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Special Report 58

SCOPE, PROBLEMS, AND POTENTIAL VALUE OF DEEP CORE DRILLING IN ICE SHEETS

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U. S. ARMY

COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

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by

Henri Bader

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U. S. ARMY COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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PREFACE

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SCOPE, PROBLEMS, AND POTENTIAL VALUE OF DEEP CORE DRILLING IN ICE SHEETS

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Introduction

This report is an attempt to show that the Project on Deep Core Drilling in Ice is of quite exceptionally high geophysical interest, and that it is worth all the support that can be mustered.

Planning, funding, and execution of a number of associated field and laboratory projects require more attention by more agencies and individuals than heretofore. The undertaking should be designated as a major scientific effort in U. S. polar research, important to geophysics and of considerable value to the international scientific prestige of the U. S. A. It should naturally come under the auspices of the Office of Antarctic Programs of the National Science Foundation and its advisory Panel on Glaciology, Committee on Polar Research, National Academy of Sciences. USA CRREL, the various institutes doing polar research, and interested individual investigators have much of the necessary technical and scientific capability for execution. A good program would require support for a period of 5 to 10 years at a total cost of perhaps 2 to 4 million dollars.

Brief history

The Project was begun in 1956 by USA SIPRE as a contribution to the I. G. Y. Four holes from 300 to 400 m were cored by modified conventional equipment: two at Site 2, Greenland; one at Byrd Station, Antarctica; and one at Little America, Antarctica. The results of measurements on these holes and cores were sufficiently interesting to justify post-IGY continuation of the project by SIPRE (now USA CRREL) with NSF support. A test hole 2000 m deep was to be sunk at Camp Century, Greenland, in 1961. The thermal coring tool was lost at 200 m; excellent core ($4\frac{7}{8}$" diam) was being pulled. A new improved tool was built by CRREL, and thermal drilling was resumed at Century in April 1962. If the Century test is technically satisfactory, present plans call for drilling to the bottom of the ice sheet at Byrd (2700 m?) and then at the South Pole (2500 m?), beginning at the end of 1963.

Technical problems

Loss of the tool in 1961 was mainly due to two inadequacies in design. One lay in the choice of the means of removing the melt water from the drill ring tip. It was pumped into a tank above the core barrel, where some was emulsified in the oil, so that it could flow out and refreeze on the ice wall, greatly increasing the force necessary to pull out the coring tool.

The other was a weakness in the attachment of the coring tool to the cable; it had withstood dry testing, but failed in the oil-filled hole. The trouble was eliminated in the new tool by having a piston in the cylindrical water tank. The piston rod rests on the top of the core. There is no pump and melt water is completely retained. Thermal coring by melting with an electrically heated annulus was originally chosen in preference to a cable-supported mechanical corer because development promised to be faster and cheaper. It was learned much later that a small-diameter cable-supported mechanical drill had been developed and used successfully in rock.

It is recommended that funds be made available to further develop and construct a mechanical coring drill for two reasons. One is that the project could continue if the thermal coring should turn out to be unreliable. The other is that coring could be continued below the bottom of the clean ice into the boundary layer (perhaps debris-laden ice) through basal moraine (if any) into bedrock. Design and construction of the mechanical drill could best be done by contract through CRREL.

It is possible that extraordinary ice conditions (structure and texture) may be encountered which would cause the hole to close relatively rapidly at some level. The hole could then perhaps be saved by placing casing at that level only.

There is today no reason to suspect that the project would encounter insurmountable technical difficulties.

Conditions at the glacier bed

These are not known, but one can usefully speculate in order to prepare for some possible events.

It is safe to assume that the material at the bed will be at a pressure essentially equal to the load pressure. Then we have perhaps three possibilities:

1. The material is solid. It is then also almost certainly of low permeability. This would be the case if the temperature is under the melting point of ice at prevailing pressure. Then there is no problem.

2. The material is solid and gaseous. It is conceivable that we may hit dry natural gas. The consequences would depend on the size of the tappable gas volume, and could be serious if it is large. In view of this eventuality alone, the pressure of the liquid in the hole should always be slightly more, and never less, than the ice-load pressure.

