Cost Analysis of Deep Large-diameter Drill Holes– 21048

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ABSTRACT
Around the world deep boreholes are being evaluated for disposal of intermediate level waste (ILW), high-level waste (HLW), spent nuclear fuel (SNF), separated plutonium wastes and some very high specific activity fission-product wastes. Estimation of drilling costs is an essential task within such evaluations. This paper provides a literature overview of drilling costs for deep drill holes based on data from geothermal wells, oil and gas wells, and CO_2 geological sequestration wells. While the diameter of such drill holes is at least two to three times smaller than the required diameter for deep radwaste disposal boreholes (approximately 0.5 to 0.7 m or 19¾” to $27^5/_8$” - depending on waste type and size of the disposal container), their cost analysis is still useful as it provides information on various cost elements (bit, mud, casing, cementing, logging, etc.), and the effect of rock type on cost (soft versus hard rock). The review shows that predictability of costs is reasonably accurate for the 1 – 5 km depth range, mainly based on geothermal wells; costs range from approximately AU$5 million for a 1 km deep hole to roughly AU$25 million for a 5 km deep hole (up to 0.25 m or $9^7/_8$” diameter). We then present detailed cost analysis for drilling and completion of deep large-diameter drill holes that are suitable for disposal of a range of radioactive wastes that require long-term underground containment and isolation. The analysis is generic in the sense that three potential host rock formations have been considered, i.e. crystalline rock, sedimentary rock and rock salt. The total drill hole depth considered ranges from 1 to 3 km, with a bottom hole diameter of 0.76 m (30”). All cost estimates are based on available equipment and technology in Australia.

INTRODUCTION
The management of radioactive wastes from medical, scientific and industrial uses of radioisotopes and from energy production poses both technological and societal challenges. Low-level and some intermediate-level radioactive wastes (LILW) might be safely disposed of in engineered near-surface repositories, but longer-lived intermediate-level waste (ILW), spent fuel from nuclear reactors (SNF), high-level wastes from the reprocessing of SNF (HLW) and long-lived spent sealed sources (SSS) are considerably more radioactive and have a higher content of long-lived radionuclides. These wastes require a higher degree of containment and isolation, typically in geological disposal facilities (GDF). A wide range of GDF designs have been developed, tailored to suit specific waste types and geological conditions. Disposal in medium-depth (tens to hundreds of metres) boreholes is considered to provide adequate isolation and containment for the safe and cost-effective disposal of relatively small volumes of certain ILW and SSS [1]. Deeper borehole disposals (up to several km) have been considered for HLW, SNF, separated plutonium wastes and some very high specific activity fission-product wastes [2, 3]. The cost of such boreholes is largely unknown since the significant inner borehole diameter required for waste disposal is not industry standard (approximately 0.5 to 0.7 m or 19¾” to $27^5/_8$” - depending on waste type and disposal container). However, precise cost estimates are essential to assess the merit of deep well waste disposal in comparison to other options, and to plan and budget demonstration projects.

This study presents a literature review of deep well costs obtained from geothermal, oil and gas and CO_2 geo-sequestration wells. The review is aimed at understanding the predictability of well cost and influencing factors, including rock type, depth and well bore diameter.

The availability of cost data for large diameter deep wells is limited due to the small number of such wells having been drilled [4]. A cost estimate for drilling and completion of an example 1 km and 3 km deep large diameter (0.76 m or 0.3”) borehole, suitable for disposal of a range of radioactive wastes requiring long-term underground containment, is presented in the second part of this study. Four different geological profiles are considered that include crystalline and sedimentary rock, rock salt and a combination thereof. All cost estimates for the large diameter hole are based on equipment and technology available in Australia. The objective of the analysis is to reduce uncertainty in cost estimates and improve the understanding of the factors contributing to the overall cost.

LITERATURE OVERVIEW OF DRILLING COSTS

Deep boreholes are commonly drilled for oil and gas production and geothermal operations [5]. Other examples include deep wells for the long-term geological storage of CO_2 [6]. Typical borehole diameters for such industries are up to 0.25 m (9.84”) for geothermal wells, which is significantly smaller than those required for deep radwaste disposal [7]. The feasibility of drilling larger diameter boreholes up to 0.45 m (17¾”) down to 5 km depth diameters has been reported, with drilling and completion estimated to take around 6 months [7]. For boreholes shallower than 5 km, larger diameters are feasible. For example, for a depth of 3 km a diameter of 0.5 m (19¾”) was reported while for 2 km depth 0.65 m ($25^5/_8$”) is feasible [7]. Boreholes of larger diameter have been drilled as part of research endeavours but require special planning and equipment. For very large diameter, i.e. more than 1 m (39.4”), and deep boreholes, new rigs, tools and materials need to be developed to overcome the challenges posed by such drilling operations [7].

In addition to size and depth of the borehole, rock type is known to have a considerable effect on drilling cost. Thus, the review presented below distinguishes between different borehole diameters, depths and rock types. Costs are adjusted to AU$2020 using the Consumer Price Index and a representative exchange rate. Most of the data included in this review are for holes drilled in crystalline rock, typically from geothermal projects. These data are more easily available as they can be sourced from published research projects. The specific cost of oil and gas wells is less frequently published as they are typically drilled for commercial projects and often confidential.

A comparison of wells with a depth of up to 5 km and a final diameter of 0.45 m or less drilled into crystalline or sedimentary formations is presented in Fig. 1. Most data are presented for wells drilled into crystalline rock. Fig. 1 indicates a linear relationship between cost and well depth for most data sets except the data from [8]. Still, large variations between costs exist. For example, at 5 km depth the costs range from ~AU$10 million to as much as ~AU$49 million. The KTB (Kontinentales Tiefbohrprogramm) pilot borehole was test hole drilled as part of Germany’s continental deep drilling programme in 1987; it was noticeably more expensive at 4 km depth due to the need to convert a conventional rig and the application of then novel engineering solutions to accomplish the deep well [9]. Variations are further caused by differences in the components included in the costing (for example, coring, logging, well testing); wellbore diameter; the complexity of the geology; differences in local cost of equipment and labour; and the period the well was drilled (while costs are adjusted to AU$2020, progress in technology is not captured by this). The cost for sedimentary rocks ranges from ~AU$1.5 million for a ~1 km deep well up to ~AU$13 million for a 3 km deep well.

