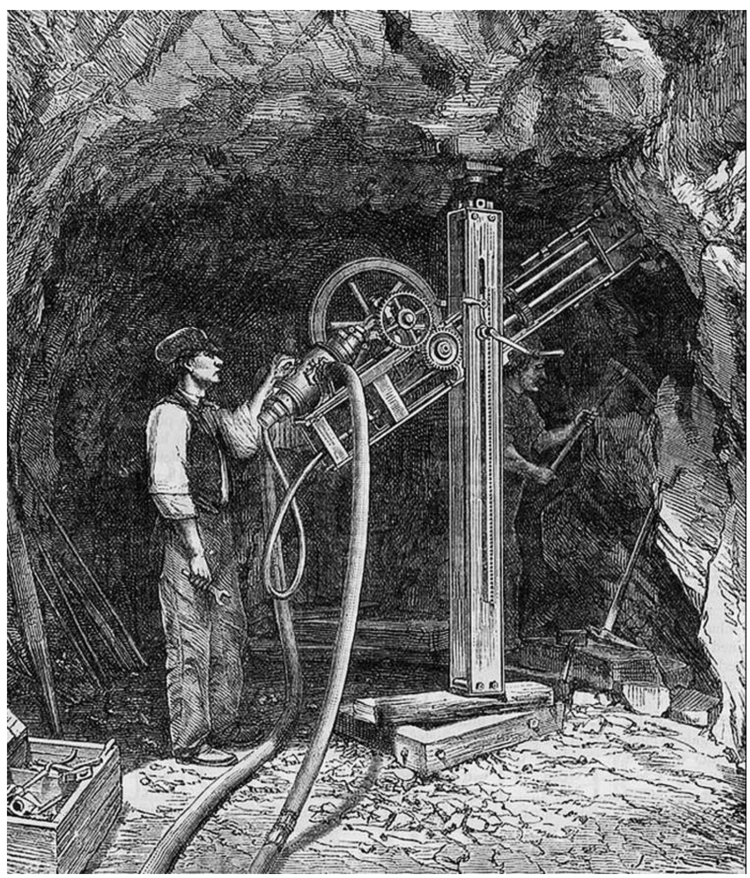
Sommeiller "Boring Machine used in Mount Cenis Tunnel," From: Thomas W. Knox, Underground, or Life Below the Surface *(Hartford: J.B. Burr Pub. Co., 1874), 519.*

Germain Sommeiller, the French-Italian engineer for the Mont Cenis project, set about designing his own machine and looked for inspiration from others who might like to try their own devices. Progress was slow and the opportunities considerable. Sommeiller's machine, driven by compressed air produced by an ingenious hydraulic compressor, was not introduced until 1861, and it took another year before it was capable of regular working and driving at a rate faster than hand labour. After that, however, the rate of driving increased rapidly and the tunnel was opened for through traffic in 1871.

The Sommeiller machine, like all of the others before it and most after, worked on the principle of a solid reciprocating and turning bit. Leschot's machine, successfully trialled in 1863, was unique in using an annular constantly rotating diamond-edged bit.[13] The former machine proved better at producing three or four foot shot holes for blasting, while the latter device offered longer holes and the useful potential to withdraw rock cores to reveal what lay hidden far ahead or below.

From that point on the further development of drilling machines divided along those lines—the solid percussion or impact type, used for sinking shafts, driving levels and, later, ore production; and the constant pressure and rotation type, used for exploration and geological analysis. Solid bit impact machines saw the most varied and rapid development, had the most immediate and visible effect on mine productivity and rate of development, and have attracted the most attention from mining historians. However, core rotary drills set the context for an increasingly close symbiosis between geology and mining and arguably have had an equal, or even greater, impact on the industry's productive potential.

The same story of slow progress, followed by mechanisation and more rapid completion, can be told for the contemporaneous driving of the five-mile Hoosac tunnel beneath the Berkshire Moun-



"Diamond Drilling Machine Used in Boring Mont Cenis," The World of Wonders: A Record of Things Wonderful in Nature, Science, and Art *(London: Cassell, Petter and Galpin, [1888]), 117.*

tains of Western Massachusetts. Started as early as 1851, driving was constantly interrupted by a lack of funds and not completed until four years after the Mont Cenis venture. The rate of driving was dramatically increased in the 1870s after the introduction of the compressed-air Burleigh shot-hole drill, invented by Charles Burleigh of Fitchburg, Massachusetts. No evidence has been found of experiments with rotary drills in this venture, but, as will be seen, they had become common in the U.S. by the mid-1870s and it is quite likely that they might have found use in the project.

Diffusion

Although Leschot patented his invention he appears to have made no sustained attempt to exploit it on his own account. However, word of mouth and references in the mining and scientific press soon spread details of the potential advantages of the new drills and the up-take was rapid and widespread. Attention here will be confined to the United States and Britain but their experience was paralleled in major mining districts everywhere.

The United States

Rodolphe Leschot first patented his drill in the U.S. in 1863. It was noticed from an early stage in mining press reports of its use in driving the Mont Cenis and Terase tunnels,[14] and as early as 1866 interest was being shown in how inexpensive diamonds might be sourced for such drills. When and where the machines were introduced in the U.S. is unclear, but certainly several were operating in various parts of the country by the end of the decade.

To track the story of their take-up over the next ten years, reference here has been made to two principle sources—papers presented to the American Institute of Mining Engineers (AIME) and reports published in the weekly editions of the *Mining and Scientific Press*. Both sources suggest that progress was very rapid and that by 1880 diamond-tipped drills of various types had proved their utility and reliability and had become a standard item in the equipment for the exploration and development of mines. However, these sources do tend to tell different regional stories. Papers in the AIME's *Transactions* tend to focus on the use of diamond drills in the eastern U.S., and in coal mining, while reports in the *Mining and Scientific Press* are largely drawn from the western hard rock mining industry. At the risk of repetition, it is worth considering them separately.

The Western U.S.

Possibly the first machine to be trialled was introduced by Charles Parsons, the resident manager at the St. Joseph Lead Mining Company's operation at Bonne Terre, Missouri, in 1869. He was acting on the recommendation of its successful use at a marble quarry in Vermont a year or so earlier. It had its limitations but soon proved effective in drilling down to previously unworked depths at Bonne Terre, leading to the discovery of numerous large ore bodies.[15] In the summer of that same year, a "Professor Whitney" contracted to use a diamond drill for exploration work at Fletcher Mountain, Summit County, Colorado, with the intention of drilling a six-inch hole to intersect some expected leads at twelve hundred feet. Again, in November 1869, William Latimer brought one from New York for exploration at the South Aurora mine on Treasure Hill, White Pine, Nevada.[16] The experience here, and at some other nearby mines, produced no major new discoveries but proved the viability of the diamond core drills for deep exploration.[17]