Under this condition, the volume of the hole may constantly increase somewhat faster than make-up volume for material removed by drilling. The liquid level must be monitored, and any sudden raising or lowering should ring an alarm. The drilling crew must then be ready to seal the hole to prevent development of a gusher. The tapping of the gas would most likely happen during a coring run, and would perhaps only reveal itself by abnormally low cable tension while the tool is being raised. Perhaps the best remedy would be to have an inflatable plug between the tool and the cable. This problem must be thoroughly investigated.

3. The material is solid, liquid and gaseous. Measurements of temperature as the hole is sunk will indicate whether liquid water may be present. Wet ice is thermally unconductive, hence if water is present, it will be the product of geothermal melting ± frictional heating of ice. If the glacier is more than 600 m thick, all the air in the bubbly ice is dissolved in the melt water, so that if we hit water, nothing should happen beyond a lowering of the liquid level to establish pressure equilibrium at the bottom of the hole. A somewhat more dramatic speculation on what could be expected is given in the following abstract from "Glaciology" by A. P. Kapitsa and I. A. Zotikov; Moscow, Nedelya No. 49, December 1961, page 18:

"Igor Alekseyevich Zotikov, a participant on the Fourth Antarctic Expedition, has developed a hypothesis concerning certain aspects of the Antarctic ice cap. He states that the ice is continually thawing from the bottom and that this thawing is particularly pronounced in the central parts of the continent, whereas it does not occur near the coast. The thicker the overlying ice, the warmer it will be underneath it. The thawing occurs due to heat flux from the earth's interior. Beneath the thick mantle of ice the surface contains many basins and depressions which are filled with water. The ice of the central Antarctic is porous — at certain depths the pores becoming closed air bubbles. At a depth of three kilometers the pressure becomes 300 atmospheres. The stores of energy of the compressed air which has accumulated during the time of the existence of the icecap is tremendous and could turn the giant turbines of a great electric power station for many thousands of years."

Measurements, etc., to be made on the hole

a. During boring

1) Temperature to 1/10 degree absolute, and to 1/100 degree centimeter differential at appropriate depths.

2) Changes in liquid level between shifts.

3) Fluid pressure, to be checked against load pressure, calculated from core densities.

4) Filter melt water from each run and retain filter and some water samples. This may not be very useful unless the hole-filling liquid is also filtered.

5) Keep appropriate drill log, with special mention of non-routine events.

b. Immediately after hole is finished

1) Register liquid level as function of time. Keep supply of heavy and light liquid ready for corrective action.

2) Rate of horizontal shear deformation at different levels, beginning at bottom or top. Shear rate is larger at bottom but there is also the danger of losing tool. Bottom first is preferable if cable can be pulled loose at inclinometer if it should jam. Knowledge of vertical distribution of horizontal shear strain rate is pertinent to knowledge of flow law of glacier.

3) Change in hole diameter at same time as shear rate. This is per se relatively uninteresting, but is check on hole condition if liquid level changes rapidly. (Danger of pinching off, have casing ready.)

4) Seismic velocities by geophones in hole.

c. If hole can be kept open for longer periods

1) Vertical strain rate at different levels. Pertinent to flow law.

2) Total vertical strain rate, by single wire from top to 200 m, from 200 m to top of high shear rate level (if any) and from there to bottom. Pertinent to general state of ice sheet, i.e., stationary, thickening or thinning.

Measurements,etc., to be made on core

a. Immediately after core is pulled

1) Clean off fluid.

2) Accurate spot densities for comparison with later redetermination.

3) Stratigraphy.

4) Observe cracking around air bubbles.

5) Spot checks on structure and texture.

6) Rate of dilation by relaxation.

7) Pack some core pieces in pressurized containers to prevent dilation.

8) Cut core lengthwise into halves, pack both separately for separate shipment. Samples to be used for analysis of enclosed air must be sealed hermetically.

b. Later laboratory work

1) Density, structure and texture.

2) Stratigraphy in detail.

3) Air bubble investigation. Mean pressure, pressure distribution function, chemical and isotopic composition of air.

4) Chemistry of soluble impurities.

5) Isotopic composition of ice.

6) Electrical conductivity of ice and melt water.