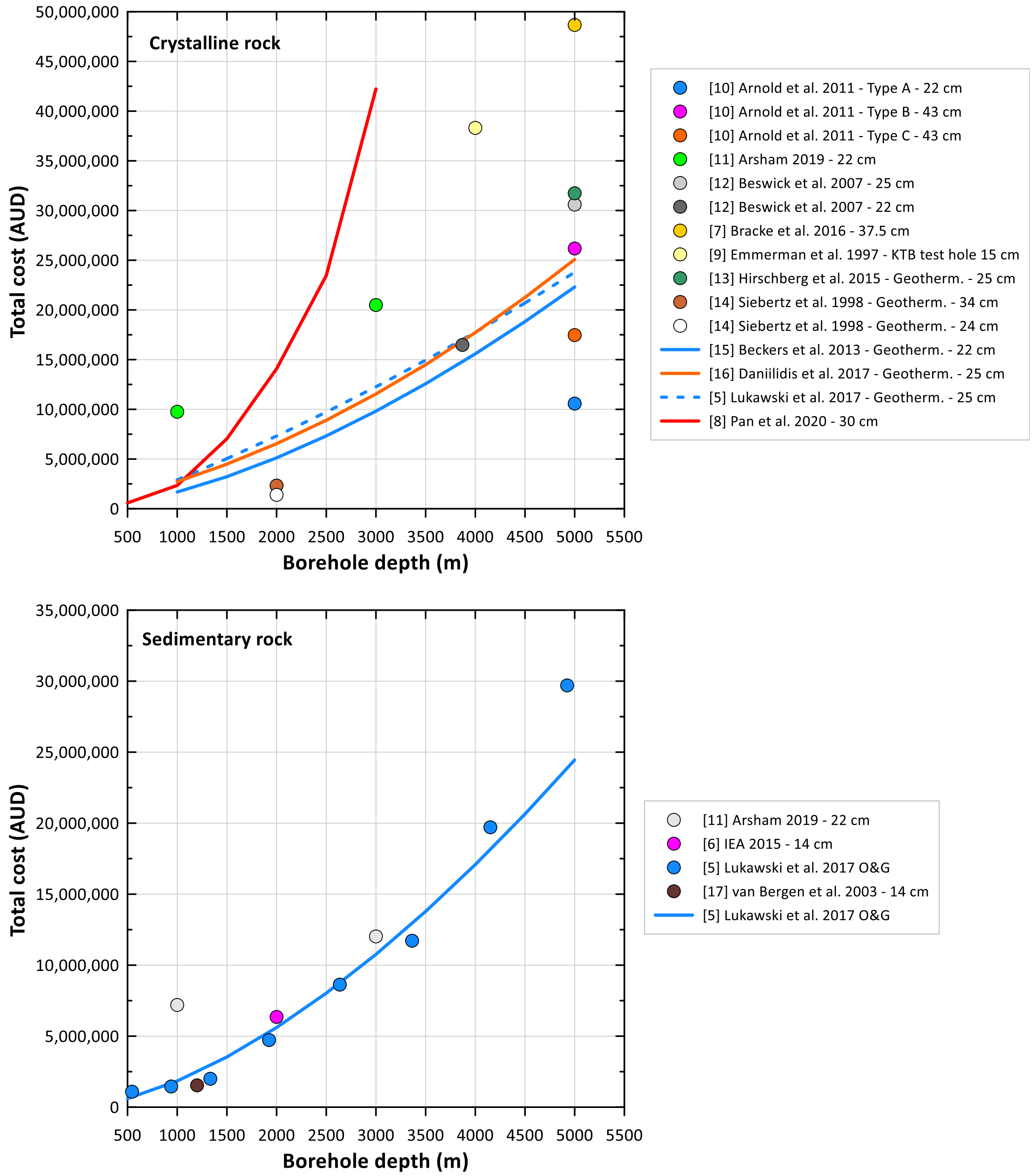

Fig. 1 Cost of wells with a final diameter up to 0.45 m (17¾") drilled in crystalline (top) and sedimentary (bottom) rock in AU$2020. Data sources: [5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

Costs of non-standard wells with diameters from 0.66 m (26") upwards are presented in Fig. 2, including the cost estimates presented in the subsequent section of this paper. Cost increases with depth but also with hole diameter. For example, for crystalline rock the cost estimated in this study for a 0.76 m diameter 3 km deep well is approximately AU$39 million, while [18] predict the cost for a 0.91 m (36") diameter drill hole at the same depth is close to AU$68 million.

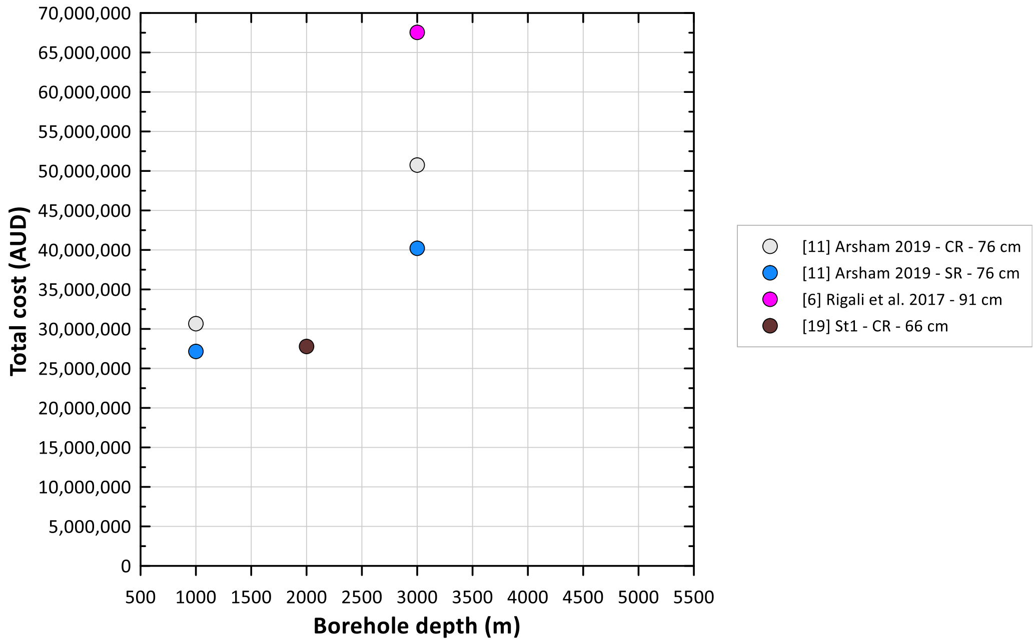

Fig. 2 Cost (AU$2020) of deep drill holes with a diameter of 0.66 – 0.91 m (26" – 36") drilled in crystalline rock (CR) or sedimentary rock (SR). Data sources: [6, 11, 19].