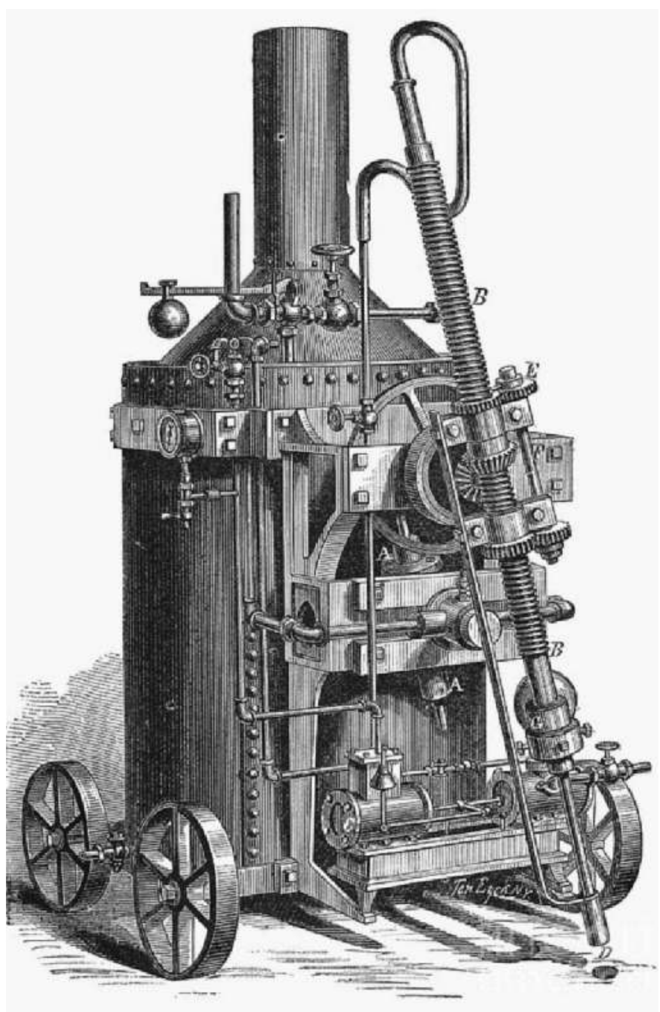
The origin of these early drills—whether manufactured domestically or imported from France—is unknown. For widespread adoption, however, it was clear that a major domestic manufacturing capability would have to be developed. This began to emerge around 1870, with one of the most significant steps being the acquisition of Leschot's patent rights—reissued and purchased in 1869—by the machine manufacturing company of Severance and Holt, based at their Fulton works in Connecticut.

At the time the principal partners in the business were A. J. Severance, Charles W. Randall, and J. Gus Burt, though Severance acquired sole ownership in November 1871. Their foundry had an established business supplying equipment such as shafting, gearing, and castings to mines and municipal authorities in the West, and through its offices in New York and San Francisco the company was well placed to promote the new machine.[18]

Severance and Holt clearly thought that the Leschot name was already well known in the mining community and they continued to advertise their equipment as "Leschot Patent Diamond Drills" for many years. Their first catalogue declared that "the superiority of these Drills over all others has been fully demonstrated in this country and in Europe, and they are rapidly superseding all other inventions for rock-boring."[19] However, the company immediately began to make improvements to the original design, celebrating their reputation as "practical mechanics" and soon claiming to have greatly improved its performance and reliability.[20]

When their machines were first introduced on the Pacific Coast in the spring of 1870, the *Mining and Scientific Press* reported that Severance and Holt had "rendered more secure and convenient the setting of the diamonds, increased the speed, and regulated the feed gear so as to adjust the feed to the varying hardness of the rock." It noted that the company already had several different designs of drill, the most common of which was "the 'prospecting drill', so called because of its general use in testing the character and value of mines and quarries."

The company's catalogue provided a detailed, illustrated description of the drill and its working, and assured potential customers that "the whole machine is so simple, both in its construction and operation, that any intelligent mechanic can easily learn to operate it and make all necessary repairs." Simplicity and ease of maintenance were essential for any machine that was to see service in remote mining districts, as were the reassuring notes that "the cost of resetting the diamonds so as to present new points is very slight, and no special skill is required for the operation" and that "the drill length could be easily extended to any depth, using readily available common gas pipe."[21] It was these machines of which *Manufacturer and Builder Magazine* wrote in the spring of 1870 when it declared that "the economical supe-



#1 Prospecting Drill, Engineering and Mining Journal Supplement, *3 January 1874.*

riority of diamond drills over all others, even in rock drilling, however improbable at first sight, has now been perfectly established."[22]

Alongside their specialised exploratory or prospecting diamond drills, Severance and Holt also began to venture into the production of more common percussion drills, correctly seeing this whole new category of equipment as a major growth area. Their advertisements presented them as manufacturers of "diamond pointed drills and drilling machinery for mining, quarrying, shafting, tunnelling, prospecting, draining, grading and submarine blasting. Special attention given to deep boring for testing the value of mines."[23]

One of the company's principal original contributions in this area was the development of a tunnel drilling machine. This used the rotary diamond drill principle, but applied it to drilling short shot holes. The machine consisted of separate light, manoeuvrable drills, measuring only twenty-four inches long and twelve inches wide, attached to a framework upon which the drills could be arranged in any pattern. The rig was operational by late 1870 and was specifically designed for use by the Blue Gravel Company for driving a long tunnel at its pits in Smartsville, California.

This project provided an opportunity to assess the productivity of the drill against more traditional hand labour, which had been used when the 1,563-foot tunnel was started. Whereas hand labour drove twelve-inch shot holes and advanced no more than that in a shift, the diamond pointed drills drove thirty-inch holes—and did the work with two rather than eight men.[24]

Starting in the same year, these drills were also used to drive a six hundred-yard tunnel by the Consolidated Bullion and Incas Silver Mining Company in Colorado. Adapted to be driven remotely by compressed air, rather than by a direct mechanical drive, the drills also helped to resolve ventilation problems in the tunnel. The set of four drills at this mine cost ten thousand dollars, but Severance and Holt offered an arrangement whereby the work could be conducted by subcontractors for those who did not wish to tie up their capital.[25] Together with good reliability and simple and easy maintenance they proved a considerable success.

By early 1871, just two or three years after their first introduction, the *Mining and Scientific Press* could report that "all of our readers are undoubtedly familiar, to some extent, with the diamond drill."[26] Similarly, a contributor to a meeting of AIME in that year spoke of the diamond core drill as "the boring tool of the future," and predicted that, with careful use and improvement, it could successfully investigate at depths down to fifteen hundred feet or more.[27]

In the West, they had already proved their worth in California, Colorado, and Nevada. At the Union Mine, Calaveras County, California, for example, an attempt to revive mining by drilling a 234-foot-deep hole, at a 45-degree angle, had successfully struck a predicted and potentially productive ledge.[28] The successful use of diamond shot-hole drills was also frequently reported.

The up-take of the machines proceeded rapidly everywhere, spurred on by the increasingly positive reports from existing trials, but it was soon the deep mines of the Comstock that became the main focus of attention. As has been seen, diamond core drills were first tried at Aurora in 1869 and by the summer of 1872 they had bored at least three holes down to a thousand feet and were being used alongside Burleigh drills in driving and sinking shafts on the Sutro tunnel.[29] In 1873 there was very active exploration elsewhere in Nevada in White Pine's Chloride Flat district, close to South Aurora, as well as at Eureka Consolidated Mines.[30]

Experience with the machines was also now beginning to show their usefulness for purposes other than exploration. At Crown Point Mine, at Gold Hill, Nevada, for example, a fifteen-foot bore hole was kept ahead of a cross cut being driven on the 1,400-foot level "as a precautionary measure against a heavy inflow of water being encountered."[31] Later, such holes were purposely drilled to drain water from the flooded 1,300-foot level. In 1878, one commentator observed of the Comstock that "there are scores of diamond-drill bore holes, each some hundreds of feet in length, on different levels in all parts of the lode."[32]

A *Mining and Scientific Press* editorial review of the new machines and methods pioneered on the Comstock included core drilling with steam power, tramways, and "giant powder" as one of the most strategic innovations of the age. It concluded that "diamond drills are used in certain localities with great effect and will no doubt be considered more necessary mining implements, for prospecting purposes in ten years from now, than they are at present."[33]

Certainly by 1875, Severance and Holt had taken a very positive view of the future and moved its main manufacturing plant to the Miner's Foundry in San Francisco.[34] (Severance and Holt already had a long association with this works, which it had used to manufacture drills for the Harpending Mines in New Mexico and the Black Diamond Coal Mine at Mount Diablo, California, some years earlier.[35]) However, the up-take of the machines appears to have been patchy outside of Nevada, with significant consequence for the pattern of mining investment.

On the principle that attention in a shadowy room focuses on patches of light, some mine promoters in California began to take the view that the greater certainty and reduced risk to investment in Nevada mines—informed by core analysis—was depriving California mining of much-needed capital. Unwisely they chose to campaign for a stop to diamond drilling in Nevada rather than taking up the machines themselves. The reasoning behind this campaign was convoluted, but it does demonstrate that by 1879 there existed a clear and widespread perception of the usefulness of core analysis for making informed investment decisions.[36]

The Eastern U.S.

