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"DEEP LAB CONFERENCE"

OCTOBER 12, 1965

CORNER HOUSE, RAND MINES
JOHANNESBURG, SOUTH AFRICA

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FOREWORD

This document is an edited transcription of a meeting held at the Corner House in Johannesburg. It is hoped that the informal flavor of the meeting has been preserved in the translation to the more compact written form. This record has been checked by the participants to insure that it reflects accurately not only their words but also their intent. The assistance of the United States Atomic Energy Commission and the Office of Naval Research, in supporting the preparation of these proceedings, is gratefully acknowledged.

Frederick Reines

Deep Lab Conference

Attendees

M. Barcza - Mining Research and Ventilation Engineer, Rand Mines

F. G. Hill - Manager of Technical Services, Rand Mines

A. A. Hruschka - Research Associate Engineer, Case Institute of Technology

L. O. Nicolaysen - Director of Bernard Price Institute of Geophysical Research, University of the Witwatersrand

F. Reines - Professor of Physics, Case Institute of Technology

M. D. G. Salamon - Director of Collieries Research Laboratory, Chamber of Mines

J. P. F. Sellschop - Professor of Physics, University of the Witwatersrand

and for the latter part of the meeting

Messrs. Wagstaff and Southall - Mechanical Consultants of Rand Mines

Summary

The usefulness to neutrino and cosmic ray research of a very deep underground laboratory housed in a spherical cavity 100 feet in diameter and 15,000 feet below the surface is described.

It appears from this meeting that the two major problems in providing such a location, i.e. temperature and mechanical strength, can be solved within existing technology.

Various locations in the United States and South Africa which seem most suitable for such a laboratory were mentioned and the merits of locating below an existing mine, e.g. Anglo-American's Western Deep Levels west of Johannesburg, were discussed. The estimated cost of the laboratory ranged from 4 to 40 million dollars and the time for construction ranged from under two to eight years, depending on the location.

Morning Session

Reines: We are here to think about a novel and difficult problem which is rather in the future but nonetheless has to be thought about early enough to measure its extent, - it is the problem of the provision of laboratory facilities for cosmic ray experiments very deep underground, perhaps as deep as 15,000 feet. As you well know, we from Case Institute are at present engaged at 10,492 feet in a useful and happy collaboration of cosmic ray neutrino studies with Wits University, with the considerable help of our hosts from East Rand Proprietary Mines, many of whom are represented at this informal conference. The kind of research which we do deep underground, and which might more usefully be done in a quite special installation, deals primarily with the study of neutral cosmic radiation, neutrinos, which readily penetrate the earth, as opposed to the charged components which do not so easily reach great depths. The steady flux of about one charged particle per cm^2/minute, which passes through each of us at sea level can be screened out by enough earth and hence we go underground in order to see these penetrating neutrinos. However, even the residual radiations from the atmosphere (μ mesons) are interesting deep underground because of their enormous energies. The point is that a charged particle which has penetrated to great depth must have been of very high energy (>1000 BeV), a higher energy than any accelerator can make at present. So as we study these, although they are so to speak our residual background, we learn something new about this kind of radiation that other people have not been able to. In brief, we are currently doing ultra-high energy muon physics as well as neutrino physics in E.R.P.M. It is to do this kind of physics that we go deep down underground.

A word or two about where we stand now in the South African mine. We have been associated with you for two years during which time we have set up the largest particle detector ever built, weighing about 15 tons.* It is certainly the largest geometrically as it now extends some 120 feet. Ours is the deepest more or less continuously-attended laboratory in which people have done physical research. We have succeeded in seeing charged cosmic rays more deeply underground than has anyone before us. We have been first to see a neutrino produced without the intervention of man; a "natural" neutrino made in our atmosphere by the interaction of high cosmic ray primaries. There is no doubt that this is the opening gun in an extremely interesting area of research, because some of these neutrinos are of much higher energy than man is going to make in the laboratory for a long time to come, if ever. We have here a very high energy particle which in principle can be used to probe the structure of nuclear constituents.

I would like to call your attention to another feature of the neutrino spectrum which is of interest, namely the low energy end. These are believed to come from the sun and if they can be detected (and several groups are currently in this work) then this information could be used to deduce the central temperature of the sun. So we go into the deepest mine in the world to look at the center of the sun, and measure its temperature! A few

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*As of 12 October 1965. This figure is now (January 1966) 25 tons.

years ago this was sheer fantasy on two counts: first it was completely absurd to imagine that anyone could provide such a deep laboratory and second, such large detectors were beyond the state of the art. It is not sheer fantasy now and right at the moment we find that the sensitivity of equipment under design and the attainable background reduction with relatively simple equipment* are possibly compatible with solar neutrino detection. If the sun produces fewer neutrinos of this character than theory predicts we may be able to place only an upper limit on it. However it goes, it will surely force those who conjecture about the center of the sun to either modify or accept the theory, and we are close to this point.

I should comment that although the present theory of solar energy generation is considered to be reasonably good it is based on much less direct information than that which could be obtained from a neutrino signal. A detection of this solar neutrino signal would be quite exciting.

We are now operating the equipment, modifying it slightly as we go: it runs about 70% of the time despite the requirements of maintenance and modifications. We have already completed the first stage and now are entering on the second which is to make a larger, more sophisticated detector. The third stage is already being set, namely to have even more sophisticated detectors in a much larger array, a new laboratory on 77 level, Hercules shaft, E.R.P.M.

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*Solar neutrino detection at the surface of the earth is made difficult if not impossible by the presence of cosmic radiation. As the detector is lowered into the earth such backgrounds diminish to the point where they can be discriminated against by means of charged particle anticoincidence shields. At E.R.P.M. depths the cosmic ray problem vanishes completely, greatly simplifying the detector design.

What is the future for this kind of physics, and what kind of laboratory is required? To find an answer we must consider the limitations of the present setup. The fundamental limitation of the present laboratory is its configuration, i.e. the long tunnel into which we can at best place a detector of relatively small mass so that we must now rely on the surrounding rock to provide the necessary target for neutrinos. The difficulty with this arrangement is that the events occur in the rock and not in the detector itself so that valuable information is lost. It is therefore highly desirable to have a large and massive detector, so that the interaction would originate within it and could be studied in detail. As already indicated, the laboratory would be deep underground - let us assume for purposes of discussion 3 miles with dimensions approximately 100 feet on edge. Such a cavity, taken as hemispherical, as shown in Figure 1, could contain an iron detector of approximately 25,000 tons.* In addition it is desirable to have not just one cavity but also others at lesser depths such as two and one miles, for instance. Each of these cavities would house a massive detector, perhaps of the spark chamber or scintillation variety.

Another fascinating astrophysical question in addition to the solar energy source relates to the mechanism of supernovae. A supernova is a star that suddenly goes berserk producing energy at a greatly increased rate. Astronomers estimate that, on the average, one supernova appears

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*A detector of this mass should see a few hundred high energy neutrinos per year. Our present rate is an order of magnitude smaller.

once in a hundred years in a volume 100 light years in radius. This could be seen by a detector which could be housed in the laboratory under discussion. The signal might be a relatively short burst (approximately 10 minutes) of neutrinos.* A detector of sensitive mass 10 to 100 thousand tons might give a chance of seeing one supernova a year. These estimates are highly preliminary but they suggest we might have some chance of engaging in a completely new kind of astronomy in many ways as exciting as the traditional kind.