DETAILED COST ANALYSIS OF LARGE-DIAMETER BOREHOLES

This section presents the costs for deep boreholes (1 – 3 km) with a bottom hole diameter of 0.76 m – sufficiently large and deep for emplacement of a variety of disposal containers [7]. The costs are representative for Australia, quoted in 2019 Australian dollars[1] (AU$2019) and assume all necessary equipment and technology to drill such a borehole can be sourced in Australia, i.e. no overseas shipping of drilling rigs and other equipment is considered [11]. The conceptual design of a deep borehole (3 km) is illustrated in Fig. 3. In this study, a 1 km and a 3 km deep disposal borehole are considered and their details are summarised in Table I. For the 3 km borehole, the design consists of:

- a surface shaft, 2 m (78¾") diameter and 9 m deep, with a 1.82 m (7⁵/₈") diameter casing;
- an intermediate shaft, 1.3 m (51³/₈") diameter from 9 to 50 m, with a 1.2 m (47¼") diameter casing;
- a 1.067 m (42") diameter hole from 50 – 2,000 m with a 0.914 m (36") diameter casing;
- a 0.762 m (30") diameter hole from 2,000 – 3,000 m with a 0.61 m (24") casing [11].

The casing has the purpose of stabilising the borehole (i.e. prevent collapse) and seal it from the surrounding rock to:

- protect groundwater;
- separate formations with different pressures and fluids;
- prevent flow from the formation into the borehole (e.g., gas, oil, water);
- prevent fluid flow out of the borehole into the formation (loss of drilling fluid).

The number of casings and their diameters required is primarily determined by the geology at the drill site. More complex sedimentary sequences require additional casing strings [4].

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[1] *The year on year Australian Consumer Price Index from June Quarter 2019 to June Quarter 2020 is -0.3%, indicating a negligible difference in AU$2019 and AU$2020. Thus, the borehole costs are quoted in the original cost year of 2019 but are also representative of 2020 costs.*

Thus, depending on the actual site and its geology, the depth ranges presented here may change and additional casing strings may be necessary. The distance from the borehole wall to the casing should be around 2” to 3.5", based on experience in deep drilling technology.

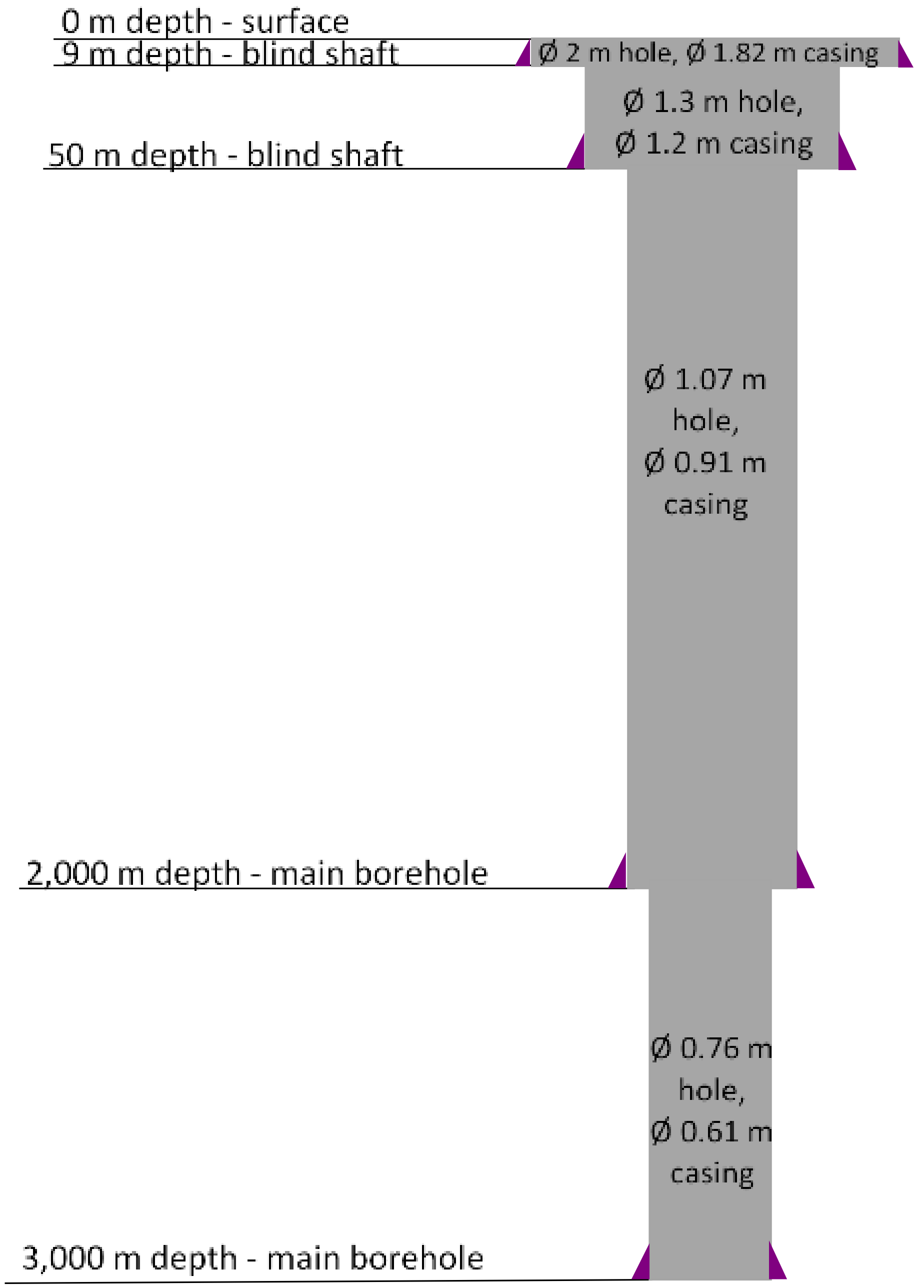

Fig. 3 Schematic of the 3 km deep large diameter disposal borehole considered in the cost estimation. Disposal zone in bottom 500 m. Schematic not to scale.