As has been seen, the very earliest diamond-tipped drills in America were used in the marble quarries of New England. How and when they spread from there to the coal and metal mines of the wider eastern part of the country is not known. *Mining and Scientific Press* reported a successful 750-foot exploration diamond drilling near Pottsville, Schuylkill County, Pennsylvania, in 1870, but gave no details.[37]

It is clear, however, that the potential of the new machinery was not missed and that it began to be increasingly taken up during the early part of the 1870s. A paper delivered to AIME by Louis Riley, simply looking at exploration on coal lands belonging to the Lehigh Valley Coal Company in the Mahanoy, Lehigh, and Wyoming regions of Pennsylvania, identified thirty-five test holes, with a combined length of almost ten thousand feet bored by early 1876, most of them "for the purpose of proving the lower veins of coal."

By that year, test drilling had become an established part of the company's activities and Riley's paper concluded that "it is not necessary for me to state the value of the diamond drill for exploring work, as that is probably known to all members of the Institute." Given the considerable cost of the drills, their power source, drill rods, machinists' tools, diamonds, and a portable operators' house—estimated together at about five thousand dollars—the demonstrable value of their use was clearly very high.

The company was keeping two machines, of different sizes, in constant work, the smaller of them being described as of "the ordinary pattern used by the Pennsylvania Diamond Drill Company." They were manufactured by the local machine builder, Messrs. Allison and Bannan of Port Carbon, which provided an "improved" device with a hydraulic drive. It seems likely, however, that this machine was based on the Leschot design, since estimates of drilling costs included a "royalty for use of patent right." Each drill was operated by an average of three men, with the drill being withdrawn every ten feet to obtain the core. Labour accounted for just over half of the cost of driving, which was estimated to occur at a rate of just over two feet an hour.[38]

While some took up core drills for exploration, others experimented with solid diamond-tipped drills for driving long shot holes. In a paper on sinking two shafts for a new anthracite mine near Pottsville in Schuylkill County, Pennsylvania,[39] presented to the AIME in 1872, Eckley Coxe reported on the "novel" method of drilling blast holes, with the diamond drill being favoured over more traditional hand techniques. "This had been already been done in other places" but "a new plan of working with the diamond drill" was to be tried.

That plan had been proposed by men named Shelley and M. C. Bullock, respectively the former superintendent of the nearby William Penn Colliery and the Pennsylvania Diamond Drill Company. After sinking down to solid rock, "a number of diamond drills, each driven by its own machine, [would] bore a series of holes about 300 feet deep, which would be so arranged as to dispense with further drilling for blasting, until the depth had been reached." One shaft used twenty-five holes and the other thirty-five. The machines were said to be "much more compact and simple than the old diamond drill apparatus," and eight to ten could be operated in the shaft at the same time.

This is somewhat suggestive of the Severance and Holt Tunnelling Machine discussed earlier, but the drills used here were not solid arrangements but rather hollow "gas pipes" of 1.5-inch diameter. Unlike exploration drills, however, no core was withdrawn during drilling. The diamonds were so arranged as to crush the rock to fine powder, which was then flushed up the interior of the pipe by pressurised water. This greatly reduced the need for stoppages to withdraw the drills.

The improved, more compact drills were specially designed for the purpose by Bullock, and nine of them were constructed by the local engineers, Allison and Bannack. In taking their initiative, Shelley and Bullock were clearly looking for an extended use for an already well-proven drilling technology, further evidenced by their patenting of their shaft sinking technique shortly after its successful conclusion.[40]

Around the same time as the experimentation in Schuylkill County, Oswald Heinrich was conducting comparative drilling experiments in Midlothian, Virginia. These were designed to test the relative merits for exploration drilling of diamond core drills and more traditional percussion, or chip, drills. He produced detailed data on three diamond drillings that were conducted on the Midlothian property in 1873, comparing them with data that he had obtained for other means of deep boring in Chesterfield County, Virginia, Germany, and England.

The latter data included experience with Messrs. Mather and Platt's percussion chisel drill. Invented in England by that firm in the 1850s, this drill had previously been the industry's leading boring and exploration device. However, Heinrich concluded that "no dispute can now exist in regard to the great suitability of the diamond drill for use in the harder or hardest rocks. In fact, it will perform its work almost with more ease in a hard granite, or hard siliceous sandstone, than in softer rocks."[41]

By 1880 diamond core drilling had become commonplace in most parts of the U.S. and the mining press and engineering societies began to find it unremarkable. Attention instead turned to improvements in drill design and how the exploitation of the drills might best be organised. In the spring of 1883, *Mining and Scientific Press* referred to the introduction of improved core drilling machines that "are sold without any restriction"—possibly a reference to the expiration of the original Leschot–Severance and Holt patent.

The best of the new devices appears to have been the Dauntless Drill, manufactured by the

Bullock Manufacturing Company of Chicago and, particularly, the Sullivan Prospecting Machine—a simple, strong, but light machine—designed by Albert Ball and manufactured by his employer, the Sullivan Machinery Company of Claremont, New Hampshire.

Sullivan had been in business since the early 1850s, producing its first diamond-tipped drills in the late 1870s for use in New England quarries. *Mining and Scientific Press* announced the Sullivan Company's new core drill in October 1883,[42] naming the Berry and Place Machine Company of San Francisco as their agents.

A year later, Frederick Copeland, a coal mine manager with experience of using Sullivan machines in Iowa, established the Diamond Prospecting Company of Chicago. Using only Sullivan drills, this company was soon to become a national and international contracting service, with particular success in the early development of the Mesabi iron range in Minnesota. Not to see its own markets lost, the Sullivan Company also rapidly expanded its activities as a contract driller as well as a machine manufacturer.

As time passed, the different manufacturing companies began to specialise in different forms of machinery. Sullivan, for example, continued to dominate the surface drilling sector, while Bullock, with machines like its Badger drill, began to prevail underground. Companies also gradually evolved different methods for advancing the drill rods, which was a critical aspect of the overall technology. Two different methods of boring became common—hydraulic and mechanical screw—each with advantages and disadvantages. Thus whereas the American Diamond Rock Drill Company favoured the hydraulic system, the Bullock Company favoured positive gear drives. Particular attention was also given to ensuring the accuracy of drill holes, devising systems that prevented the drill from drifting from its planned course and measuring any deviations that did occur.[43]

Clearly diamond drills were no longer new when Edmund Longyear used them to explore the Minnesota Mesabi iron range in the summer of 1890. Certainly they played a critical role in the discovery and development of the "hidden" deposits of those districts, but by that time many prospectors were already widely experienced in their use. Diamond drills had already firmly established themselves alongside traditional churn drills[44]—still extensively used in exploring soft ground—as the principal method of ground penetration exploration, and were having an important impact on revealing major new ore deposits

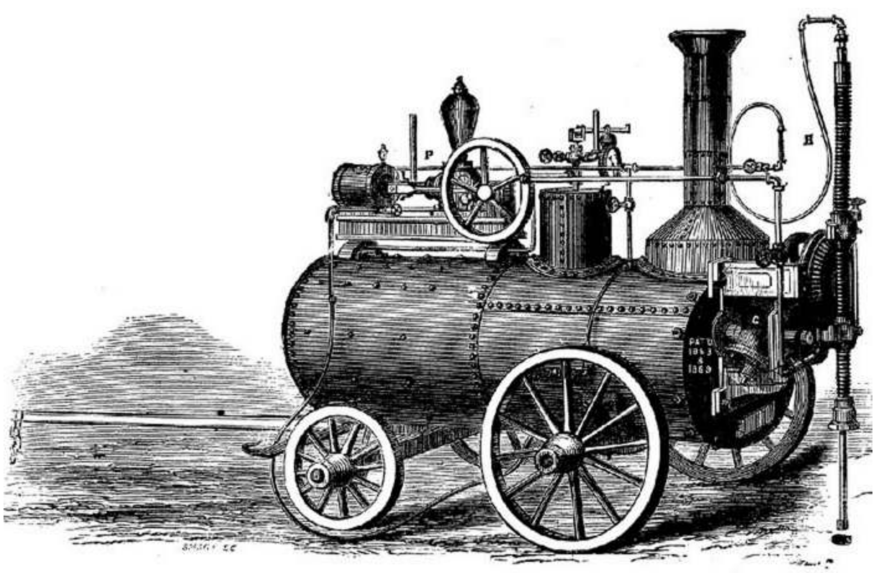


Fig. 2.