7) Radioactivity of ice or residues.

8) Study of insoluble particles. Concentration and size distribution. Nature of particles.

9) Determination of age by all available means.

10) Determination of annual increments and correction for strain (thinning or thickening).

11) Organic content. Biology.

Determination of age of ice

a. By counting of annual layers

Identification of annual layers is always based on some difference between summer and winter layers. All methods, except stratigraphy in snow, are likely to fail in areas of very low accumulation.

1) Stratigraphy. Here the existence of slight summer thaw is a great advantage, as is also a considerable difference in density between summer and winter snows. This method, generally restricted to snow layer, probably fails in ice.

2) Oxygen isotope ratio. Based on summer-winter difference. May fail at greater age if lattice oxygen self-diffusion is high. If it is low, determination of paleo-surface temperatures is possible. Requires small samples, but is expensive.

3) Fallout of terrestrial dust. Picked up and transported by wind. There should be a summer-winter difference, easily determined on very small samples. Sampling techniques critical.

4) Specific electrical conductance of melt water. Depends on summer-winter difference in ionic content. Easily measured on small samples. Sampling techniques critical.

5) Ratio of soluble salts. Summer-winter difference not very promising, but worth investigating. Expensive. Samples small, sampling technique critical.

6) Fallout of cosmic material. Possible annual cycle associated with annual meteoric showers. Worth investigating. Necessary sample size unknown.

b. Methods unrelated to counting of annual layers

1) Tritium. Useless for ages larger than a few decades. Requires fairly large samples.

2) Carbon 14 from air in bubbles. Very good for great age but requires samples of the order of tons, possibly obtainable by melting out at selected depths, which may be technically very difficult to do without contamination.

3) Long-lived natural unstable isotopes. Presently no more than a possibility.

4) Fallout of cosmic material. Correlation with historic and cyclic prehistoric events, such as recorded intense meteoric activity and comet approaches. Depends on identification and separation of cosmic material.

c. Determination of recent rate of accumulation in Antarctic low-accumulation areas where stratigraphic counting is unreliable

1) Tritium. Determination of depth of 1954 layer if Castle shot fallout reached Antarctica.

2) Volcanic ash fallout. Determination of 1884 layer (Krakatoa ash) if Antarctic volcanos were quiescent at that time.

Determination of total strain (due to flow deformation) on core ice

1) Structure and texture. Not promising.

2) Air bubble elongation. Worth investigating.

3) Count of partic tes. It is possible that some fraction of the insoluble particles, either terrestrial or cosmic, falls out at a constant rate. If this were true, the measured concentration would be inversely proportional to the rate of accumulation. If the thickness of the annual layer can be determined, then the total vertical strain is calculable.

Associated tasks

Much of the glaciological interpretation of measurements on hole and core will depend on a number of things that must be done in the vicinity and upstream from the hole. These are at least:

1) Measurement of rate of horizontal motion of drill site, by accurate astrofixes, trilateration or geodetic satellite.

2) Preparation of a map of surface and bed centered on drill site.

3) Determination of local rate of accumulation by pitwork and snow-stake farm.

4) Measurement of rate of accumulation upstream to divide, by pitwork.

5) Determination of surface and bed profile upstream to divide. We must know ice thickness and surface and bed slopes.

6) Determination of horizontal surface strain rate vectors at several points between drill site and divide.

Choice of drilling sites and drilling schedule

It is obviously convenient to drill at existing camps where power and facilities are available, but such camps happen not to be located where the glaciological situation is simple. At Byrd, for instance, it is not even known in which direction the ice is flowing. If at all feasible, sites should be chosen where the glaciology is two-dimensional, i.e., where there are no strains normal to the plane containing the flow lines.

It would also be very helpful if the vertical cross-section containing the flow lines intersected surface and bed in simple curves. It should be possible to find at least one such situation not too far from the divide in Greenland and to establish and support a small temporary summer camp there for one or two seasons. In Greenland, a hole can be sunk in one summer season, but hardly so in Antarctica. Over-wintering there will have to be at existing permanent stations. Location and scheduling after Century must be carefully considered in the light of available logistics. Drilling of a second hole in an optimum Greenland location before moving to Antarctica would be desirable. An effort should be made to obtain the necessary military logistic support.