Table I Conceptual design of the 1 km and 3 km deep boreholes. The drilling technologies identified are indicative and alternative methods may be employed.

Depth interval, m		Borehole diameter, m	Casing outer diameter, m	Comments
1 km hole	3 km hole			
0 - 9	0 – 9	2.000	1.820	Surface shaft
9 - 50	9 – 50	1.300	1.200	Surface shaft
50 – 500	50 – 2,000	1.067	0.914	Initial hole of 0.66 m, widened to 1.067 m with hole opener using rotary rig
500 – 1,000	2,000 – 3,000	0.762	0.610	Drilled with rotary rig

We estimated the cost for the 1 km and a 3 km deep borehole for four different geological profiles (Fig. 4 and Table II), resulting in eight cases.

Table II Four geological profiles investigated in this study for the 1 km and the 3 km deep borehole (eight cases).

Geology	1 km deep borehole	3 km deep borehole
Sedimentary rock throughout	1 km sedimentary rock	3 km sedimentary rock
Sedimentary rock overlying rock salt	0.8 km sedimentary rock 0.2 km rock salt	2 km sedimentary rock 1 km rock salt
Sedimentary rock overlying crystalline rock	0.5 km sedimentary 0.5 km crystalline rock	2 km sedimentary 1 km crystalline rock
Crystalline rock throughout	1 km crystalline rock	3 km crystalline rock

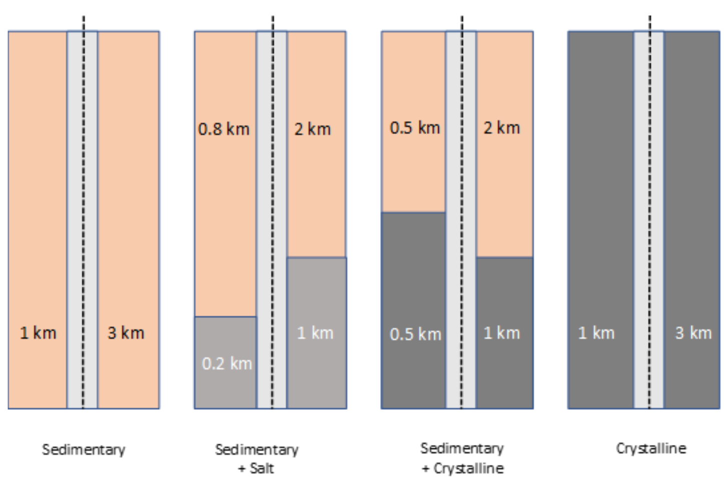

Fig. 4 Schematic of the four geological profiles considered for the costing of the large diameter borehole. Left side of the dashed line indicates the geology for the 1 km deep hole, right side indicates the geology for the 3 km deep hole. Schematic not to scale.

The process of constructing a large diameter deep borehole can be separated into different phases:

1. Planning and approval phase (assumed identical for all geologies and depths investigated);

2. Site preparation;
3. Drilling and completion, including rig mobilisation and demobilisation.

The costs incurred during these phases are described in detail below. Activities such as logging and coring are not included in the current cost estimates; they are costed separately and involve a comprehensive list of non-traditional investigations [20]. The cost for sealing the borehole is reviewed separately and is not discussed as part of this study. The costs of borehole closeout and site remediation are also not considered based on the assumption that the drill site will continue to be used, e.g. as a research and training facility.

PLANNING AND APPROVALS PHASE

The planning and approval phase includes the kick-off meeting, securing of the site, completion of the relevant regulatory approvals, the final drilling and test plan, public outreach activities, project management and safety management plans. The individual costs of these items are listed in Table III. This phase of the project is independent of the rock type and borehole depth, thus costs are the same across the eight cases investigated. This phase is estimated to take 6 months, which is reflected in the costs. Total costs for the planning and approval phase are estimated as AU$840,000.

Table III Activities and costs in the planning phase for a deep borehole.

Phase	Activity	Cost
Public outreach, planning, approval	Project set-up, public outreach, approvals	AU$390,000
	Final drilling and test plan	AU$270,000
	Project management, safety management plans	AU$180,000
Total cost planning and approval		**AU$840,000**

SITE PREPARATION PHASE

Prior to drilling, equipment will be mobilised and the site needs to be prepared. Access roads and the drill pad have to be constructed and on-site staff require housing. A list of items and their respective costs is presented in Table IV. Due to the lesser depth of the 1 km borehole and the shorter drilling time (compare Table VI), bottom hole assembly components, accommodation, as well as tools and motors are estimated to be half the cost of the 3 km hole. The main cost item during the site preparation phase is the installation of a hazardous weather bunker at the drill site, which is independent of geology and depth. Total costs of the site preparation phase are estimated to be AU$2,515,000 for the 1 km hole and AU$2,730,000 for the 3 km hole.

DRILLING AND COMPLETION PHASE

Drilling of the deep hole can be broadly separated into two stages – drilling of a large but short surface shaft (blind shaft) and a smaller but much deeper main borehole. The two stages are costed separately as per Table V V (blind shaft), Table VI (1 km deep borehole) and Table VII (3 km deep borehole). The surface shaft is drilled by a specialised blind shaft drilling company, while the deep borehole is drilled using a rotary rig. This implies two mobilisations for the drilling of the deep borehole - one for the surface shaft and one for the main borehole.

Table IV Activities and costs (AU$) in the preparation phase of drilling a deep borehole.