In summary, there are many reasons for wanting to go underground to see the heavens. Admittedly this approach violates common sense but as indicated it may be precisely the right thing to do in this instance. The neutrinos penetrate superbly well, the background is inhibited by the earth.

<u>Hill</u>: What kind of detector do you propose?

<u>Reines</u>: A liquid scintillator which gives a light flash when a particle passes through it, or a different kind of detector called a spark chamber which signals the passage of the particle by becoming conducting.

So much for the motivation. The next question is 'what is the problem in building such a laboratory? Is it in any sense practical given the money? How much money is required and how long would it take? Is it

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*The supernova would be seen by this "neutrino light" because neutrinos penetrate the body of the supernova directly while visible radiation diffuses from the hot center of the surface. (See M. A. Ruderman, Astrophysical Neutrinos", Reports on Progress in Physics, Vol. 38, 411 (1965).

reasonable to build this large facility in association with an operating min~~d~~e which is dedicated to a different purpose or should it be quite separate? Because the facility could be expected to be used by many scientists there are strong arguments in favor of locating it in a center of population like the United States. The remoteness of South Africa may not deter some of us hardy souls who travel 10,000 miles in pursuit of our science, but I don't think the bulk of the physicists who are interested in such research are prepared for that. Perhaps the supersonic jet of the future will change the picture. So our object here today is to explore with you, the experts, the nature of the problem of preparing such a deep laboratory.

Sellschop: There are a few points I would like to make, recapping what has just been said. First of all I think it has now been shown, in good part through this work at E.R.P.M., that the field of neutrino studies is rich in physics, in astronomy and in cosmology - it is a very rich field for scientific investigation and therefore must be pursued. As to the time scale for our underground investigations, our operation at 76 level will have stretched from 1964 to 1967. Our operation on 77 level will start next year (1966) and go on to perhaps 1970. It is what happens next, after 1970, that is under discussion now. If it turns out that to establish a laboratory at these depths and of these dimensions is so expensive that the actual cost of making a mine becomes small in comparison, then you make it at the most convenient spot, which is not Johannesburg but in your own back garden. The best course of action will depend in primary measure on the answers we hope you will give us on these basic engineering questions.

Hill: I do not think the technical aspects present any insurmountable difficulties. The financial limitations are probably dominant. Now where do your instruments go in relation to your target, do they go in it, or underneath it?

Reines: In it. The target itself is the detector.

Hill: Well, then I think what you could do is to take out a cut and fill it with broken rock and take out another cut continuing until the excavation is a 100 foot cube.

Reines: You are proposing to make a honeycomb in effect.

Hill: You would excavate small volumes cutting and filling say 8' x 5' sections in turns.

Reines: There is a difficulty with this approach - it may limit the kinds of detector which can be used. Ideally, the detector would be located in a huge open space and be readily accessible throughout. Most conceivable designs would be modular and the detector would consist of an array of these with appropriate access between modular groupings. In one approach each module would consist of 10 ton spark chambers each of a mass sufficiently small to be handled. There would be thousands of them and their outputs would be fed to a computer in order to sort out and analyze the information. Accessibility for the purpose of construction, operation and maintenance rules out a compact stacking of the elements.

Sellschop: Does not this bring one back to your thought of some kind of honeycomb?

Hill: It would help in the matter of mechanical strength if instead of thinking of a cubic void 100 feet on edge, one thinks of this broken down into many many connected sections with the wall material serving as neutrino targets and the chambers or voids housing the detector elements.

Salamon: Actually I think the difficulty with the honeycomb arrangement is the strength, because at 15,000 feet this may well be the limiting factor.

Sellschop: Forgetting for the moment the honeycomb approach, would it be possible to make a cubic void of these dimensions at 15,000 feet?

Salamon: Physically, I think it is possible. Obviously there are certain requirements one would have to fulfill. One would have to avoid excessive blasting in the area after construction because of the rock instabilities that would result. I would rather think in terms of a better shape than a cube.

Reines: How about a sphere?

Salamon: That is an improvement, but one must face it that in those extreme depths, the stresses induced around the excavation would be in the order of the strength of the most competent rock and if you make a bigger excavation, the chances of failure increase. I am sure that in a 100 foot sphere we would have to face the possibility of rock failure - we would have to build in a supporting structure.

Reines: The optimum design from the physics point of view is to have the detector mass interpenetrated in tremendous detail with what amounts to crevices. It has to be done so that there are pathways through which you get at the equipment in each crevice, test it, adjust it and so on, and there would be thousands of these.

Salamon: Must there be no movement?

Reines: Well we would like to know the geometry: we would have a multitude of cells, thousands of them, and what we would do is trace our particles through. We would get information as to the cells through which it passed and send this information to an on-line computing machine to reconstruct the tracks. The computer must therefore be given the cell locations.

Salamon: Do I understand correctly that an empty void would be a good starting point from the physics point of view and that the detector elements would then be racked up in this volume?

Reines: Yes.

Salamon: The racks could be as heavy as you want and act as a support.

Reines: Yes, they can and they have to be rather heavy because the total weight of the elements might be approximately 10^5 tons. Each one of these spark chamber detector elements could be made of a frame which is filled with iron ore for example, and have plates between the boxes to provide the necessary electrical gaps.

Salamon: I presume for possible maintenance reasons and so forth you would require access room.

Reines: Exactly. If it were not for the problem of access we could then go to the ocean deeps for example, where we could arrange to put whatever we pleased.

Salamon: Since you need thousands of these things the resultant fine honeycomb would not be structurally strong enough if made of rock.

Reines: Well, could I back off just a little bit and ask from what is known in your experience, what size cavity is reasonable to consider at these depths?

Salamon: Without any kind of support?

Reines: Without any kind of mechanical support, exactly.

Salamon: The best bet would be a sphere and I think in these depths one must accept the need for some sort of support, for even in the competent rocks one must assume there will be some movement in time. I visualize that this support would have to be something of a composite nature: Say for example a steel shell behind which there is a material which allows movement but, as the deformation increases, the resistance of this increases also. It would be quite unrealistic to think in terms of the usual concrete because it has the same modulus as the rock.

Sellschop: So are you thinking of locating the lab in a sphere made out of some kind of steel shell, for example, which is floating in a rubbery material which lines the rock cavern.

Reines: -So as to allow the rock to come to equilibrium by itself outside this shell?

Salamon: Yes, because I think a rigid support is a bit difficult to visualize when you are talking long terms because we cannot really predict what will happen to the rocks in time.

Hill: Mind you 15,000 feet is not much deeper than we are now.

Salamon: Yes, I quite agree Mr. Hill, but the trouble is that unlike the contemplated laboratory, we can tolerate all sorts of movements in a working mine without any hardship. I should perhaps point out that this is not the sort of place where you would get a rock burst, as I am assuming a single chamber at the bottom of a 15,000 foot hole. It is nothing comparable to the vast network of excavations such as at E.R.P.M. where huge areas are mined.

Sellschop: What you are suggesting is that one must define its edges with a material possessing a suitable modulus, not because of the danger of any violent explosion or burst but because of creep.

Reines: As mentioned earlier the research would require a fairly stable laboratory.