It is suggested that after the hole at Century is successfully completed, a conference on further development of the deep drilling project be called by NSF or CRREL. All interested institutions and individuals should get together for a thorough discussion of means and ends. The scope of the project is so broad that it should be handled by a steering committee with power to allocate tasks and funds.

Potential value of the project

The wide ramifications of the project are evident from the foregoing notes. Its primary high value is to Glaciology, Paleoclimatology, and Meteoritics. It will also be a school for development of glaciologists and geophysicists. New methods and instruments will be devised to solve some of the problems raised. Glaciology will benefit enormously from the data obtained, particularly that pertaining to the present state of the ice sheet. From strain rate measurements our knowledge on how ice deforms will be greatly advanced, permitting a corresponding development in theory which is not only of scientific interest, but also applicable to engineering hydrology.

The view into the past will reach back at least several tens of thousands of years. We will see such things as changes in rate of precipitation, temperatures, composition of the air, salt nuclei content and dustiness of the atmosphere, and frequency of major volcanic eruptions. The changes with time in concentration and nature of meteoric fallout will be of great interest to Astrophysics and perhaps not insignificant in relation to the technology of space exploration.

A great deal will depend on the skill and imagination which individual investigators bring to bear on work with ice cores. Structure, texture and composition are the products of many interesting events, some of which can be reconstructed.

Sheet glacier ice is unique as a thick continuous stratigraphic sequence reaching back at least many thousands of years, perhaps as many as 50 to 100 thousand years. The relatively modest price of its detailed study will be well spent.

This project is one that grips the imagination and creates enthusiasm. It is a challenge which will attract high scientific talent. If well administered and funded, it can become a focal point of polar research for a number of coordinated research activities.

APPENDIX A.

ESTIMATE OF AGE OF ICE TO BE REACHED BY DEEP CORING

As suggested by John F. Nye

There is not sufficient data on conditions upstream for anything except a first estimate, based on the assumptions that ice thickness is constant, the rate of accumulation is constant, and the glacier is stationary.

It is also assumed that the whole ice sheet consists of bubble-free ice, and that the vertical strain rate is constant (independent on depth).

A = rate of accumulation, g cm^{-2} year^{-1}
h = ice thickness, cm
γ_i = density of pure ice, g cm^{-3}
$\dot{\varepsilon}$ = vertical strain rate, year^{-1}
y = depth below surface, cm
L = thickness of annual layer, cm
t = age, years

$$\dot{\varepsilon} = \frac{1}{L}\frac{dL}{dt} = -\frac{A}{\gamma_i h}. \tag{1}$$

The vertical downward velocity of an ice element at depth y is

$$V = \frac{dy}{dt} = \int_y^h \dot{\varepsilon}\, dy = \frac{A}{\gamma_i}\frac{h-y}{h}. \tag{2}$$

Eliminate A from eq 1 and 2

$$\frac{dL}{L} = -\frac{dy}{h-y}$$

$$L = L_s \frac{h-y}{h} \tag{3}$$

where $L_s = \frac{A}{\gamma_i}$ is the thickness of the annual layer at the surface.

We obtain age as a function of depth by integrating eq 2

$$t = \frac{h\gamma_i}{A} \ell n \frac{h}{h-y}. \tag{4}$$

At constant vertical strain rate, the thickness of the annual layer as a function of time is

$$L = L_s \ell^{-\frac{A}{\gamma_i h} t}. \tag{5}$$

The following table was calculated by eq 3 and 4, with the following parameters:

	h meters	A g cm^{2}year^{-1}
Century	2000	31.8
Byrd	2700	15.7
South Pole	2500	6.6

y	Century t	Century L	Byrd t	Byrd L	South Pole t	South Pole L
meters	years	cm	years	cm	years	cm
0	0	34.6	0	16.9	0	7.2
400	1290	27.7	2600	14.4	6000	6.0
600	2060	24.2	4000	13.1	9500	5.5
800	3000	20.8	5600	11.9	13400	4.9
1000	4000	17.3	7400	10.6	18000	4.3
1200	5300	13.8	9400	9.4	23000	3.7
1400	6900	10.4	11700	8.2	28000	3.2
1600	9300	6.9	14300	6.9	35000	2.6
1800	13300	3.5	17600	5.6	44000	2.0
2000	-	-	22000	4.4	56000	1.4
2200			27000	3.1	73000	0.9
2400			35000	1.9	-	-

APPENDIX B.