Phase	**Activity**	**1 km drill hole**	**3 km drill hole**
Site preparation and mobilization	Installation of hazardous weather bunker	1,800,000	1,800,000
	Site preparation, including well pad, cellar, access roads, signage, etc.	500,000	500,000
	Other bottom hole components	50,000	100,000
	Accommodation during drilling phase @ $25,000/month[2]	125,000	250,000
	Tool rental and motors	40,000	80,000
Total cost site preparation		**2,515,000**	**2,730,000**

SURFACE SHAFT DRILLING AND COMPLETION

To enable the final borehole diameter of 0.76 m, a large surface shaft is required. The surface shaft only penetrates the top 50 m and thus is the same for the 1 km and 3 km hole. Therefore, the cost for drilling and completing the shaft are the same across the two depths investigated. However, the cost of the surface shaft is impacted by the rock type. At a depth from 0 – 50 m two rock types are considered as part of this study – sedimentary and crystalline rock (compare Table II and Fig. 4) – for which the costs of the blind shaft are presented in Table V. The cost includes mobilisation and demobilisation of the blind shaft drilling equipment (assuming a distance of 800 km or less), the rental of the equipment, cost of the drill bits, drilling fluid, fuel, casing, other equipment and consumables as well as the site supervisor. As stated previously, coring and logging is not included in this cost estimate based on the assumption that a characterisation hole is drilled prior to the disposal hole. The cost for the surface shaft varies between sedimentary rock and crystalline rock, with the shaft constructed in the crystalline rock being almost 70% more expensive than the shaft in the sedimentary rock at about AU$2,240,250 and AU$1,328,100, respectively. The cost is dominated by excavation, which especially at the surface is more challenging for the crystalline rock than for the sedimentary rock since there is no weight on bit to push through the rock. The difference is a result of the rock properties, in particular the strength of the crystalline rock. This results in slower drilling progress (lower rate of penetration [ROP]) and a higher number of operating days – requiring a longer rental period of the equipment, more fuel and more labour [21, 22]. For the sedimentary rock the ROP is 1.8 m/d for the 2 m wide and 9 m deep shaft and 4.5 m/d for the 1.3 m wide and 50 m deep shaft. In comparison, for the crystalline rock the ROP is only 0.6 m/d and 2.05 m/d for the 2 m and the 1.3 m wide shafts, respectively. The ROP are based on operator experience with wide diameter boreholes.

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[2] *While the cost of accommodation varies with the number of drilling days, the highest accommodation cost associated with drilling crystalline rock, is budgeted for.*

Table V Activities and costs (AU$) for drilling a blind shaft for a deep borehole.

Activity	**Item**	**Sedimentary rock**	**Crystalline rock**
Mobilisation of blind shaft (~800 km distance)		330,000	330,000
Blind shaft: 2 m (78.7”) diameter hole, 0 - 9 m depth, cased and cemented	Operating days	5	15
	Fuel @ $3,500/d	17,500	52,500
	2 m blind shaft	65,000	325,000
	1.82 m (72”) casing & cementing	50,000	50,000
	Other equipment/ consumables & labour	95,000	95,000
	Site supervisor @ $1,650/d	8,250	24,750
Blind shaft: 1.3 m (51.2”) diameter hole, 9 – 50 m depth, cased and cemented	Operating days	9	20
	Fuel @ $3,500/d	31,500	70,000
	1.3 m blind shaft	136,000	680,000
	1.2 m (48”) casing & cementing	105,000	105,000
	Seal annular space	50,000	50,000
	Other equipment/ consumables & labour	195,000	195,000
	Site supervisor @ $1,650/d	14,850	33,000
Rig demobilisation: down, move out		230,000	230,000
Total cost surface shaft		**1,328,100**	**2,240,250**

DEEP BOREHOLE DRILLING

The main borehole is drilled using a high spec rotary rig capable of achieving a bottom hole diameter of 0.76 m. Similar to the surface shaft, the total cost of the main borehole includes mobilisation and demobilisation of the rig, cost of the drill bits, drilling fluid, fuel, casing, cementing, other equipment, as well as the cost of consultants (engineers and site supervisor). As stated previously, coring and logging is not included in this cost estimate. We distinguish costs for the 1 km and the 3 km deep borehole and for the four different geological profiles from Table II. All holes are drilled with the same high spec rig. The costs for the 1 km deep hole are presented in Table VI**Error! Reference source not found.**, while the cost for the 3 km borehole are summarised in Table VII**Error! Reference source not found.**. Examination of the individual cost items demonstrates that the primary cost contributors are rig mobilisation and demobilisation at AU$3,800,000 each for the high spec rig, the rig rental (determined by the number of drilling days and the rig rate), followed by casings and drill bits. The rig mobilisation/demobilisation cost is independent of drilling time and geology but is determined by the rig itself and its location relative to the drill site.

Casing design and material are considered independent of geology; thus, casing costs are the same across the four geological profiles. However, the cost varies with depth - the deeper the borehole the more area needs to be cased. For the current borehole, the casing is assumed to be mild steel at a cost of AU$1,238/m for the 0.76 m (30”) casing and AU$768/m for the 0.61 m (24”) casing. The cost of casing the 3 km hole at AU$4,780,000 is close to 3.5 times higher than for the 1 km hole (AU$1,387,000).

Table VI Activities and costs (AU$) for drilling a 1 km deep 0.76 m diameter borehole.

Activity	Item	Sediment	Sedi (0.8 km) + salt (0.2 km)	Sedi (0.5 km) + crystal (0.5 km)	Crystalline (granite)
Rotary drill rig equipment mobilisation		3,800,000	3,800,000	3,800,000	3,800,000
42” diameter hole, 50 – 500 m depth, cased and cemented	Operating days	15	15	15	30
	Rig rental @ $57,000/d	855,000	855,000	855,000	1,710,000
	Fuel @ $3,500/d	52,500	52,500	52,500	105,000
	26” tri-cone drill bit + 42” hole opener	500,000	500,000	500,000	750,000
	36” casing @ $1,238/m	619,000	619,000	619,000	619,000
	Drilling fluid	220,000	220,000	220,000	220,000
	Seal annular space (cementing & pumping; hanger & float equipment)	115,000	115,000	115,000	115,000
	Other equipment	405,000	405,000	405,000	405,000
	Drilling engineer, mud engineer, site supervisor @ $1,650/d	74,250	74,250	74,250	148,500
30” diameter hole, 500 – 1,000 m depth, cased and cemented	Operating days	17	20	33	33
	Rig rental @ $57,000/d	969,000	1,140,000	1,881,000	1,881,000
	Fuel @ $3,500/d	59,500	70,000	115,500	115,500
	30” drill bit with diamond enhancement	500,000	500,000	750,000	750,000
	24” casing @ $768/m	768,000	768,000	768,000	768,000
	Drilling fluid @ $400/m in 30” hole	200,000	300,000	200,000	200,000
	Seal annular space (cementing & pumping; hanger & float equipment)	200,000	250,000	200,000	200,000
	Other equipment	720,000	720,000	720,000	720,000
	Drilling engineer, mud engineer, site supervisor @ $1,650/d	84,150	99,000	163,350	163,350
Rig demobilisation, site restoration, closeout		3,800,000	3,800,000	3,800,000	3,800,000
Total cost		13,941,400	14,287,750	15,238,600	16,470,350

Table VII Activities and costs (AU$) for drilling a 3 km deep 0.76 m diameter borehole.