Hill: In any excavation at depth the ground starts moving. Can you give some idea of the extent of the deformation which could be expected?

Salamon: Well it is a contest to make a guess. It would depend very much on the backing material I would think, but it might be held to fractions of inches.

Reines: That would be perfectly ok since this kind of accuracy is not inherent in the equipment. The point is if one of the particles makes a track through the equipment, movement of inches is going to make the track uncertain in direction by very little.

Salamon: Stability would nevertheless be useful for engineering reasons.

Hill: I would say that at your present E.R.P.M. location the movement is much greater than you would get in the 15,000 foot lab. You have had movements at E.R.P.M. without even realizing it of perhaps a couple of inches.

Reines: Well, gentlemen, I gather it is your opinion that this thing is possible providing one is willing to build some kind of structure inside.

Several: Oh, yes.

Salamon: However, I would like to emphasize again that the geological character of the rock is of great importance.

Reines: Before discussing geology I would like to ask Mr. Barcza whether he sees any difficulty in principle in connection with the ventilation end of it?

Barcza: I see no difficulty, either in principle or in fact. I reckoned up to 300° F rock temperature which I believe covers most of the envisaged situations.

Hill: One must keep in mind the question of cost.

Reines: I would prefer to worry about costs after we know what is possible in principle. The best we can do is to ask you, the experts what is possible. It may turn out that the cost is completely unrealistic, but it might just be that it is possible. I must say that the support of fundamental research in various parts of the world at this very moment exceeds all of my wildest extrapolations of fifteen years ago. So we will try to come to the cost with your good help, and we will see whether what is to be learned will justify it in the market place that supports such efforts.

Nicolaysen: I think there is a difference between the engineer and the physicist, in the way each talks in the market place.

Reines: Certainly, there is a different approach and a different goal. The engineer has an economic tie to every breath he draws, and must or else society would collapse.

Hill: I do not think that there is any great difficulty with either of the two main questions you raised, i.e. rock mechanics or ventilation.

Sellschop: To what extent does the kind of rock mechanical "okay" that was expressed just now relate to the geology?

Reines: I should like to amplify Sellschop's question. If you were willing to drill and test your sites after having made a rough geological study then could you probably find something almost anywhere in the world that would be suitable to the purpose?

Hill: Yes.

Nicolaysen: In general, a twofold classification can be made for rocks in the United States*. One group consists of tough "shield" rocks and these are, in general older, constituting a platform on top of which softer, porous rocks were deposited. Over large parts of the eastern and central United States these softer, porous rocks predominate. Thicknesses of 10 to 20 thousand feet of these soft rocks occur over wide regions of the eastern and central United States. One would want to keep out of these soft, sedimentary rocks; and locate deep chambers in hard crystalline rocks such as our South African quartzites. For shallower voids we might be able to accept sandstone or some less competent rock. The geology is generally much more disturbed in western United States and hence that region is not the best site for a very deep excavation. The rocks are heavily fissured and broken.

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*Reference: "Tectonic Map of the United States" published by the American Association of Petroleum Geology, Tulsa, Oklahoma.

Reines: Where in the United States looks most promising?

Nicolaysen: In northern Wisconsin and parts of Minnesota where you have these heavy, dense, compact "shield" rocks actually occuring at the surface, and where the geology gives you every indication of long, continued stability. The mountains in northern New York state might also be a potential candidate.

The pink areas of the map[*] show parts of Western North Carolina, Virginia, and West Virginia where the basement rocks have been brought to the surface during the Appalachian Mountain belt thrusting and crumpling movements along the eastern seaboard. But again, this is an area that is faulted, fissured and broken, and one would certainly not think of those areas of compact rocks as being as good as the areas of the northern states.

Reines: It is not a matter of great importance where in the United States one would place this laboratory.

Nicolaysen: I want to add that most of central and eastern Canada[†] is composed of the desirable sort of geology characteristic of northern Wisconsin and Minnesota. These regions - all of Ontario, Manitoba, and most of Quebec - are contiguous. This part of North America contains large areas which would be very good candidates in the sense of stability, and hard, compact rocks. I could also stress that the geology of South Africa is in general very suitable for the purpose under discussion.

In view of the importance of ambient temperature to the problem, a few remarks are in order on the general relationship between thermal grad-

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[*] Ibid., footnote reference on p. 13.

[†] Map No. 820A, Geological Survey of Canada, Ottawa (1950).

ients and geology. We see listed (referring to Table I[*]) heat flow (in units of 10^{-6} calories/cm^2/sec) for various parts of the earth both on land and sea. These numbers are reasonably constant and variations of 30 to 40 per cent are about as much as occur in most areas.[**] On the other hand, Table II which lists the thermal gradients shows a variation (from 7 to 40° C km^{-1}) with location on the earth's surface. The reason for this variation, despite the relatively constant thermal flux, is the difference in the conductivity of the rocks: since flux is the product of the thermal gradient and the conductivity, high gradients necessarily imply low conductivities. Soft cover rocks for example have poor conductivities, and hence are associated with high gradients. Tough, compact "shield" rocks such as found in northern Wisconsin and Minnesota have much higher conductivities, and therefore, lower gradients.

Reines: It seems then that the area which is good from the mechanical point of view is also good from the thermal side.

Nicolaysen: That is true. We can get estimates of the range of temperatures at depth from the table 5.8. The values 19° C/km for the Calumet, Michigan, borehole (Birch, 1954) and the 24° C/km for Big Lake 1B borehole in Texas (Birch and Clark, 1945) could be regarded as typical for the lower

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[*] From a review article (Table 5-8) by F. Birch of Harvard in "Nuclear Geology" published by Wiley (1954); see also Ph.D. Thesis of R. F. Ray entitled "Heat Flow Determinations in the United States", Harvard (1963), (unpublished).

[**] We except anomalies represented by volcanic areas where the flow of heat rises by factors of 8 or 10.

conductivity higher gradient areas. A mean of 22° C/km (1.3° F/100 feet) seems reasonable.

Barcza: That places an upper limit of about 250° F for the depth at which we would be working, assuming a surface temperature of 50° F.

Nicolaysen: When we look at the gradients for such areas as Larder Lake and Timmons in Ontario and Malartic, Quebec, (10° C/km) as indicative of the gradients in Wisconsin and Minnesota we obtain a reasonable lower limit of 135° F as the ambient temperature at 15,000 feet. The surface temperature is again taken as 50° F. Table II, et seq. are of observed temperatures.* Reading from left to right the columns in these tables - surface temperature, gradient (°C m^{-1}), reciprocal gradient - the last column lists a statistical parameter for the observations which is defined by Van Orstrand in his article. Variations from about 7 to 30° C/km are seen, depending upon the kind of rock encountered.** A final word about variations in thermal conductivity. When one is in basement terrains, in an area such as northern Wisconsin or Minnesota, other things being equal, what sort of rock would have the highest conductivity? Since quartz has by

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*Review article by C. E. Van Orstrand in "The International Constitution of the Earth", edited by Beno Gutenburg, Dover Publications (1951).