A steam-powered Sullivan drill for surface work. From: Engineering and Mining Journal Supplement, *3 January 1874.*

across the United States.

The United Kingdom

In Britain, hard rock mining was past its peak by the beginning of the last quarter of the nineteenth century. Gold had never been significant, copper was declining fast, and tin and lead were struggling to maintain their own. After two thousand years of continuous activity the main producing districts were known and there was little incentive for further exploration. By contrast, the much larger coal and iron sector was in ascendancy and it was inevitable that the main focus of any advance in deep drilling would be there.

The potential of the new Leschot machine was publicised in Britain as early as 1864. An article in the *Proceedings of the Institution of Civil Engineers* for that year provided a translation of a description of the "diamond cutter" machine and concluded that it was "equally serviceable for railway works, or for mines, for the quarrying of very hard rocks and also for the sinking of shafts."[45] A few years later a British version of the machine was designed and patented by Frederick Edward Beaumont.

Captain, later colonel, Beaumont was a younger son of the Blackett Beaumont family that owned and worked extensive lead-silver, coal, and iron properties in the North Pennine area of England. Without a direct stake in those mines, he had become a career army officer in the Royal Engineers, where he established a reputation as a capable inventor. Beaumont is believed to have been involved in designing the mechanical section of the Paris Exhibition of 1867, where he would have seen Leschot's machine. A few years later, he patented a slightly improved device together with C. J. Appleby, who provided essential practical engineering skills from his railway machinery workshop.[46]

Beaumont was keen to continue to be involved in the technical development of the machine, and with the range of its possible uses, but with continuing military commitments and increasing political ambitions he was short of the time and resources necessary to ensure its optimum commercial exploitation. He therefore chose to transfer his patents to a public company in which he could retain an interest. Accordingly, the Machine Manufacturing Company undertook the first drilling contracts in 1870.

Greeted with immediate success and in need of more financial resources, the rights were passed on again in 1872 to the Diamond Rock Boring Company (DRBC). The new company, with a capital of £160,000 in £5 shares, was able to continue the expansion of the business for the rest of the decade. DRBC became as synonymous with the early take up of diamond drilling in Britain as Severance and Holt was in the United States. Improved Beaumont and Appleby machines stood alongside the American Sullivan drills as the international industry standard through to the early twentieth century.[47]

The board of Diamond Rock Boring Company consisted of Beaumont, as managing director, and six Members of Parliament, including Dr. Lyons Playfair, one of the leading geologists of the day. The new cutting-edge technology that the company represented also attracted the attention of John Pender, who had recently been involved in the project to take undersea telegraphy to the Far East and Australia.

Diamond Rock Boring took over several contracts already initiated by the Machine Tunnelling Company, such as exploration for coal and iron ore around Stanghow, near Guisborough in Yorkshire, Lindal in the Furness district of Lancashire, and the Eden Valley in Westmorland.[48] It also appears to have already diversified from the single business of exploratory core drilling into other drilling operations, such as shot holes for the Entwistle railway tunnel at Egerton in Lancashire. In all cases, it tried to keep the new technology entirely to itself, neither selling nor leasing its machines but working them only on time or depth contracts.[49]

As in the U.S., one of the earliest uses of Beaumont's diamond drill was in quarrying. He appears to have been aware of Severance and Holt's interest in sinking shafts by the use of long vertical shot holes[50] and undertook similar trials at Penmaclure in Carnarvonshire. Although they had some success, Beaumont focused his early attention on experiments with exploratory core drilling. Among the earliest of these were exploration holes for the coal deposits in Somerset, in southwest England. Interest in finding and developing new deposits there had increased rapidly after 1861 with the building of new railroad lines and widening of markets.[51] Drilling appears to have been initiated by a desire to map out the extent of the field for the mineral owners and it started around 1870.

A report in 1871 suggested that Beaumont, on his own account, had sunk a successful hole, making contact with the coal at 455 feet, and that he had also employed the drill to unwater a partially flooded shaft by driving downwards into old mine working. This technique was not new but, perhaps following U.S. experience, it was recognised that rotary drills had a capacity for sinking holes underwater that could not be matched by older percussion devices. Overall, the project was said to have demonstrated that "the Diamond Drill will stand unrivalled in every respect as an instrument for boring and proving the strata,"[52] and Beaumont's supporters started to advertise their success widely.[53]

With success in Somerset behind it, the new DRBC was in prime position to take on one of the most high-profile geological explorations of the age. In 1855 it had been proposed that the coal measure that had been worked so profitably in South Wales and Belgium passed under southeast England.

Nothing was done to test the proposition until 1872, when the British Association took up the challenge to raise money through private subscription, together with a little government help, to conduct a trial. Percussion drilling started in that year and went down a few hundred feet, but in 1873 responsibility for the project was transferred to the DRBC, which rapidly continued drilling beyond a thousand feet.[54] Three years later the company had carried the exploration to over twice that depth.[55]

The success of the project ensured wide publicity for DRBC's machines. The advantages of diamond core drilling were becoming known everywhere, and work was going on across the country, from slate mines in North Wales, to iron mines in Lancashire, Lincolnshire, Yorkshire, and Cumberland, and coal mines in South Wales.[56]

In South Wales DRBC drills were used to assist in the sinking of shafts on deep coal measures in 1875, and the following year the local Linvi and Ogmore Railway Company used them, probably in driving the Cymmer tunnel.[57] As early as 1874, the engineer Henry Huxham could declare that "so much successful boring has now been accomplished by means of the diamond drill, that the record of failure may, perhaps, be a greater novelty than that of success."[58] However, progress remained slow outside of the coal and iron districts. Another mining engineer, a Dr. Hartig, writing in that same year, could note great improvements in the design of the drills, but observed that they were still "chiefly employed in America."[59]

Nevertheless, the technology was gradually diffusing. The lead workings of the north of England certainly saw some activity, with cores being taken from the Hope Level—a mine being driven by another branch of the Beaumont family between 1868 and 1877—near Stanhope in Weardale in 1874.[60] Beaumont drills were also used in developing the Halkyn Level and lead mines in northeast Wales by 1880,[61] and possibly the highly productive Van mine in Montgomeryshire around the same date.[62]

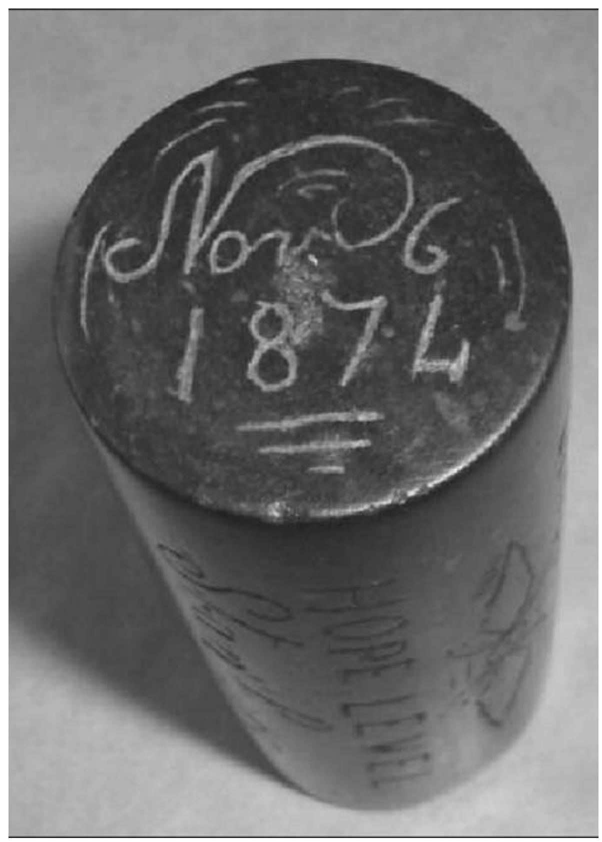
Other activity, however, seems to have been very limited. In Cornwall and Devon, Britain's leading non-ferrous mining district, it was not until 1876 that the first concerted effort was made to introduce the use of diamond drills, and that met with very limited success. In June, DRBC organised a meeting with a number of leading mineral owners, mining investors, and mine captains with a view to them jointly covering the costs of bringing machines down from the north, both for core drilling trials and experimentation in driving levels. Observers at that meeting commented that although major mines, such Dolcoath and Tincroft, had seen some of the earliest experiments with percussion drills, trialling Doering machines in the mid-1860s, the region had since fallen behind in the take-up of this important new category of mining machinery.[63]