Activity	Item	Sediment	Sedi (2 km) + salt (1 km)	Sedi (2 km) + crystal (1 km)	Crystalline (granite)
Rotary drill rig equipment mobilisation		3,800,000	3,800,000	3,800,000	3,800,000
42" diameter hole, 50 – 2,000 m depth, cased and cemented	Operating days	65	65	65	130
	Rig rental @ $57,000/d	3,705,000	3,705,000	3,705,000	7,410,000
	Fuel @ $3,500/d	227,500	227,500	227,500	455,000
	26" tri-cone drill bit + 42" hole opener	750,000	750,000	750,000	1,800,000
	36" casing @ $1,238/m	2,476,000	2,476,000	2,476,000	2,476,000
	Drilling fluid	450,000	450,000	450,000	450,000
	Seal annular space (cementing & pumping; hanger & float equipment)	405,000	405,000	405,000	405,000
	Other equipment	405,000	405,000	405,000	405,000
	Drilling engineer, mud engineer, site supervisor @ $1,650/d	321,750	321,750	321,750	643,500
30" diameter hole, 2,000 – 3,000 m depth, cased and cemented	Operating days	33	50	83	83
	Rig rental @ $57,000/d	1,881,000	2,850,000	4,731,000	4,731,000
	Fuel @ $3,500/d	115,500	175,000	290,500	290,500
	30" drill bit with diamond enhancement	750,000	500,000	1,800,000	1,800,000
	24" casing @ $768/m	2,304,000	2,304,000	2,304,000	2,304,000
	Drilling fluid @ $400/m in 30" hole	400,000	600,000	400,000	400,000
	Seal annular space (cementing & pumping; hanger & float equipment)	405,000	506,250	405,000	405,000
	Other equipment	720,000	720,000	720,000	720,000
	Drilling engineer, mud engineer, site supervisor @ $1,650/d	163,350	247,500	410,850	410,850
Rig demobilisation, site restoration, closeout		3,800,000	3,800,000	3,800,000	3,800,000
Total cost		23,078,600	24,243,000	27,401,600	32,705,350

It should be noted that each casing string reaches to the surface, i.e. the casing covering the bottom 1,000 m in the 3 km deep hole has a total length of 3,000 m. Therefore, if due to the complexities of the geology at the drill site additional casing strings to those assumed here are necessary, the casing cost would substantially increase. Note that in crystalline rock sections of the casing above the waste emplacement zone may be removed after waste emplacement and sealing [23].

Rig and drill bit costs are functions of drilling depth and rock type. The more difficult it is to penetrate the rock, the slower is the drilling progress and the more stress is on the bit, shortening bit life. Bit replacement comes at the expense of time (additional rig rental and staff costs) and the cost of a new bit. The bit life can be extended by lowering the penetration rate, but this comes at the expense of additional drilling days (additional rig rental). This indicates that the rate of penetration needs to be balanced with consideration of bit replacement and rig rental cost, though without bit performance data for a particular formation this requires experimentation. For the 3 km hole, bit cost is estimated at $750,000 for the sedimentary rock and $1,800,000 for the crystalline rock for each of the top 2,000 m and the bottom 1,000 m (see Table VII). The higher bit cost for the crystalline rock accounts for the higher stress on the bit and additional replacements. For rock salt, bit cost is lowest at $500,000 due to the salt's properties (low hardness of 2-2.5 and abrasiveness). Note that drilling in sedimentary rock overlying the salt deposits has been described as challenging [24, 25]. Cementation in salt is also more expensive, as it requires additives such as magnesia binder and different, more expensive mixing techniques.

For the 3 km hole drilling time for the top 2,000 m of sedimentary rock is 65 days, compared to 130 days for the crystalline rock (compare Table VI and VII). Similarly, drilling time for the bottom 1,000 m is 33 days for sedimentary rock and 83 days for crystalline rock, while for the 2,000 m sedimentary rock overlying 1,000 m rock salt drilling time for the bottom 1,000 m is 50 days. The drilling days are directly reflected in the rental cost of the rig at AU$57,000/d, fuel cost of AU$3,500/d and costs for consultants of AU$1,650/d/consultant. Thus, changes to the drilling days estimated here will immediately affect the total cost of the main borehole. Total cost of the main borehole for the 3 km depth is from about AU$23 million for sedimentary rock up to AU$33 million for crystalline rock (Table VII). Similarly, for the 1 km hole costs range from around AU$14 million to nearly AU$16.5 million.

SUMMARY OF BOREHOLE CONSTRUCTION COST

Costs across the different phases of construction are summarised in Table VIII, including contingencies of +50% and -20% to account for potential cost increases from project delays and challenges presented by the geology, as well as potential cost savings through faster drilling rates, etc. A breakdown of cost across the different phases is provided in Fig. 5. A drill hole in sedimentary rock has a cost range from AU$18.6 million for a 1 km hole to AU$28 million for the 3 km hole. A hole drilled in crystalline rock is the most expensive option – AU$22 million for 1 km and AU$38.5 million for the 3 km depth. The primary contributor to the total cost of the borehole is the cost of drilling and casing the main borehole (Fig. 5), which contributes 75% - 85% to the total cost. This indicates that a change in these cost items can significantly affect the total project cost.

It should be noted that any additional hole drilled immediately after the first one will cost less since the significant mobilisation/demobilisation cost has already been borne by the first one. For example, with all other things being equal, a second 3 km hole in sedimentary rock would cost approximately AU$20.4 million – AU$7.6 million less.

Table VIII Cost (AU$ million) of planning and approval, site preparation, drilling and completion phase and total borehole cost in four different geological profiles.