**Several deep boreholes are being, or will be, drilled in the United States and Canada within the next few years as part of a program of Continental Drilling under the aegis of the International Upper-Mantle Project. This project is sponsored by the International Union for Geology and Geophysics, but the major contributor is the United States where the work is done by the U.S. National Committee for the Upper-Mantle project. Dr. Leon Knopoff, Department of Geophysics, University of California, Los Angeles, is the Secretary. About six holes will be drilled to the 15,000 foot, or so, limit of the equipment available. The purpose is to study the deep structure of the continental crust, information of very considerable value for this project. The Canadians have already finished four or five holes. (Nicolaysen) far the highest conductivity of the common minerals in the earth's crust, and feldspar by far the lowest, one would like to choose quartzites where we encounter thermal gradients of 9° C/km. In addition, if one goes to regions containing tough compact quartzites, such as we have in South Africa, then we also have the best medium for an excavation from the point of view of mechanical strength.

Sellschop: Assuming an upper limit of 300° F, what kind of ventilation cost is involved?

Barcza: At 280-300° F cooling plus the necessary insulation of at least one of the two shafts (the air inlet or down-going shaft) with polyurethane foam would cost about 1 million dollars. If you work at 165° F, it would probably be half that. I assumed the foam costs $1 a pound which is probably an over-estimation, although this does include installation.

Reines: How does this cost depend on the diameter of the shaft and the number of rooms?

Barcza: Since the surface area of the shaft is at least an order of magnitude larger than that of the rooms of the size under discussion, the rooms add comparatively little to the cost of ventilation. I conclude that at 165° F you need 500,000 lbs. of insulation, at $500,000 installed. It is interesting that if you insulate one shaft, you have enough energy from the difference in temperatures of inlet and outlet air to get several hundred kilowatts from the convective movement of the air. In other words, you don't need a fan.

Sellschop: I understand. You have two shafts, one to bring down the cool air, and one to take up the warm air, and the down-going one is insulated. Is there any refrigerator?

Barcza: Yes there is. To keep the shafts comfortable, you will need about 1000 tons of cooling costing approximately $300,000. If you work at 165° F, the insulation of the shaft should become unnecessary. Even without insulation the temperature difference between the incoming and outgoing air will make a fan unnecessary in this case.

Reines: How will the air know which way to go?

Barcza: It will go the right way because the cooling plant underground rejects the heat into the outgoing air and that assists even further.

Sellschop: Are these two shafts for access as well?

Barcza: Yes they are.

Sellschop: Why cannot you have just one?

Barcza: You could do it with one, but I am guessing that the United States government would not like an excavation 15,000 feet deep with only one shaft. I think that when it comes to costs, one shaft divided should be seriously considered, insulating only the part which carries the air down.

Hill: The decision would depend on what the ruling on double entry means, i.e. whether or not one shaft split into two is regarded as two.

Break for Lunch

Afternoon Session

Reines: Having determined that there are certain sites in the United States and elsewhere which would be suitable both from the structural and thermal points of view, the questions are what will it cost, and what would the time scale be? If we can come within 50% either way it would be extremely helpful in getting a feeling for the situation.

Hill: In South Africa, starting from the surface, it would cost about a quarter or a third of what it would cost in America.

Reines: A point made by Professor Sellschop is well to keep in mind. Namely, the equipment in this instance will be a significant fraction of the total cost, so though you are undoubtedly correct in the cost of the laboratory, the equipment associated with it would not be markedly altered. Also one would have to add costs if scientists came from all over - a round trip from the United States costs $1,200.

Sellschop: In order to estimate the costs perhaps we might proceed as follows: let us break it down first into the question of capital, and then try to decide on how many headings there are in this category. Included would be ventilation, the sinking of the shaft or shafts, the cavern itself, and the cost of the skip hoist plus the winding gear.

Hill: A depth of 15,000 feet will probably require three lifts although it may just be possible to do it in two. You could not do it in one because the weight of the rope itself is fantastic. For safety reasons you would require two hoists on each horizon or lift level. This, then is the list of necessary hoists and winding equipment.

Sellschop: What other headings might there be? What we would also like to arrive at is the time, from site-decision until it was handed over to the physicist.

Hill: If you want a rough idea, we will ask our Rand Mines Mechanical Consultants.

Barcza: If time is important, you can sink the shaft faster by purchasing more powerful hoists. I would recommend a single shaft with partitions if permitted by local regulations.

Sellschop: For purposes of orientation let us enquire as to whether there is any great difference in cost between a site in the United States and one in South Africa. Now I presume that the $1 million ventilation figure that I put down would be much the same in either location.

Barcza: The $1 million is based on 280 or 300° F. I indicated that that cost would be halved if you chose a cooler area such as in Minnesota or South Africa.

Sellschop: While we are waiting for the Rand Mines Mechanical Consultants to appear, perhaps it would be useful to ask how long will it all take?

Hill: Assume you start from the surface. First is the ordering of the hoists. Delivery of those items might take 12 to 18 months. The pre-foundation work can all be done while waiting for the hoists. Once the hoists were delivered, assuming they were very large, you would be able to sink at an average rate of say 500 feet (or more) a month for the first 6 thousand feet. This makes 12 months. It would take 6 more months to cut hoist chambers for the next lift and installation of the hoists at 6 thousand feet would take another 3 months. Then down another 6 thousand feet at the same rate of 500 feet per month. Again the problem of cutting out the hoist chamber, etc. and installation of a smaller hoist for the remaining 3 thousand feet. This too will take about 6 months for a grand total of 45 months. Two lifts would of course take a lesser time and would probably cost less.

Sellschop: Since we have not allowed time for preparatory work on the surface. It seems reasonable to state that it will take about 5 years from decision to get to depth. Mr. Hill, is it reasonable to expect that as much as two years might be added for each exploratory drilling?

Hill: Yes, but despite this it is possible to do the job in 5 years if the rate of expenditure is sufficiently great. For example, we are sinking shafts in Africa now at the rate of 1 thousand and more feet per month, using very big hoists and skips.

Sellschop: I think we have a figure then, between 5 and 8 years.

Barcza: As stated the time and cost are closely related. For instance, it is cheaper with only two stages, because that means only two levels and four hoists. However, I think it will take longer to sink two 7 thousand foot shafts than it will to sink three 5 thousand foot shafts.

Hill: I assume you will have to do some scouting around the country too, and you are going to run into other factors.

Sellschop: It seems to add up to about seven and one-half years all told, before you can start using it.

Hill: I would suggest that $20 million is in the order of what you will have to spend. I recently saw an estimate of $5 million for a 6 thousand foot deep shaft, including accessories. Once you go below 6 thousand feet you have your new hoist and the cut for it. Multiplying by 3 gives about $15 million. The factor is actually greater than three because the shafts do not start from the surface but are end to end.

(Messrs. Wagstaff and Southall, Rand Mines Mechanical Consultants joined the meeting at this point.)

Hill: Mr. Wagstaff, we are trying to figure out what it will cost to sink a 15 thousand foot shaft. We are assuming two or three lifts, and a shaft at the bottom of which a laboratory would be located. Thus, once the laboratory is completed you would only be lowering personnel and stores. This exploratory meeting is to get some sort of global figure, whether it is even as much as 50% off is not material at this stage.

Reines: Assume at the outset a shaft 20 feet in diameter with a lift capable of handling 20 tons.

Wagstaff: Well, if you had a 20 foot diameter you could put a partition in.

Southall: In 1960 we sank a shaft 20 feet in diameter at a cost of R670 or approximately $1000 per foot of depth. This included everything.