STATION GLACIOLOGY AND THE DEEP DRILLING PROGRAM

by

Carl S. Benson

Introduction

The following paragraphs constitute a first draft of a Station Glaciology program. The concept of Station Glaciology expressed here includes an extended area of at least 50 km radius which is to be studied each year during the lifetime of the station. Preliminary discussion of these ideas by A. J. Gow and myself took place at the South Pole Station in January 1962; our thoughts seemed to be in accord with certain requirements of the proposed deep drilling project which was discussed at length during the Glaciology Panel meeting in March 1962.

Topography

One subject of the panel discussion was a study of parameters such as accumulation and rate of flow "upstream" from the bore hole. It was also pointed out that knowledge of surface relief features in all directions from the bore hole is desirable. Several scales of relief are observed on both the Greenland and Antarctic ice sheets. First, of course, are the large relief features which show up on reconnaissance maps. Second are relief features such as ridges, troughs, step-like descents along slopes, etc. Dr. Lister mentioned the existence of a ridge-trough topography in some locations along the trans-Antarctic expedition, with approximately 50 m amplitude and 20 km from crest to crest. Similar features were reported from Greenland by Dr. Hoffmann at the Symposium "Physical Geography of Greenland" held in Copenhagen, July 1960. A finer scale of relief can be observed within dimensions of 5 km. Bentley and others prepared a topographic map of an area 4 x 9 km near Byrd Station, Antarctica. They observed features similar to those presented in the map of a 3 x 5 mile area north of Site 2 on the Greenland ice sheet (Benson 1959, Fig. 14).

These relief features control distribution of accumulation on a meso or micro scale with higher accumulation in troughs than on crests. The survey in SIPRE Research Report 26 was initiated with the idea of determining the extent of this control on accumulation and the manner of migration of these relief features. The smallest relief features are sastrugi, barchan-type dunes, ripple marks, etc. However, these are often less pronounced when observed in pit walls than on the snow surface, and the mechanism of erosion of sastrugi and the resulting variability of the snow surface with storms or seasons should be studied.

The importance of these relief features can be illustrated by an example. Assume that accumulation is constant for 500 years in a given square area 100 km on a side. Assume also that a ridge and valley topography exists in the area and migrates over the surface at a rate unrelated to the flow of the ice itself. Therefore, its motion relative to the bedrock will be different from that of a fixed surface point such as Byrd Station. Indeed, the ridges and troughs will move past the station, and if the period of time between successive crests is 50 years, one will observe a 50-year period for variation in accumulation. When examining the core from such a station one would, of course, not record variations in topography, but only variations in accumulation, even though accumulation had been constant in the extended area around the station. We should seek to learn as much as possible about these surface features - what causes them? How, and at what rate do they move? Are they most pronounced on crests of large ridges or on broad slopes? Are they related to bedrock irregularities, flow characteristics, or solely due to wind? These and other questions may be considered.

Diagenesis of snow strata

Another important thing to observe at and around stations is the diagenesis of specific layers and annual units over a long time span. The physical characteristics of given layers can be observed during the entire lifetime of the station by digging pits every year at selected points. After a 5 or 10 year period the pits will be dug through a sequence of annual units which have been studied intensively each year since their original deposition. This study will consist of the standard measurements of density, ram hardness, temperature, grain size and description of strata, but it should also include O^{18}/O^{16} ratios of individual layers, particulate counts, electrical conductivity of melt water, tritium and deuterium counts, and other things as they are thought of. The final result will be a more refined study of a sequence of layers than was done in northwest Greenland where sequences of 4 years strata were followed year-by-year at selected points by standard methods of snow stratigraphy (Benson 1959, Fig. 36; Benson, 1962, Fig. 22, 23, 24, 25 and data sheets, especially data sheet #4).