Phase	**1 km borehole**				**3 km borehole**			
	Sed	**Sed (2 km) + salt (1 km)**	**Sed (2 km) + cryst (1 km)**	**Cryst**	**Sed**	**Sed (0.8 km) + salt (0.2 km)**	**Sed (0.5 km) + cryst (0.5 km)**	**Cryst**
Planning and approval	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Site preparation	2.52	2.52	2.52	2.52	2.73	2.73	2.73	2.73
Drilling and completion								
Surface shaft	1.33	1.33	1.33	2.24	1.33	1.33	1.33	2.24
Main borehole	13.94	14.29	15.24	16.47	23.08	24.24	27.40	32.71
Total cost	**18.62**	**18.97**	**19.92**	**22.07**	**27.98**	**29.14**	**32.30**	**38.52**
+50%	27.94	28.46	29.88	33.10	41.96	43.71	48.45	57.77
-20%	14.90	15.18	15.94	17.65	22.38	23.31	25.84	30.81

Fig. 6 demonstrates the correlation between drilling time and borehole cost, which can be approximated by a linear relationship. For the same depth, drilling time is a direct reflection of the difficulty of drilling a specific geology, which also affects other cost items such as drill bit life and fuel consumption. Also note that no breaks to the drilling process for in-hole logging are considered here. Drilling time increases in a disproportionate way with increasing depth [26].

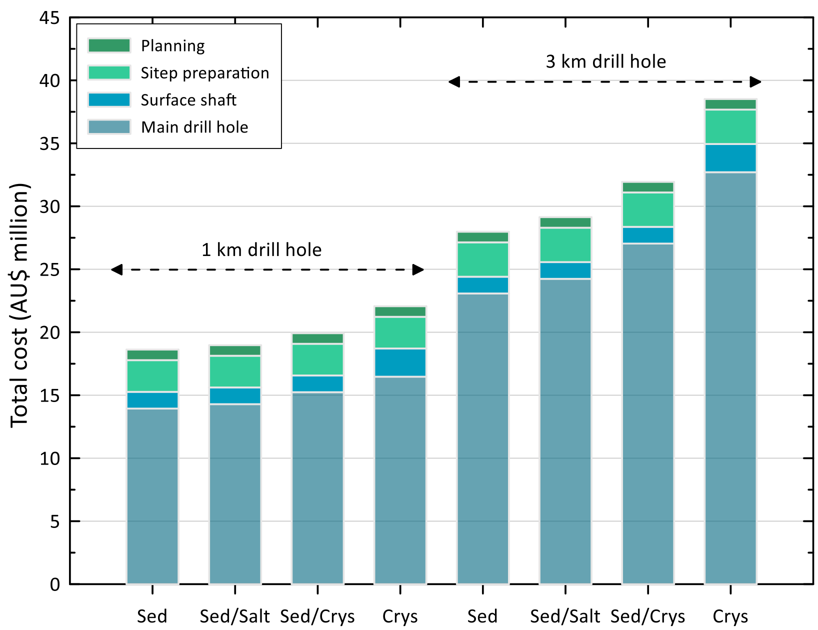

Fig. 5 Cost breakdown across the different phases of borehole construction for four geological profiles (Sed = sedimentary rock, Salt = rock salt, Crys = crystalline rock).

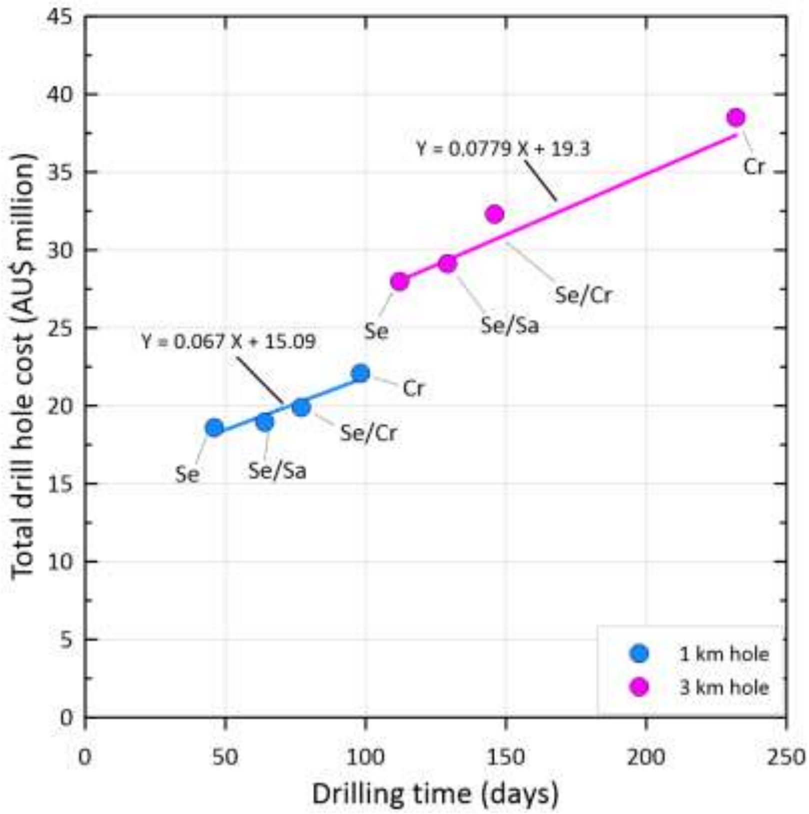

Fig. 6 Drilling time vs borehole cost. Se = sedimentary rock throughout, Se/Sa = sedimentary rock overlying rock salt, Se/Cr = sedimentary rock overlying crystalline rock, Cr = crystalline rock throughout.

CONCLUSIONS

The literature review of deep borehole costs indicates that for standard drill holes with a diameter of 0.45 m or less drill hole cost can be reasonably estimated as a function of depth, though a significant degree of cost uncertainty remains. For large diameter drill holes (>0.45 m) this uncertainty is even greater owing to the lack of experience and data for this type of hole. Detailed cost estimates are necessary to reduce uncertainty in cost and enable project planning and budgeting. The cost analysis of a 0.76 m diameter drill hole at depths of 1 and 3 km highlights that the geology has a significant impact on cost. The geology directly affects the drilling rate (ROP) and thus the number of drilling days, which are correlated with the total cost. From the geological profiles studied in this paper, the crystalline rock is the most expensive to drill, while sedimentary rock is the cheapest option.