There is some evidence that the DRBC undertook work at the Carn Brea mines in the late 1870s, but this appears to have been for sinking blast holes for driving adit headings rather than for exploratory purposes. Otherwise references to the use of diamond core drilling in the southwest of Britain remained uncommon before the early twentieth century.[64]

Geological and mineral exploration was not the only task found for the new machines. They also became increasingly important in drilling for deep aquifers. In 1872 Beaumont machines were trialled, at the company's own expense, in attempts to improve the water supply to Dublin,[65] and in 1874 Messrs. Bell Bros. engaged DRBC to put down a 1,355-foot bore hole close to their ironworks at Port Clarence on the north bank of the Tees. Bell had sunk for water before, with a percussion drill in 1859, but wished to increase the rate of flow. The desired effect was achieved but also discovered much more—salt. Soon boreholes were being sunk across the area, establishing a new industry and adding greatly to geological mapping.[66]

Water was the big new area of demand, however. In Britain, as in many other fast developing countries, rapid industrialisation, population growth, and urbanisation were producing a nascent water crisis by the mid-nineteenth century. Rivers were generally too small and polluted to provide good supplies and industrialists and local utilities had already begun to look downward for sustainable supplies of pure water. This demand had already led to advances in drilling technology during the second quarter of the century, evolving very efficient forms of percussion churn drills such as that developed by the Salford firm of Mather and Platt in the early 1850s.[67] (Drills of this type were used for the first oil drilling operations in the U.S.[68])

When the industrial sector went into depression in the mid-1870s, with a turn down in coal and iron exploration activity, it was this market that DRBC turned to for new orders. By 1876 the company was developing a new range of machinery for boring larger gauge artesian wells[69] and was shifting its attention from its usual base in the north to southern England. In London DRBC again followed up on an earlier Mather and Platt drilled hole to sink about a thousand feet into



1874 Diamond Rock Boring Company core from the Hope Level, Weardale, England. Photo by Bernard Moore. Used with permission.

the underlying Chalk and Greenstone formations to secure pure water supplies for Messrs. Meux and Company's brewery in Tottenham Court Road, and Messrs. Mann, Crossman and Company's brewery in the Mile End Road. Just outside of London, in Caterham in Surrey and Ware in Hertfordshire, DRBC drilled holes for local water supply companies. The market became so active that the Diamond Rock Boring Company began to sub-contract some of its work to local engineers on a royalty basis.[70]

The Rest of the World

Little evidence has been found of the speed of take up of the new core drills in other parts Europe, but it seems to have been quite slow. Historian Thierry Veyron noted their use in coal mines near Liege in 1868, but commented that they were primarily developed in the United States and only came back to Europe in the late 1870s.[71] France's premier mining journal, *Annales des Mines*, did not make its first mention of the use of diamond drills until 1872, and that for the rotary drilling of shot holes rather than core drilling.[72] In 1884 the *Engineering and Mining Journal* reported that the diamond drill had been mainly used in England, America, and Germany but provided no details of the latter.[73] Certainly Scandinavian mines had experimented with them by the mid-1870s,[74] but the speed of diffusion generally seems to have been much slower than in the United States and Great Britain.

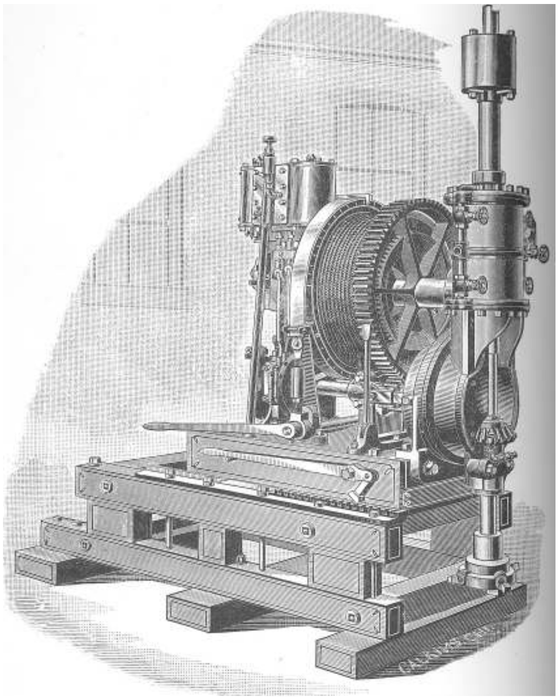
It is clear, however, that from the early 1880s diamond drills began to be used with increasing frequency in all of the world's new mining districts, sponsored both by mining companies and public authorities. In many parts of the British Empire, for example, colonial governments frequently purchased and employed or rented-out diamond drills as a means to encourage mining investment.

Thus the government of the Australian state of Victoria, alarmed at the decline in gold output in the 1880s, brought in Leschot patent drills manufactured in San Francisco—probably Severance and Holt machines[75]—to investigate mineralisation at depth. Around the same time, in the neighbouring state of New South Wales, diamond drills were reported to be doing good work in discovering and proving major coal deposits.[76] They also played a significant role in the development of the vast Broken Hill deposits, and Australian engineers were developing their own improved machines—such as the Victorian Giant Drill—to push ever deeper and more efficiently.[77]

In Southeast Asia the colonial government of Perak provided diamond drills and accessories in the search for gold and tin.[78] In Canada, the government of New Brunswick used its own diamond drills to search for iron ore deposits. In South Africa, the Railways Department of the Government of the Cape of Good Hope rented out Sullivan diamond drills for exploration and drilling water bore holes.[79]

As early as 1890, John Hays Hammond acted on behalf of the Sullivan Company in supervising drilling in the Transvaal to prove the geological strike of the main reef. Hammond brought in Sullivan's network of international contractors to assemble 250 drills to plot accurately the surface boundaries of the lode. [80] By the mid-1890s one observer could record that there "was so much activity in drilling operations in this country that the contractors [who dominated the activity] were practically able to fix their own prices, and at one time almost made a favour of undertaking work at all."[81]

Not all of the work was conducted by large mechanical drills. By the late 1890s hand-operated diamond drills, manufactured by both the Sullivan and Bullock companies, were being used widely for exploration in remote, fuel-and-water-scarce locations. Such operations also required hand-operated pumps to flush the holes, but the system proved popular in areas with plentiful, low-cost labour. In South Africa holes were sunk to five or six hundred feet using these machines.[82]



A Sullivan Drill. From: E. H. Davies, Machinery for Metalliferous Mines *(London: C. Lockwood, 1902).*

Albin Wicklund's book, *A Diamond Driller Reminisces*,[83] ably demonstrates how ubiquitous diamond drilling had become by the beginning of the twentieth century, but it is important also to note that much of the mining press still contained correspondence enquiring about the nature of the benefits of such machines and how they could be best employed.[84]

A Strategic Invention

The concept of "exploration" with a diamond core drill is something of a misnomer. The initial exploration and discovery process—finding a new site of potentially economic minerals—is much like the process of invention. It is based on the assemblage of a wide range of information, including practical experience and scientifically derived data, which is then given practical expression by acts of human insight, driven either by an expectation of new wealth or the exigencies of dire poverty.

