GL01287

# Earthquake prediction

*By ROBERT DEAN CLARK*
*Assistant Editor*

Among the planet's self-generated terrors, earthquakes have no rival for instantaneous, large-scale ferocity and destruction. Leviathan quakes release energy in seismic waves comparable to that of nuclear bombs; the seismograms are almost identical. If its energy could be harnessed, a 6.8-magnitude earthquake could power a city of 100,000 inhabitants for a year. A true monster of 8.75 could keep it running for over 600 years.

Earthquakes have consistently caused deaths throughout the millennia of human record-keeping, claiming perhaps 75 million lives, and only recently has warfare, one of its few rivals in megadeath genesis, proved as physically catastrophic. Earthquakes and 20th Century weaponry alone can reduce a major city to rubble in seconds.

The awesome menace of quakes has been but mildly tempered by human ingenuity, a status perhaps unique among natural terrestrial phenomena. They remain one of the few forces constraining man from total control of his environment. Historian Will Durant waits only until the second paragraph of his master work to pay homage to their puissance, majesty, and immunity in Volume 1, page 1 of the 11-tome *Story of Civilization:*

"Or the demon of earthquake, by whose leave we build our cities, may shrug his shoulders and consume us indifferently."

Statistics exonerate Durant from overstatement. During an average year, nearly 1,000 quakes occur above magnitude five, including one immense shock of eight or larger. In this century, earthquake-related deaths average 10-15,000 per year. Annual property damage is $7 billion. Every three years a single temblor will be responsible for at least 10,000 deaths.

Despite their bloody history, quakes are not as innately murderous as hurricanes (even more powerful but not in so short a time), tornadoes, floods, or landslides. Fatalities resulting directly from earthquake tremors are rare. People out of doors and away from buildings are rarely harmed physically, even by the most cataclysmic variety.

Confirmation of the demon's relatively benign nature is offered by an imposing witness, Charles Darwin, who experienced the great Chilean temblor of February 20, 1835, probably one of the half-dozen most powerful in the world in that decade.

"This day has been most memorable in the annals of Valdivia," Darwin wrote in his journal later published as *The Voyage of the Beagle,* "for the most severe earthquake experienced by the oldest inhabitant. I happened to be on shore, and was lying down in the wood to rest myself. It came on suddenly, and lasted two minutes, but the time appeared much longer.

"The rocking of the ground was very sensible. The undulations appeared to my companion and myself to come from due east, whilst others thought they proceeded from south-west: this shows how difficult it sometimes is to perceive the direction of the vibrations. There was no difficulty in standing upright, but the motion made me almost giddy: it was something like the movement of a vessel in a little cross-ripple, or still more like that felt by a person skating over thin ice, which bends under the weight of his body.

"A bad earthquake at once destroys our oldest associations: the earth, the very emblem of solidity, has moved beneath our feet like a thin crust over a fluid; — one second of time has created in the mind a strange idea of insecurity, which hours of reflection would not have produced. In the forest, as a breeze moved the trees, I felt only the earth tremble but saw no other effect. Captain Fitz Roy and some officers were at the town during the shock, and there the scene was more striking; for although the houses, from being built of wood, did not fall, they were violently shaken, and the boards creaked and rattled together. The people rushed out of doors in the greatest alarm.

"It is these accompaniments that create the perfect horror of earthquakes, experienced by all who have thus seen, as well as felt, their effects. Within the forest, it was a deeply interesting, but by no means an awe-inspiring event."

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*The seismograms of the last three Parkfield earthquakes are so similar that a conclusion leaps out at you — the same earthquake is occurring over and over.*

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Human tragedy is almost always an indirect earthquake product. They are inimical to the permanence, embodied mostly in architecture, which civilization tries to engineer on a dynamic geology. Man, in effect, abrogated his détente with earthquakes by his recent, unnaturally orderly rearrangement of rocks and minerals whose distribution is properly a province of tectonics.

A corollary is that the vast majority of earthquake-related fatalities could be prevented if the shocks were predicted in a narrow time frame. Extraordinary precautions, such as mass evacuation, would rarely be necessary. In most cases, all that would be needed to save thousands of lives would be for those inhabiting buildings of suspect construction to spend a few hours outside.

Earthquake prediction, however, has only recently been elevated from scientific limbo, where it coexisted with alchemy, astrology, etc., to a status deemed worthy of serious investigation. The catalyst was the 1960s plate tectonics revolution. The new theory clarified some earthquake enigmas (the source of the rock-fracturing stress, the reason 90% are clustered in certain regions) and hinted that computerized geophysical models could be developed, probably rather quickly, to yield accurate predictions.