REFERENCES

1. INTERNATIONAL ATOMIC ENERGY AGENCY (2005). *Disposal options for disused radioactive sources. Technical Report Series No. 436*, IAEA, Vienna, Austria.
2. G.A. FREEZE, E. STEIN, P.V. BRADY 2019. Post-Closure Performance Assessment for Deep Borehole Disposal of Cs/Sr Capsules. Energies 2019, 12, 1980.
3. D. MALLANTS, K. TRAVIS, N. CHAPMAN, P.V. BRADY, AND H. GRIFFITHS (2020). The state of the science and technology in deep borehole disposal of nuclear waste. *Energies* 13(4), 833; https://doi.org/10.3390/en13040833.

4. A. BESWICK, F. GIBB, K. TRAVIS (2014). *Deep Borehole Disposal of Nuclear Waste: Engineering Challenges*. Institution of Civil Engineering Paper 1300016. February 2014. 20 pp. URL: http://www.mkg.se/uploads/disposal borehole/Deep_borehole_disposal_of_nuclear_waste-engineering_challenges_Beswick_Gibbs_Travis_Proceedings_of_the_Institution_of_Civil_Engineers_April_2014.pdf
5. M.Z. LUKAWSKI, B.J. ANDERSON, C. AUGUSTINE, L.E. JR. CAPUANO, K.F. BECKERS, B. LIVESAY, & K.W. TESTER (2014) Cost analysis of oil, gas, and geothermal well drilling. Journal of Petroleum Science and Engineering, 118: 1–14.
6. IEA (2005) *Building the Cost Curves for CO2 Storage: European Sector. IEA Greenhouse Gas R&D Programme*. Report Number 2005/2. February 2005.
7. G. BRACKE, F. CHARLIER, H. GECKEIS, U. HARMS, O. HEIDBACH, B. KIENZLER, A. LIEBSCHER, B. MÜLLER, B. PREVEDEL, T. RÖCKEL, F. SCHILLING AND A. SPERBER (2016). *Tiefe Bohrlöcher*. GRS-423.
8. S. PAN, Y. KONG, C. CHEN, Z. PANG, & J. WANG (2020) Optimization of the utilization of deep borehole heat exchangers. Geothermal Energy, 8 (6).
9. R. EMMERMAN, J. LAUTERJUNG (1997). The German Continental Deep Drilling Program KTB: Overview and major results. Geophysical Research Letters 102, NO. B8: 18,179-118,201.
10. B.W. ARNOLD, P.V. BRADY, S.J. BAUER, C. HERRICK, S. PYE, J. FINGER (2011). *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste.* SAND2011-6749.
11. A. ARSHAM (2019). *Consulting assistance to provide a set of costings to CSIRO Land & Water for undertaking borehole drilling in Australia.*
12. J. BESWICK (2008) *Status of Technology for Deep Borehole Disposal. EPS International, Contract Nr. NP 01185, April 2008.*
13. ST. HIRSCHBERG, ST. WIEMER, P. BURGHERR (EDS.) (2015) *Energy from the Earth. Deep Geothermal as a Resource for the Future? Zentrum für Technologiefolgen-Abschätzung. TA-SWISS 62/2015. VDF Hochschulverlag AG an der ETH Zürich, ISBN 978-3-7281-3654-1.*
14. T.H. SIEBERTZ, H. WOLFF, E. HUENGES (1998) *Technische-wirtschaftliche Aufschlussalternativen hydrothermaler Ressourcen. GeoForschungszentrum (GFZ) Potsdam, STR98/09, Geothermie-Report 98-1, PDF-Version.*
15. K.F. BECKERS, M.Z. LUKAWSKI, T.J. REBER, B.J. ANDERSON, M.C. MOORE, J.W. TESTER (2013) *Introducing Geophires V1.0: Software Package for Estimating Levelized Cost of Electricity and/or Heat from Enhanced Geothermal Systems. Proc. Thirty-Eigth Workshop on Geothermal Reservoir Engineering, Stanford University, USA, February 11–13, 2013, SGP-TR-198.*
16. A. DANIILIDIS, B. ALPSOY, R. HERBER (2017). Impact of technical and economic uncertainties on the economic performance of a deep geothermal heat system. Renewable Energy 114, 805-816.
17. G. VAN BERGEN (2003). *Feasibility study on CO2 sequestration and Enhanced CBM production in Zuid-Limburg.*
18. M.J. RIGALI, E.L. HARDIN, E. STEIN, & J.-CH. (2017) *Large diameter deep borehole disposal concept for HLW Glass*. SAND2017-0130C.
19. T. SAARNO (2020). St1 Oy, personal communication, 2020.
20. K.L. KUHLMAN, E.L. HARDIN and M.J. RIGALI (2019). *Deep Borehole Laboratory and Borehole Testing Strategy: Generic Drilling and Testing Plan*. SAND2019-1896. Sandia National Laboratories, Albuquerque, NM.
21. T. WARREN (1987). Penetration Rate Performance of Roller Cone Bits. SPE Drilling Engineering 2, 9-18.
22. M.M. EL-BIBLAWI, M.A. SAYED, M.T. MOHAMED, W.R. EL-RAWY (2007). Some Drilling Parameters as a tool to predict different categories of rocks. Journal of Engineering Sciences, Assiut University 35, 995-1008. http://www.aun.edu.eg/journal_files/14_J_9745.pdf
23. P.V. Brady, B.W. Arnold., G.A. Freeze, P.N. Swift, S.J. Bauer, J. L. Kanney, R.P. Rechard, J.S. Stein (2009). *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009-4401.

24. M.B. DUSSEAULT, V. MAURY, F. SANFILIPPO, F. SANTARELLI (2004). Drilling around salt: stresses, risks, uncertainties. American Rock Mechanics Association.
25. P. FARMER, D. MILLER, A. PIEPRZAK (1996) Exploring the Subsalt. Oilfield Rev. 8, 50–64.
26. J.C. ROWLEY, F.J. SCHUH (1987). Experience from Crystalline Rock Drilling and Technology Directions for Effective Ultra-Deep Coring and Drilling. In: A. Bodén & K.G. Eriksson (editors), Deep Drilling in Crystalline Bedrock. Volume 2: Review of Deep Drilling Projects, Technology, Sciences and Prospects for the Future. Proceedings of the International Symposium held in Mora and Orsa, September 7–10, 1987, Springer-Verlag.