The prospector divines where payable minerals might be and then—and only then—drills are introduced to explore the sub-surface. Holes are not drilled randomly everywhere; they are driven where geologists or other discoverers think that they will yield positive results. As such, core drills are essentially proving machines rather than finding machines, or, as mining commentator Andrew Duval has called them, "truth machines."[85]

This in no sense diminishes their significance to the industry. By providing reliable information, they reduced risk. Risk is the deadly enemy of investment and information the only way of controlling it. The mining industry is unusually subject to many types of risk—production risk, metallurgical risks, transportation risk, external interference risks, market changes, etc.—and was traditionally seen as a highly speculative industry. Of these, production risks are the most immediate and important. If there is no certainty that paying ore is present then all of the other issues become irrelevant. By providing reliable information on geological structure, average milling grades of the ore, and its extent and potential tonnage, core drilling laid the foundations of the trust needed for the heavy investment required to work the deeper, more difficult, more complex, and lower grade ores that became the mainstay of the industry from the late nineteenth century.

Core drilling did this not simply by enabling investors to estimate the probable profitability of a mining project, but also by facilitating the most efficient layout of the workings and their long-term development. As mining engineer George Denny opened the introduced to his book on diamond drills and gold prospecting in 1900: "The business of gold mining is being rapidly evolved from the sometimes blindly speculative to a legitimate commercial enterprise."[86] Of course diamond core drills were not alone in filling the information gap. Churn drills also continued to play a major part in researching softer strata where intact cores could not be retrieved, and the contribution of ground penetration equipment must be read together in assessing the overall effect on the industry.

A context for this proposition on the contribution of drills is provided by the economic historian Christopher Schmitz in his analysis of the growth of big business in the copper industry.[87] He argues that the great expansion in the asset values of the giant companies that came to dominate the industry in the late nineteenth and early twentieth centuries—Anaconda, Calumet and Hecla, Kennecott, etc.—was driven partly by a process of amalgamation, but particularly by the "technological imperative" to invest heavily in new mass production ore extraction, processing, smelting, and transport equipment required for working lower grade deposits.

That investment was only forthcoming when investors were assured of long-term returns and mining was put on the same kind of secure footing as manufacturing industry. Ore bodies had to be carefully delineated and assessed ahead of any major commitment of funds. Schmitz also shows how this process was made more difficult by the nature of ore bodies. He claims that, in very general terms, as ore grades declined, the size of the ore bodies increased and that the cut-off point for profitable extraction became progressively less clear. Under such circumstances the need to drill became paramount, not just single holes to prove the existence of an ore body, but multiple holes to map accurately its extent and values.

Such mapping not only helped to provide investor security, it helped greatly to improve the optimum layout of the mine and to maximise the efficiency with which the deposits could be worked, balancing development with extraction. The importance of this issue cannot be exaggerated. Poor mine design can result in the inefficient handling of materials, poor equipment utilisation, the sterilisation of reserves, or unforeseen faulting and stability issues. As *Mining Magazine* recently concluded, the impact on the profitability of the operation can run from a slight increase in operating costs to complete failure.[88]

With all of this in mind, it can clearly be argued that the introduction of the diamond core drill in the 1870s was one of the most strategic inventions of the nineteenth century. It provided the essential requirement for a quantum leap forward in mining, from traditional selective hand techniques to modern non-selective mass-production extraction, and as such underpinned the expansion of the supply of the commodities that fuelled international industrialisation in the late nineteenth and early twentieth centuries.[89]

Like other strategic inventions, the core drill's impact continued to grow as it was constantly improved. During the next twenty years different models were introduced, for exploratory, surface, and underground use; they were made lighter and more manoeuvrable, including simple hand-powered devices;[90] they became more directionally controllable and operable with less labour. Above all, experience in use gathered by their operatives improved the accuracy of the interpretation of data, demonstrated the need for multiple drill holes, and cemented the role of the geologist as essential in exploration and operational mine management teams.

To give these conclusions a wider context, it is useful to look briefly at the current state of the mining industry. Unlike the late nineteenth century, the early twenty-first century has seen a rapidly developing crisis of mineral supply. Whereas once supply expanded ahead of demand and prices fell, now supply responses have lagged behind the rising consumption of the new industrial nations and prices have boomed. More specifically, while the rate of discovery of new deposits once raced ahead of active mine exploitation, now it has begun to slow dramatically. From oil to copper to gold, new discoveries have become less frequent, of lower quantity and quality, and more difficult and expensive to extract.

The recent history of gold provides one small example. In terms of the discovery of large deposits, of twenty million ounces or more, the number has fallen from fourteen in the 1980s, to eleven in the 1990s, to five in the 2000s. Even the incidence of smaller discoveries has declined. Taking the two-year period 2003-04, more than 400 million ounces of new gold was found—the peak discovery for the decade—at an average of grade of 1.65 grams per ton. Over a similar two year period 2011-12, less than 225 million ounces were proved at a reduced grade of 1.17 grams per ton.[91] Over the whole period 2002-12, gold prices rose consecutively each year. Of course there were factors other than supply affecting prices, but clearly the mining industry was proving incapable of producing a smooth and appropriate response to the market.

When looking for explanations for this phenomenon, it is common for contemporary commentators to blame it on the need of the industry to concentrate increasingly on "far-flung locations with limited infrastructure,"[92] and the cost-raising consequences of harsh environments. This, of course, is nonsense. The mining industry has always operated on the frontier—beyond the frontier—of civilisation. The difficulties faced by those who prospected and developed mines in Alaska and the deserts of Australia in the nineteenth century were relatively far greater than anything encountered by the 'fly-in' industry of today.

Rather, the answer is to be found in the laggardly progress of exploration technology. Today's prospectors can take advantage of a great new array of sophisticated techniques of satellite imagery interpretation, airborne surveying, ground-penetrating radar, and integrated multivariate (i.e. geological, geochemical and geophysical) data analysis packages, but they continue to rely on 150-year-old diamond core drilling technology as the principal ground-penetration technique and the only reliable key to proving deposits.[93]

Unfortunately, like all strategic technologies, the diamond core drill has seen an impact cycle, and has now long since passed its peak capacity for significant further improvement. Of course major design refinements have taken place. Indeed, it might well be argued that the speed, depths, directional dexterity, and accuracy of today's drills make them something entirely new, effectively creating the fracking industry and its associated power revolution. But for the metal-mining industry none of these technical developments have done much to improve the search for and investigation of new deposits or to ward off sharply diminishing returns.

Pierre Lassonde, chairman of Franco Nevada, astutely identified the problem in a recent speech to a mineral exploration conference in Vancouver, Canada. He said "give me a new technology that has really shaken our world in the last 30 years. . . . We're still using the same stupid drill rigs that we've used for 100 years. Maybe they're a little faster . . . but there's nothing dramatically new." He called for the mining industry to invest more in research and development "in order to bring about a 'paradigm shift' in mining and exploration technology."[94]

Unfortunately, that may be some time in coming. The mining industry has never been good at generating effective research and development activity and has for long relied on importing new machinery from other sectors. Railway and civil engineering, for example, were the developers of rock drilling technology, and much other rock machinery later adopted by mines and the direction of technical progress in those sectors might not encompass the kinds of devices now required by mines. The potential for the metal-mining industry to take another great leap forward will not be achieved until another Leschot begins to think "outside of the box."

Born in 1942 and educated at the London School of Economics, Roger Burt spent his academic career at the University of Exeter in the South West of England teaching economic history and researching and writing world mining history. He has published on most aspects of the technical, financial and social organisation of the industry and was latterly appointed to a personal Chair in Mining History, one of the few to hold such a position.