Wagstaff: A similar shaft in the United States would cost about the same in Australia, but this time the hoists would be extra. That gives you some idea of likely costs in the United States. About a third of the total cost is the hoist.

Hill: If you figure $1000 a foot you have made a reasonable start. To this you must add a dividing wall, two underground hoist chambers, and all their auxiliaries. Have you got any figures on cutting an underground hoist chamber?

Wagstaff: $280,000 should suffice for the cutting of the chambers and the winding machinery. Since they will have to take down some pretty large material, I envisioned a shaft with the dividing wall off center; the large half would be for the purpose of getting material down, the smaller section would serve as an emergency exit or personnel lift.

Sellschop: It looks as if the shaft and hoist, according to my sum, is about $18 million or $20 million if we make appropriate allowances for the extreme depths, i.e. the travel time, etc.

Wagstaff: If we did it in 3 stages, it would cost only an additional $100 thousand, for the additional lift engine and chamber.

Hill: This gives the price of the sinking using South African crews. Labor costs in America are so much higher that I would guess that you add at least 30 per cent to those figures.

Sellschop: Could I ask what portion of our present figures is labor, then we could know how to scale.

Hill: About 30 per cent of our mining costs are labor.

Sellschop: Can we get some idea of how much more expensive labor is in the States than here in Africa?

Hill: An African shaft sinker, including his meals and lodging, would get about a shilling an hour (20¢).

Sellschop: I would say that the labor costs 5 to 10 times as much. This means that the labor cost in the United States is about 70% of the total cost. Viewed differently, if out of our $20 million estimate for South Africa about $5 million was for the hoist, then of the remaining $15 million approximately $5 million is labor. Now you multiply that by, let us say 5 and get $25 million for labor to which you must add your $12 million for your hoist and equipment, giving a total of about $40 million.

Wagstaff: I think that when we try to calculate it on a realistic basis the labor will come out to more than 5.

Hill: There is a South African firm going shortly to Canada to sink a shaft. They will have lots of figures. There are several firms (e.g. Roberts Construction and the Cementation Company) which do shaft sinking all over the world, and besides probably being very willing to discuss our problem, they may even give you a more precise idea of what it might cost.

Reines: How does the cost vary as a function of depth? Is it linear? Or does it go up more rapidly?

Barcza: Hoisting cost is probably linear with an intercept at zero depth. For a 20 foot diameter shaft you would have to handle about 30 tons of rock for each foot of depth in your shaft. Since hoisting a ton costs about 10 shillings per foot and is one of the important costs, I estimate that it would cost about $50 to hoist 30 tons from 15,000 feet.

Hill: I would say that more than half the costs will be reasonably independent of depth. This relatively fixed cost is effected by the length of travel time, though, and the movement of the storage of cement, etc., to different depths as is the labor; since each transfar point must be manned.

Sellschop: We still have to add the cost of the cavern to the $40 million for the shaft.

Hill: This should cost approximately 30¢ South African per cubic foot. So that 10^6 ft^3 should cost $450,000.

Sellschop: What about heavy electrical gear?

Wagstaff: That is included in your hoisting equipment as is electric power for the pumps in the mine and the electric power for the lights in the mine.

Sellschop: What about water pumping stations?

Wagstaff: Though these volumes seem large they are small compared with an operating mine and the pumps required would be quite modest. If you do have a water problem you will try to seal it off straight away.

Barcza: I understand that estimates in Australia gave a figure of $1500/ft including hoist. If we round it off to $2000/ft for the United States then $30 million is the resulting figure to which must be added the cost of the laboratory excavation.

Sellschop: If this is going to cost not much less than $30 million in the States, what would it cost here?

Wagstaff: Very much less, especially if we started in an existing and permanent (>30 years future) mine like Anglo American Western Deep Levels. Now there they have got two shafts, one from surface, and one submerged which takes them down to 9,000 feet. If all they had to do was go down an additional 6,000 feet it should not cost more than R3.5 million. This figure includes R2 million for sinking cost, R.75 million for the hoist plus R.75 million for unforeseen contingencies.

Reines: So you would estimate R3.5 million, if you could go down from the bottom of Western Deep Levels and build the lab spaces there. Is there not some concern regarding the stability of an active mining area?

Wagstaff: No, because it would actually be so distant.

Reines: Then the fact that there is mining going on a mile away would not matter. The other point is a practical one. How could the laboratory function efficiently without unduly disrupting the normal operation of the mine?

Wagstaff: You are probably conditioned by your experience at E.R.P.M.'s long series of inclines. The situation at Western Deep Levels is different with its quick drops down to the main station. They go down the main shafts quite regularly because they are exploring the lower regions. I don't think the traffic to the laboratory would interfere with regular mine traffic very much.

Reines: Could one imagine 100,000 tons of stuff being brought down there without upsetting them?

Barcza: Now that would upset them a bit. However, it is possible that after the construction phase, small service cages could be replaced with those having faster hoists, for your use.

Reines: This is a very interesting and financially attractive idea. Now to the question of why 15,000 feet and not some other figure. This is a question that has no simple answer. As far as neutrinos are concerned, depth and background reduction are synonomous. If we had a large non-directional detector in our present 10,492 foot E.R.P.M. laboratory, we would get about 150 ordinary cosmic rays per year, as compared with a signal of perhaps 20 per year. To discriminate against the background we make use of various features of the signal and background. I must admit that the cosmic rays are not without utility because they come down often enough to trigger our equipment and tell us the system is functioning. Why at the 15,000 foot depth we might even have to build a particle accelerator to kick our equipment once in a while to know that it is alive! The drive has always been to go as deeply as we can so that we greatly reduce irrelevant background, cosmic rays being in some sense irrelevant. The 15,000 foot depth should accomplish the desired reduction. In addition, the use of two chambers a few thousand feet different in depth would enable a measurement of the diminution of the cosmic ray background. Having said we would like to go so deep that the cosmic rays are virtually eliminated, I should add that the character of these residual rays are of great intrinsic interest because they represent the passage of extrordinarily energetic particles (muons) through great thicknesses of matter. Since the variation of muons with depth is not known below our present E.R.P.M. level where we have measured it, we can only guess that 15,000 feet will give the desired reduction. Actually we could build the first chamber at approximately 13,000 feet to aid in our extrapolation to the desired greater depth.

Wagstaff: That is in rock with a density of about 2.7 gm/cm^3?

Reines: Yes.*

Sellschop: We would also like to get some feeling as to the running costs.

Reines: Why not ask one of the experts here what he thinks?

Wagstaff: How often do you want to go down?

Reines: A few times a day.

Wagstaff: You would require a hoist driver, a banksman, and an electrician on duty all times. Though you would have at least two serviceable hoists at each horizon or hoist level you would operate only one hoist on each horizon.

Hill: What from an engineering point of view would be required at each level?

Southall: One would need an engineer, an electrician, a fitter, three banksmen and three drivers. This makes a total of 10 men.

Reines: This would cost 50 to 100 thousand dollars a year.

Sellschop: What does this mean in practice? If you have this kind of

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*The Kolar Gold Fields are located on an anomaly where the rock has density of 3.0 gm/cm^3 instead of 2.7 gm/cm^3 at E.R.P.M. This means that their effective depth is up on this account by 10%: 10,000 feet at Kolar is equivalent to 11,000 feet here. The situation is even more favorable to Kolar because the stopping power for muons varies as Z^2/A (Z=nuclear charge, A=atomic weight) and this quantity is greater there: Z^2/A = 6.5 (Kolar), 5.5 (E.R.P.M.).

crew does it mean that they will want to get off at 4:00 p.m. when the shift ends?