Detailed and annually repeated physical measurements, over an extended area surrounding a station, on snow layers as they are buried will eliminate all uncertainty in the interpretation of snow stratigraphy and its dependence on micro- or meso-relief features. Also, such measurements will provide invaluable information for determining the specific time-dependent mechanisms of densification of snow. We essentially have laboratory conditions with known rate of stress application and known temperature conditions. The experiment is always underway, and conveniently located at a multi-million-dollar research establishment — the only lacking ingredient is the experimenter with a long range plan in his head.

With the preceding paragraphs as introduction, the following is a draft of a Station Glaciology program to be used at Byrd and the South Pole Stations in Antarctica and at Camp Century in Greenland. It is only a draft, and critical comments are welcome.

Station glaciology program

Topography and accumulation and the relationship between them will be measured in the region surrounding a station by detailed sampling in a system of smaller areas within larger areas and by less detailed sampling in the larger areas.

The largest area is to be marked by a cross of accumulation poles with surface-marker plates, as used in Greenland (Benson, 1959). The cross will center on the station and extend 50 km outward in directions parallel and perpendicular to the prevailing wind. The poles will be spaced 1 km apart on each line. At least once a year accumulation will be measured by probing to the surface markers, in combination with pit studies made year after year at selected points along the lines, as already done over a 4-year period in northwest Greenland (Benson, 1959).

At Byrd Station, one arm of this cross will be identical with the stakes established for Dr. Brandenberger's program of observing absolute movement of Byrd Station by photogrammetric methods (Conference, 1962).

A square area, 10 km on an edge and parallel with the extended lines, will be established around the station. Poles will be surveyed into this area at 1 km intervals on a grid. A topographic map may be made annually of this area by photogrammetric methods. As a result of discussion with Dr. Brandenberger it is expected that this map can be made with a 1-m contour interval each year. Some of the stakes in this grid will be the ones used in Dr. Bull's proposed measurement of surface strain at Byrd Station (Conference, 1962).

A smaller area of 1 km² will be established within the 100-km area mentioned above. This area will be used for detailed surface-relief studies by photogrammetric methods with accurate ground control. At Byrd Station, it will center on one of the areas to be established by Dr. Bull for measuring surface strain.

Within the 1 km² area a smaller one will be established where small-scale relief features will be measured in the same manner as done by Long (1961). Detailed observations of the formation and dissipation of sastrugi and dune features will be carried on in this area to serve as an aid in the interpretation of such features when seen in pit walls or core.

As mentioned above, under "Diagenesis of snow strata", it is essential that detailed pit-study measurements be made annually within the survey network. In addition to stratigraphic data, this will provide valuable information for the study of mechanisms of densification.

Seismic studies along the traverses described above will help determine whether or not the observed surface relief is controlled by bedrock. Work of this nature has already been done at Byrd Station by Bentley. Some aspects of it as summarized by Bentley are:

1) Two long-refraction profiles were made at right angles to each other, one extending 16 km (March 1957) and the other 22 km (March 1958). Wave velocities throughout the ice were measured on both, and velocities in the subglacial rock on the latter.

2) A map of ice thickness and surface topography was made of an area 4 x 9 km with a 1-km grid spacing. At each point of the grid seismic reflection shots were fired and relative surface elevations determined by transit.

3) Gravity and magnetic measurements were made on the same grid, and extended over another 30 km , including Byrd Station itself.

This work indicated no relationship between surface relief and the ice-bottom topography.

Seismic and gravity work must be done in the extended area to determine the slope of the bedrock surface for analysis of flow geometry. This work should be coordinated with the survey network outlined above.

This is submitted as a first draft of an overall plan to tie in various aspects of glaciological studies with the deep-drilling program at Byrd Station. However, the extended-area Station Glaciology study is important for its own sake and should also be set in motion at the South Pole Station and at Camp Century in Greenland. The study should basically be integrated at N. S. F. level with participation of interested groups of qualified people at CRREL, Ohio State University, University of Wisconsin, University of Miami, California Institute of Technology, and the University of Alaska. Details of handling the program have not been handled here and it is well to close by reemphasizing the opening sentence. This is a first draft of what will hopefully become a proposal, or series of proposals, grouped around a single U. S. master plan.

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