Notes:

1. See: C. J. Schmitz, *World Non-Ferrous Metal Production and Prices 1700-1976* (London: Cass, 1979).
2. M. E. Charton, *Le Magasin Pittoresque* (Paris: s.n., 1866), 5.
3. W. P. Blake, "Recent Improvements in Diamond Drills and in the Machinery for their Use," *Transactions of the American Institute of Mining Engineers* 1 (1871-3): 395-400.
4. Tunnels were driven by drilling hard rock, blasting it, and then removing the broken material. Hand drilling, which had been the established technique from the seventeenth century, was difficult, slow, and the bottleneck in the whole process.
5. *Memoires de la Societe des Ingenieurs Civils de France* 37, no. 3 (Mars 1884): 269; L. Figuier, *Les Nouvelles Conquetes de la Science* (Paris: E. Girard & A. Boitte, 1885), 382.
6. D. Colladon, *George Leschot et L'Invention des Perforatrices A Diamant* (Paris: impr. de E. Capiomont et V. Renault, 1884).
7. He received the gold medal of the Society of Arts of Geneva for the design of this machine. Although not itself capable of large scale production, the pantograph reduction milling machine has been seen as an important precursor to the mass production of cheap watches by the Waltham Watch Company several decades later.
8. The drills were hardened around the edges with tough minerals. It might be assumed that the Egyptians favoured "wearing" drills because of the lack of available of hard metals for impact drilling. Flinders Petrie, in *Pyramids and Temples of Giseh* (London: Field, 1885), argued that the tubular drills must have been set with gem stones, but it is more likely that abrasive powders were used. See: J. D. Cumming, *Diamond Drill Handbook* (Toronto: J. K. Smit & Sons, 1951), 1.
9. *Engineering and Mining Journal*, 3 May 1884, 333. The *Journal* noted that Georges-Auguste had been honoured by the French Academy of Sciences in 1845 for his work on watch design with Vacheron and Constantine. He never received similar recognition for his far more consequential drilling machine.
10. See, for example, the Italian patent description in *Descrizione della Machine e Procedimenti per Cui Vennero Accordati* (Torino: Ministro d'Agricoltura, Industria e Commerce, 1862) v. 8, 275.
11. A. Burat, *Traite du Gisement et de la Recherché des Mineraux Utiles* (Paris: Garnier, 1870) bk 2, 415.
12. L. Day and I. McNeil, *Biographical Dictionary of the History of Technology* (London: Routledge, 1996). It is notable, however, that the Leschot name in fine engineering continues to be celebrated by the Leschot Holding Company, which controls Leschot Engineering, Leschot Tourbillon, and Mikron Manufactures, though this is probably more in deference to the work of Georges-Auguste than that of Rodolphe.
13. The number and type of diamonds used on the cutting edge were varied over time to maximise results. Leschot's drawing suggests six, possibly of Brazilian origin, but up to fifteen may have been tried, some later ones being derived from South Africa.
14. The Terase tunnel was excavated for the Borbonais Railway in France. See *Mining and Scientific Press* 1 June 1867, 339.
15. T. A. Rickard, *A History of American Mining* (London: McGraw-Hill Book Co., 1932), 173.
16. *Mining and Scientific Press* (hereafter *M&SP*), 4 July 1869, 60; 27 Nov. 1869, 343.
17. In a discussion of the activities at Treasure Hill at an early meeting of AIME, the president of the Institute concluded, "I do not think drills can quite supersede exploring drifts. On the other hand it must be said for this drill, that it is the only one permitting the boring of long holes in any straight line," with the ability to determine the succession of strata, the order and character of veins or beds, and the nature of the rock to be worked in mining. *Transactions* 1 (1871-3): 399.
18. Severance and Holt's customers for these products included Vance's Mill at Mountain City, Nevada, the Oakland Water works, and the Sierra Butte Company. See: *M&SP* Oct 1870; 10 Dec 1870, 393.
19. Severance and Holt, *Leschot's Patent Diamond Drills, with Improved Machinery for Drilling in Mines and Quarries, Tunnelling, Prospecting, etc., Manufactured by Severance and Holt, Middlesbury, Vermont and Noc. 14 and 16 Wall Street, New York* (New York: The Company, 18??), Trade Cat .S498 18--, Hagley Library, Wilmington, DE.
20. See various advertisements in the *Mining and Scientific Press* during 1870.
21. See also: *M&SP*, 7 May 1870.
22. See "Rock Boring with Diamonds," *Manufacturer and Builder Magazine* 2 (Mar. 1870): 385-7.
23. *M&SP*, 9 July 1870, 156.
24. *M&SP*, 3 June 1870, 344.
25. *M&SP*, 5 Nov. 1870, 314.
26. *M&SP*, 11 Mar. 1871, 152.
27. O. J. Heinrich, "The Diamond Drill for Deep Boring Compared with Other Systems of Boring," *Transactions* 2 (1873-4): 241-61.
28. *M&SP*, 17 Sep. 1870, 208. See also: R. H. Limbaugh and W. P. Fuller Jr., *Calaveras Gold* (Reno: University of Nevada Press, 2003), 83.
29. *M&SP* 10 Aug. 1872, 82; 2 Nov. 1872, 280.
30. *M&SP*, 13 Sep. 1873, 168.

31. *M&SP*, 7 June 1873, 357; 28 June 1873, 405.
32. J. A. Church, "The Heat of the Comstock Mines," *Transactions* 7(May 1878-Feb. 1879): 66.
33. *M&SP*, 18 Jan. 1873, 33.
34. *M&SP*, 1 May 1875, 282; 15 May 1875, 313.
35. See: L. R. Bailey, *Supplying the Mining World: The Mining Equipment Manufacturers of San Francisco, 1850-1900* (Tucson: Westernlore Press, 1996), 62.
36. *M&SP*, 27 Dec. 1879, 416. Californian promoters reasoned that there was a perception in the East that the Comstock was part of California. This was because most of the stocks transacted on the San Francisco Exchange were those of Comstock mines, while most Californian mines were worked by individuals or private companies. At the time, the prospects of Comstock mines were at a very low state, with further major finds "proved" unlikely by the results of diamond drilling. There was thus an Eastern perception that mining in California was finished and that investors' attention should best be turned to South Dakota, Colorado, and Arizona.
37. *M&SP*, 17 Dec. 1870, 411.
38. L. A. Riley, "Cost and Results of Geological Explorations with the Diamond Drill in the Anthracite Regions of Pennsylvania," *Transactions* 5 (1876-7): 303-8.
39. This mine became the East Norwegian Colliery, situated on lands owned by the Mammoth Vein Coal and Iron Company.
40. E. B. Coxe, "A New Method of Sinking Shafts," *Transactions* 1 (1871-3): 261-76.
41. O. J. Heinrich, "The Diamond Drill for Deep Boring, Compared with Other Systems of Boring," *Transactions* 2 (1873-4): 241-63.
42. *M&SP*, 13 Oct. 1883, 223.
43. See: *Mines and Minerals* XX (Aug. 1899): 7; (Jan. 1900): 243.
44. For a detailed discussion of drilling on the Mesabi, the various drills used, and the methods and man power, see: M. G. Lamppa, *Minnesota's Iron Country: Rich Ore, Rich Lives* (Duluth: Lake Superior Port Cities, 2004), Ch. 8. Walker is repeating local folklore when he ascribes the invention of the diamond drill to Longyear and the churn drill to John Mallmann. See: D. A. Walker, *The Iron Frontier: The Discovery and Early Development of Minnesota's Three Ranges* (St. Paul: Minnesota Historical Society Press, 1979), 32. Longyear would have become aware of the diamond drill from the numerous technical treatises in the Michigan Mining School library describing its use.
45. T. Sopwith Jr., "The Actual State of the Works of the Mont Cenis Tunnel, with Descriptions of the Machines Employed," *Minutes of the Proceeding of the Institution of Civil Engineers* XXIII (1863-4): 306. Sopwith returned to the subject with a further lecture to the Institution on the Mont Cenis Tunnel, at which Beaumont was present (*Minutes* XXXVI, pt. 2 (1872-3): 17).
46. In describing the difference between a Leschot drill, expressed in the form of a Severance and Holt machine, and Beaumont's device, Andrew Ure observed that the boring bits were the same, but in the Beaumont drill the mechanism was worked by an independent engine and driven by leather or other belts, the circular motion given to the boring rods being conveyed by a bevel gear. See: A. Ure, *Dictionary of Arts, Manufactures and Mines* (London: Longmans, Green, and Co., 1878): 444.
47. E. H. Davies, *Machinery for Metalliferous Mines* (London: C. Lockwood, 1902), 203-14. This source provides details of the operation.
48. *Mining World*, 7 Dec. 1872, p.1866; 12 Apr. 1873, 707.
49. Prices per foot increased with the difficulty of working, from £0-9-0d per foot for the first 100 feet to £7-7-0d per foot after 2,100 feet. H. Huxham, "On Some Particulars of Boring with the Diamond Drill," *Proceedings of the South Wales Institute of Engineers* 9, no. 4 (1874-6): 201-20. (Paper read in 1874.)
50. See: W. Topley, "Sub-Wealden Exploration," *Transactions of the North of England Institute of Mining Engineers* XXIII (1871): 190.
51. See: C. G. Down and A. J. Warrington, *The History of the Somerset Coalfield* (Newton Abbot: David and Charles, 1971), 18.
52. A. Bassett, "The Diamond Drill," *Transactions of the North of England Institute of Mining Engineers* XXIII (1871): 179-83.
53. Bassett published a version of the same paper in *Proceedings of the South Wales Institute of Engineers* IX, no. 2 (1874-6): 131-6. (Paper read 1874.)
54. Topley, "Sub-Wealden Exploration," 185-96.
55. *Mining World*, 26 Feb. 1876, 308.
56. W. Rowley, "Deep Mining and Recent Achievements of Engineering in Connection Therewith," *Proceedings of the Geological and Polytechnic Society of the West Riding of Yorkshire* VI (1871-7): 163-78.
57. Multiple drills were used together in both ventures. See: T. F. Brown and G. F. Adams, "Deep Winning of Coal in South Wales," *Minutes and Proceedings of the Institution of Civil Engineers* LXVI (1881): 39, 110.
58. Huxham, "Boring with the Diamond Drill," 201; *Journal of the Iron and Steel Institute* 8 (1877): 473.
59. Dr. Hartig, "On Rock Drills," *Minutes and Proceedings of the Institute of Civil Engineers* XLI (1874-5): 266.
60. K. C. Dunham, *Geology of the Northern Pennine Orefield* 1 (London: H. M. Stationary Office, 1949): 249.
61. D. C. Davies, *A Treatise on Metalliferous Minerals and Mining* (London: C. Lockwood and Co., 1881), 329.
62. A 1,100-foot bore hole was put down from the 150 fathom cross cut. See: O. T. Jones, *Lead and Zinc: The Mining District of North Cardiganshire, and West Montgomeryshire* [Special Reports of the Mineral Resources of Great Britain, no. 20] (London:

H.M.S.O., 1922), 159.

63. *Mining World*, 3 June 1876, 810.

64. T. A. Morrison, *Cornwall's Central Mines: The Northern District, 1810-1895* (Penzance, UK: A. Hodge, 1980), 181.

65. N. Parke, "On the Water Supply of the City of Dublin," *Minutes and Proceedings of the Institute of Civil Engineers* XXXVIII, pt. 2 (1873-4): 25.

66. See: E. Wilson, "On the Durham Salt District," *Quarterly Journal of the Geological Society of London* 44 (1888): 761-5.

67. The Mather and Platt machine was considered to be the best of the churn drills, often working below a thousand feet, and it continued to be used in soft ground, sometimes in preference to diamond drills. For details of its design and operation, see: Ure, *Dictionary*, 445-6.

68. Diamond drills were rarely used to drill oil wells because of the expense of the large crowns needed to drill holes of ten inches plus. Churn drills or rotary drills using chilled shot were usually employed instead. See: A. B. Thompson, *Petroleum Mining and Oil Field Development* (London: C. Lockwood and Son, 1910): 165.

69. *Mining World*, 26 Feb. 1876, 308.

70. J. Barrow, "Large and Deep Bore-holes with the Diamond Drill," *Proceedings of the South Wales Institute of Mining Engineers* 11, no. 5 (1878): 315-28.

71. T. Veyron, *L'Evolution Technique des Houlleres Francaises et Belge 1800-1880* (Paris: Harmattan, 1999), 143, 145.

72. M. A. Pernolet, "L'Application Faite a la Vieille-Montagne des Perforateurs Mechaniques a Air Comprime au Creusement des Galeries a Travers Bancs," *Annales des Mines*, 7th Ser., v. 1 (1872): 17-35.

73. *Engineering and Mining Journal*, 3 May 1884, 333.

74. See: W. Meyerriecks, *Drills and Mills: Precious Metal Mining and Milling Methods of the Frontier West*, 2nd ed. (Tampa, FL: W. Meyerriecks, 2003), 83.

75. T. A. Rickard, "The Bendigo Gold-Field," *Transactions* 20 (1891): 536.

76. *Mining World*, 5 Dec. 1885, 558.

77. C. Le Neve Foster, *A Textbook of Ore and Stone Mining* (London: Charles Griffin and Co., 1897), 121-2.

78. F. Owen, "Mining in Perak," *Transactions of the Institution of Mining and Metallurgy* VI (1898): 74, 78.

79. J. E. Hardnan, "A New Iron Ore Field in the Province of New Brunswick," *Journal of the Canadian Mining Institute*, Ottawa Meeting (Mar. 1908): 160; *Cape of Good Hope: Report of the Select Committee on the System of Deep Well Boring and the Use of Diamond Drills* (Cape Town: Cape Times, 1903).

80. D. Fivehouse, *The Diamond Drilling Industry* (Saanichton, BC: Hancock House, 1976), 117-20. This company merged with the Sullivan Machinery Company in 1894. N. B. Hammond makes no mention of exploration drilling in his autobiography.

81. W. Wybergh, "On Diamond Drilling in the Transvaal," *Transactions of the Institution of Mining and Metallurgy* VI (1898): 164-74.

82. *Mines and Minerals*, XX (Aug. 1899): 244.

83. A. Wicklund, *A Diamond Driller Reminisces* (s.l.: Iron Range Historical Society, 1977).

84. See, for example, *Mines and Mineral* XIX (June 1899): 492. The use of diamond exploration drilling in Japan appears to have been delayed until the first years of the twentieth century. See *History of Engineering in the Meiji Era: Mining Volume* (s.l.: Nihon Kogakki (Japan Federation of Engineering Societies), 1930).

85. *Mining World* 1, issue 3 (2012): 8-13.

86. G. A. Denny, *Diamond Drilling for Gold and Other Minerals* (London: C. Lookwood and Son, 1900), 1.

87. C. J. Schmitz, "The Rise of Big Business in the World Copper Industry, 1870-1930," *Economic History Review*, 2nd series, XXXIX, no. 3 (1986): 392-410.

88. See *Mining Magazine*, Mar. 2012, 27.

89. See: H. Barger and S. H. Schurr, *The Mining Industries, 1899-1939: A Study of Output, Employment and Productivity* (New York: National Bureau of Economic Research, 1944), Ch. 6.

90. Small hand-powered devices were developed in the U.S., Britain, Sweden, and several other countries and saw considerable success. See: D. C. Davies, *Metalliferous Minerals and Mining*, 351-2; Foster, *Ore and Stone Mining*, 123; and E. H. Davies, *Machinery for Metalliferous Mines*, 201.

91. *Mining Journal*, 29 Mar. 2013, 2.

92. *Mining Journal* 4/11 Jan. 2013, 2.

93. *Mining Magazine*, Mar. 2013, 66-75; *Mining Journal*, 25 Jan. 2013, 28.

94. K. Keen, "Lassonde Lambasts Miners, Industry for Failures in Gold Hunting," *Mineweb*, posted 1 Feb. 2013, http://www.mineweb.com/mineweb/content/en/mineweb-gold-analysis?oid=175883&sn=Detail