Wagstaff: It depends on whether the shaft system would be operating in South Africa for the underground laboratory only.

Reines: If we double the number of men to allow for 24 hour access this would raise the cost to $100 to $200 thousand per year. To be realistic about South Africa we should seriously consider the possibility of Western Deep Levels, as suggested by Mr. Hill and estimate costs on that basis.

Wagstaff: Ir would clearly be much less expensive, perhaps one quarter the cost of separate operation. We should discuss this whole question of costs with the appropriate representatives of Anglo American.

Sellschop: Now can we get some idea of the cost of running skips up and down?

Wagstaff: At $3/round trip and 10 trips per day it would cost approximately $12,000/year.

Reines: That will probably be more than the cost of power for the transistorized scientific equipment! I would like to ask a question of Professor Nicolaysen. To what extent do you think geologists and geophysicists would be interested in inhabiting such a place? Would such a location have some special interest from their point of view?

Nicolaysen: The Lamont Geological Observatory of Columbia University, currently occupies a seismic station about 1,000 feet deep in a disused mine in Ogdensberg, New Jersey. They have solved all of their noise problems at depths of only 500 feet. In other words, they can get all the magnification they need at comparatively modest depths. I would imagine that as one went to these ultra-deep levels, although you could solve the basic mechanical problem of rock creep, you would have a continuous seismic noise problem. I imagine that you would still hear popping around you all the time. It therefore does not appear to be obviously helpful to go to great depths to do seismic studies.

There are other respects in which earth scientists might be interested in a very deep lab, but these would be one-shot experiments and not on a continuous basis. For example, measurements could be made of radioactivity, magnetic fields, heat, rock stress at different levels, resistivity, gravity, combination of electrical measurements, etc. Perhaps the most interesting experiments would be in the rock mechanics field.

Reines: If we build the laboratory it might be well to invite other scientists to suggest experiments for which it is well suited.

Nicolaysen: In connection with possible exploratory drilling, I might comment that Dr. Knopoff of U.C.L.A. can also give information on technical aspects of deep drilling, associated with this upper-mantle project: a 12" diameter has been put down to 12,000 feet in Wyoming and an 9,000 foot hole of the same diameter has been put down in Alaska.

Hill: Let us estimate what a 15,000 foot borehole would cost. A borehole 7,000 - 8,000 feet deep and one and one half inches in diameter would cost about 50 thousand pounds sterling. The problem here would be to keep the hole vertical. The drifting is tremendous, and adds very much to the cost. On this basis I think a 15,000 hole would cost between 100 and 150 thousand pounds sterling.

Reines: It might be useful at this point to give some measure of the total level of operation in the "steady state." If I add all the operating costs, the scientific equipment, and staff, I guess that such a laboratory would cost upwards of $1 million per year. Since Western Deep Levels have figured so prominently in our discussion, perhaps Mr. Hill can be persuaded to tell us something about them: Where they are located, how deep are they, who is the management, etc.

Hill: The Western Deep Levels is an Anglo-American mine and, I believe, is now at a depth of 10,000 feet. I discussed this project with their consulting engineer, Mr. Mudd, recently and I asked his opinion of what he might say if I suggested that you put your detector there. He said he was sure that they would cooperate.

Sellschop: When we were looking for sites for the work now being done at E.R.P.M., I considered Western Deep Levels and exchanged a few letters with them. Although it was pretty clear that E.R.P.M. was more suitable at that time, their letters were extremely warm and encouraging.

Hill: The mining industry in South Africa is interested in seeing this research go ahead. They would probably support a move from Rand Mines because of E.R.P.M.'s limited life when compared with the projected life of the deep lab. Surely you cannot invest a huge sum of money for a limited life. Western Deep Levels is 40 miles to the west of Johannesburg by good highway. It has the particular virtue that just three straight vertical drops would be required to get to the lab. You get down very quickly, I don't think it would disrupt the work in the mine, although preparation of the laboratory would require that they get rid of large quantities of rock, etc. The time for doing the job starting from this 10,000 foot depth would be much shortened. From the time the green light was given it could take as little as two years.

Reines: So it would be two years as opposed to seven to seven and one-half if we started from the surface.

Hill: It could even be faster if one wished.

Reines: A map of Western Deep Levels is exhibited in Fig. 2.

Sellschop: Mr. Hill, I wonder if you would like to make any comments about this concept of a very deep lab. We are very much amateurs in this business. Have we forgotten anything important?

Hill: From what I have learned in this meeting this seems to be a field that is opening up, and will become more exciting as time passes. Therefore, one should not think in terms of short term work. I believe the essential points have been mentioned in today's exploratory meeting.

Sellschop: I would be quite surprised if some very important technical point has escaped us today.

Reines: Then we have at least mentioned the kind of problems, if not having solved them.

Hill: In summary, the essential problems are heat and pressure: one is soluble by adequate ventilation, the other by our knowledge of rock mechanics.

Sellschop: I thought the rock mechanics people were going to have a field day by terrifying us, but apparently 15,000 feet has not frightened them at all. I marvel at the advanced state of knowledge in this field of very deep mining.

Nicolaysen: One small point regarding Western Deep Levels, they have a seismic locating network, which is capable of studying and locating the elastic releases of energy when rock fails. As deeper shafts are sunk there, they will undoubtedly follow the response of the rock with this seismic network as well as with measurements of strain gauges, etc.

Reines: Anything else?

Barcza: One has to bear in mind that wherever this laboratory is it will be in the deepest mine, and we will have to make sure that certain facilities are, if necessary, duplicated including pumping machinery. Not that I envisage any inrush of water, but one does not want to get flooded under any circumstances.

Hruschka: Does this mean that if you are going to put a cavern at 15,000 feet that you should have a sump which is even deeper?

Barcza: Yes, but if as expected, there is no water problem, then of course the sump is not important.

Reines: This has been a fascinating discussion and may well be a milestone in the development of facilities for the study of cosmic rays. I would like to thank all of you for your participation and especially I would like to thank our host, Mr. Hill, and the Rand Mines for their hospitality.

Table I

Summary of determinations of flow of conducted heat

Region	Max. Depth (feet)	No. of Samples	Mean K (conductivity) millical / cm-sec*C	Mean Gradient (*C/km)	H (heat flux) microcal / (cm2-sec)	Reference
Africa						
Orange Free State						
Dubbeldevlei	4900	4	6.8	22.3	1.52	Bullard(1939),Krige(1939)
Transvaal						
Gerhardminneborn	10,000	30	13.5	9.5	1.28	Do.
Jacoba No. 3	7300	14	7.5	12.8	0.95	Do.
Canada						
Ontario						
Toronto	1000	5	6.4	16	1.03	Misener et al., 1951
Larder Lake	2700	6	9.1	9.7	0.88	Do.
Timmins	5500	9	8.0	9.1	0.73	Do.
Quebec						
New Calumet	1400	4	8.5	15.6	1.32	Do.
Malartic	1500	8	6.8	10.1	0.69	Do.
United States						
Michigan						
Calumet	6000	89	5.0	18.6	0.93	Birch, 1954
California, Berry 1	9000	34	3.5	39	1.29	Benfield, 1947
Texas,Big Lake 1-B	8300	4	8	24	2	Birch & Clark, 1945
Oceanic						
Latitude Longitude	Water Depth (m)					
Pacific						
N20 48' W159°42'	4500		1.8	70	1.3	Revelle & Maxwell,1952
N18°18' W173o23'	3900		2.2	40	0.9	Do.
Atlantic						
N49°46' W12°30'	2032		2.59	42.6	1.10	Bullard, 1954
N48°14' W16°58'	4670		2.28	25.4	0.58	Do.

Table II
Temperature Gradients Based on Observations From 2,000 - Ft. (610 M.) to Greatest Depth in the Well (Metric Units)

Colorado

Calhan	6.33	0.03507	28.5	0.37
Colorado Springs	12.71	0.02245	44.5	0.10

Town or Field	$^{o}C.^{a}$	$^{o}C.^{b}/m$	$\frac{1}{m}/^{o}C.^{b}$	$^{o}C.^{r}$

Colorado (Continued)

Florence	8.46	0.04371	22.9	0.50
Fort Collins	6.90	0.03911	25.6	0.30
Longmont	6.76	0.04641	21.6	0.47

Michigan

Houghton Baltic 16*	2.38	0.01681	59.5	0.06
Keweenaw Point	5.46	0.01609	62.2	0.71
Surrey Tp.	-2.59	0.04261	23.5	0.56

Town or Field	$^{o}C.^{a}$	$^{o}C.^{b}/m$	$\frac{1}{m}/^{o}C.^{b}$	$^{o}C.^{r}$

South Dakota

Black Hills	3.65	0.01801	55.5	0.42
Black Hills**	-0.05	0.02285	43.8	0.23

**In ore zone from 3893 to 4798 ft.

TABLE II (Continued)

Town or Section of country	$^{\circ}$C.^{a}	$^{\circ}$C./m^{b}	$\frac{1}{m}$/$^{\circ}$C.^{b}	$^{\circ}$C.^{r}
Transvaal and Orange Free State (Continued)				
Witwatersrand	17.66	0.01376	72.6	0.16
Witwatersrand	18.73	0.01324	75.6	0.10
Witwatersrand	17.51	0.00970	103.1	0.25
Witwatersrand	19.91	0.00859	116.4	0.07
Canada				
Ontario	4.09	0.00900	111.1	0.14
Ontario	5.05	0.00804	124.3	0.12

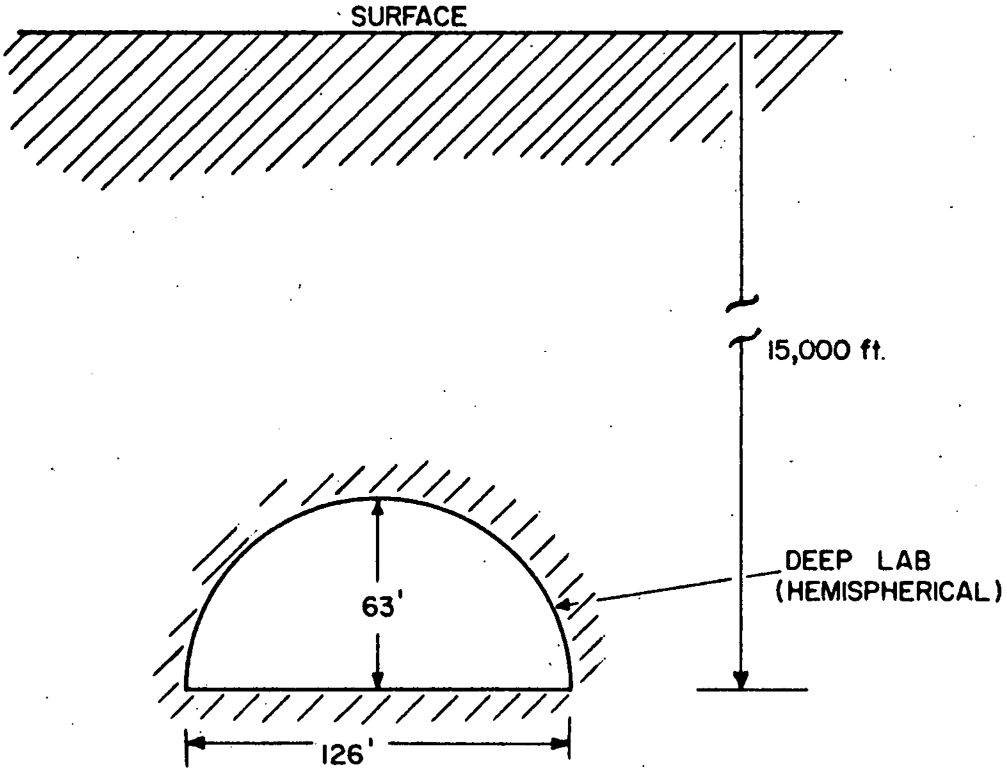
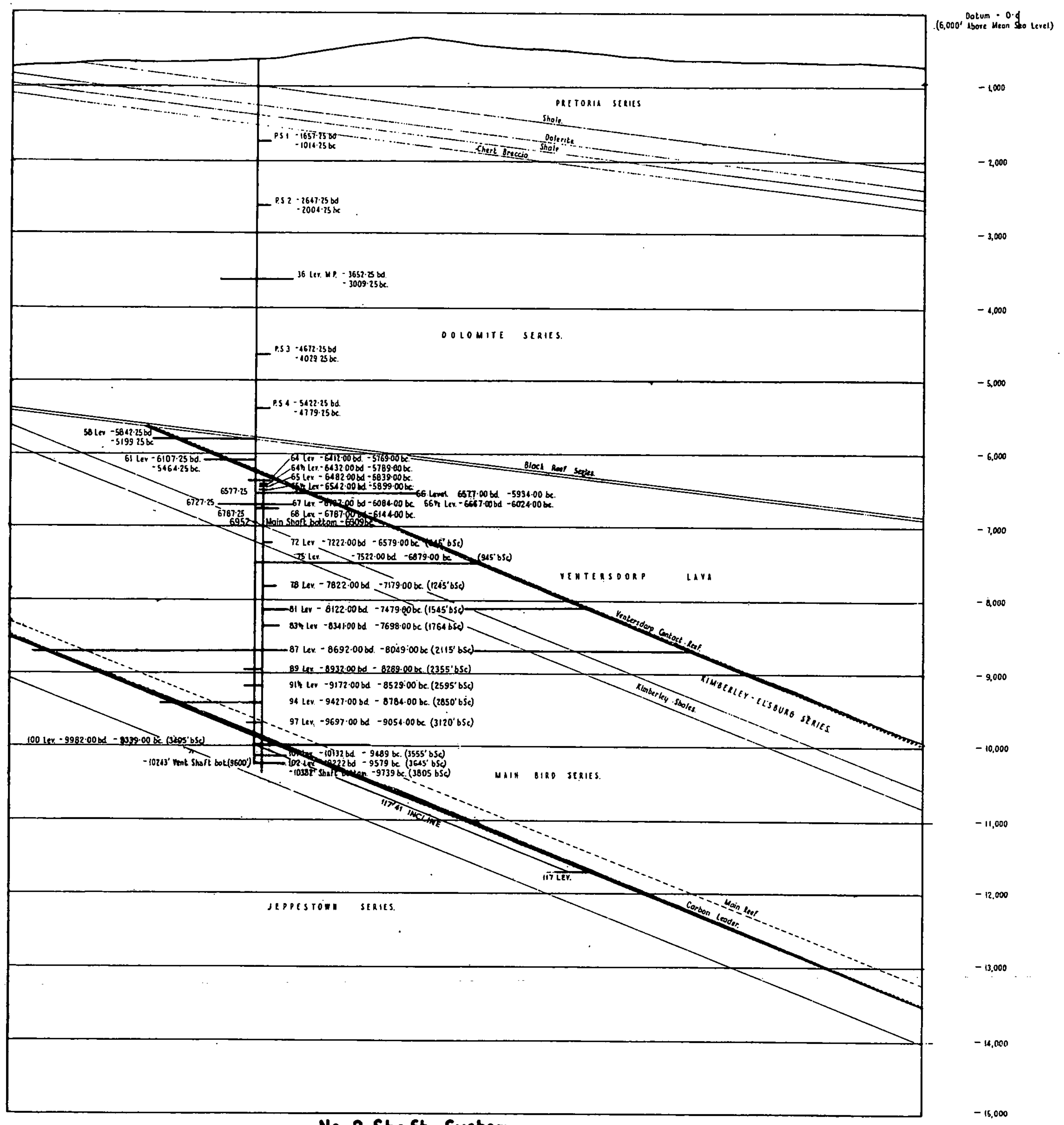
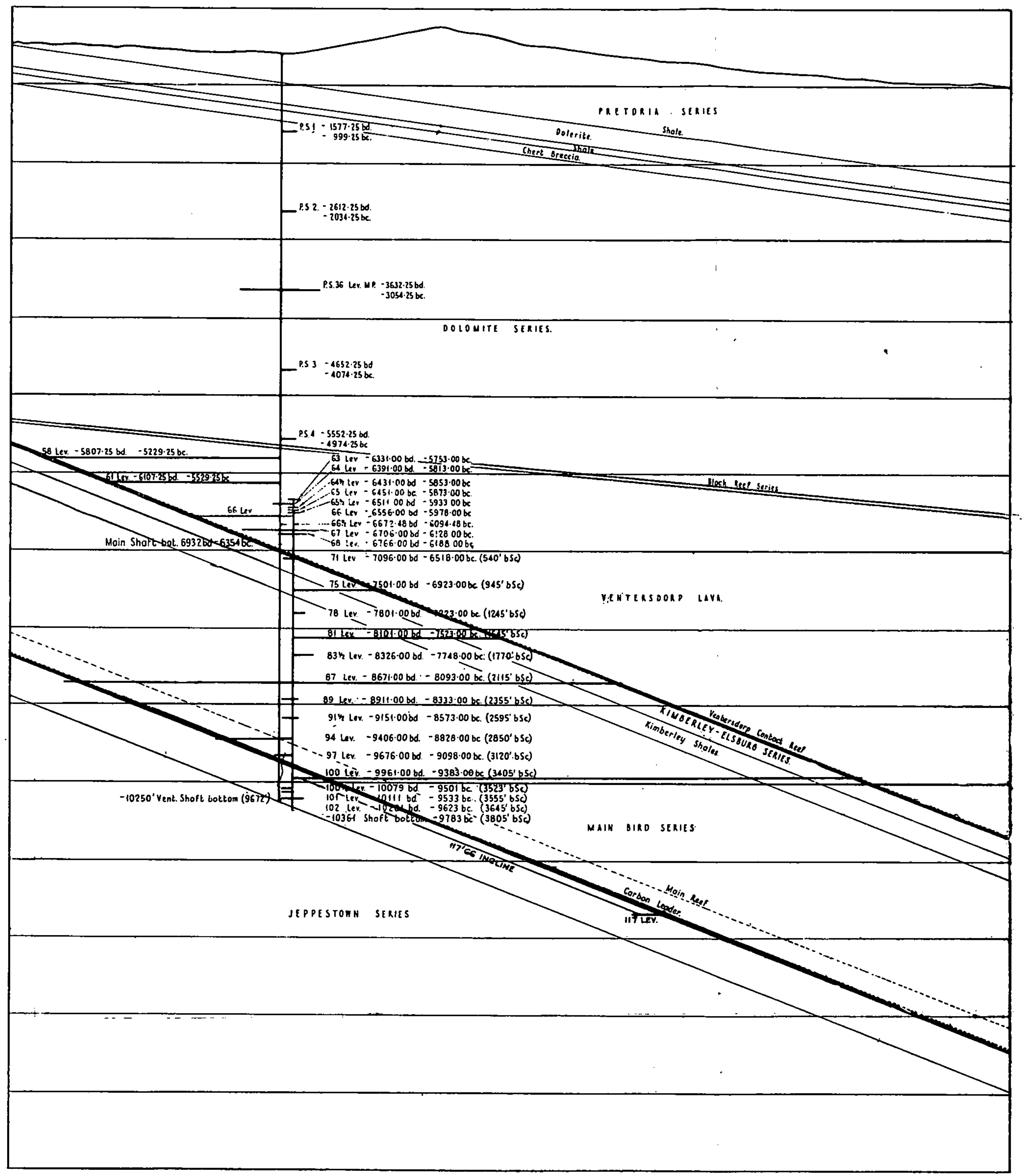


FIG. 1: SKETCH OF PROPOSED CAVITY FOR DEEP UNDERGROUND LABORATORY.

North



No. 2 Shaft System.



No. 3 Shaft System.

Pillars & Stabilizing Zones. ▭

WESTERN DEEP LEVELS LTD.

Diagrammatic Shaft Sections.

Scale 1:10,000

VERTICAL DISTANCES

Between Pump Stations

Bank (66 Lev) — 1st P.S. (75 Lev) 945'
1st P.S. — 2nd P.S. (83½ Lev) 819'
2nd P.S — 3rd P.S. (94 Lev) 1086'
3rd P.S — 4th P.S. (101 Lev) 705'

Between Permanent Pump Stations.

66½ Lev. to Int. P.S on 83½ Lev 1650'
83½ " " Main " " 101 " 1791'

Between Mud Pump Stations.

Bank — 3000' P.C. 3009'
3000' — 6700' 3075'
67 Lev — 100½ Lev 3369'
" " — 83½ " 1614'
83½ — 100½ " 1755'
Dirty Water.

VERTICAL DISTANCES.

Between Pump Stations.

Bank (66 Lev.) — 1st P.S. (75 Lev.) 945'
1st P.S. — (S.M.-825) 2nd P.S. (83½ Int.) 816·40'
2nd P.S — (S.M.-1080') 3rd P.S. (94 Lev) 1088·60'
3rd P.S — 4th P.S (100½ Lev) 673'

Between Permanent Pump Stations.

66½ Lev. to Int. P.S on 83½ Lev. 1654'
83½ " " Main " " 101 " 1785'

Between Mud Pump Stations

Bank — 3000' P.C. 3054'
3000' — 6700' 3075'
67 Lev. — 101 Lev. 3404'
" " — 83½ " 3404' {1619'
83½ " — 101 " {1785'
Dirty Water.