Frank Press and Raymond Siever in their 1974 textbook *Earth,* wrote: "Ten years ago only astrologers, mystics and religious zealots were concerned with earthquake prediction.

"Today some of the most respected scientists in seismology are actively working on this problem. Increased knowledge of the earthquake mechanism has encouraged seismologists to believe that earthquakes are preceded by events that signal the coming of an earthquake within hours or days or years.

"The challenge comes in learning to recognize them. Some encouraging leads are currently being pursued, such as anomalous ground tilt or strain changes that precede earthquakes; the bunching of foreshocks, all indicating the same slip direction along a fault plane just before rupture; and changes in such physical properties as porosity, electrical conductivity, and elastic velocity in the hypocentral region just before faulting."

The optimism grew even brighter on February 4, 1975. Chinese scientists, long in the vanguard of earthquake research, had predicted that a quake of ominous size would occur on that day near the city of Haicheng, population 90,000. The townspeople were advised to go to open-air shelters where movies helped them endure sub-freezing conditions. A 7.3 magnitude temblor thundered through the region precisely on schedule, at 7:36 p.m., damaging or destroying 90% of the city's structures. The accurate warning prevented thousands of casualties. Thus, earthquakes' reign of terror seemed about to be overthrown, relegated like many diseases to the ranks of muted horrors.

Few accurate predictions, though, followed the Haicheng success. Earthquakes continued their annual massacre. A little over a year after the successful forecast at Haicheng, Chinese scientists failed to predict a 7.8 quake at Tangshan. The official death toll was 250,000. Unofficial estimates have been as high as three times that. If the latter are accurate, that earthquake was the second deadliest ever.

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*By the early 1980s, the USGS had erected a monitoring network, featuring about 800 seismometers, through California's major fault zones which has become so refined that earthquakes can be studied almost as they occur.*

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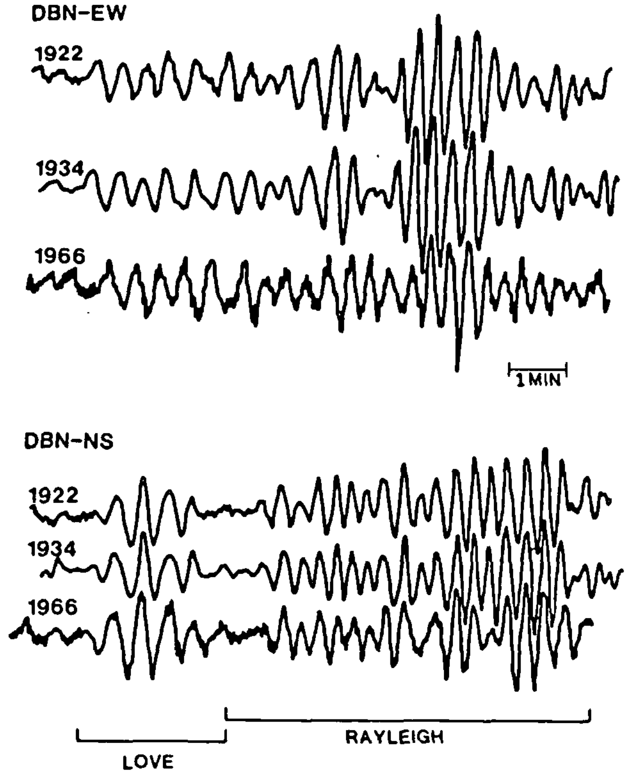
As the rest of the 1970s passed without dramatic progress toward short-term prediction models, the confidence of researchers was dimmed. At the beginning of the 1980s, although investigation proceeded along many lines and intriguing theories abounded, few, if any, earthquake experts expected quick results.

However, less than halfway into the new decade came two related developments promising to put short-term prediction back on a fast track. One was mounting evidence from the geologic record that some quakes were regularly repeating events. The other was the realization that an ideal natural laboratory in which to quickly test the hypothesis existed but a short distance from Menlo Park, California, headquarters for the US Geological Survey's Earthquake Prediction Program. The earthquake community knows the curious piece of real estate, 30 kilometers of the San Andreas fault about halfway between Los Angeles and San Francisco, as the Parkfield section. Today it is the most watched, wired, metered, measured, analyzed and thought-about fault in the world.




**The jarringly similar seismograms, recorded at De Bilt, of the three most recent Parkfield earthquakes.**

**William Bakun, prophet of repeatability.**

The reason is its remarkably consistent history of moderate earthquakes. Seismic and historical records reveal that Parkfield (the name comes from the nearest town, population 34) ruptures just about every 22 years. Should the pattern hold, the next is due in a time window falling mostly in this decade. It will probably be the first quake in history that many want to happen because it might provide a breakthrough to consistently successful earthquake prediction.

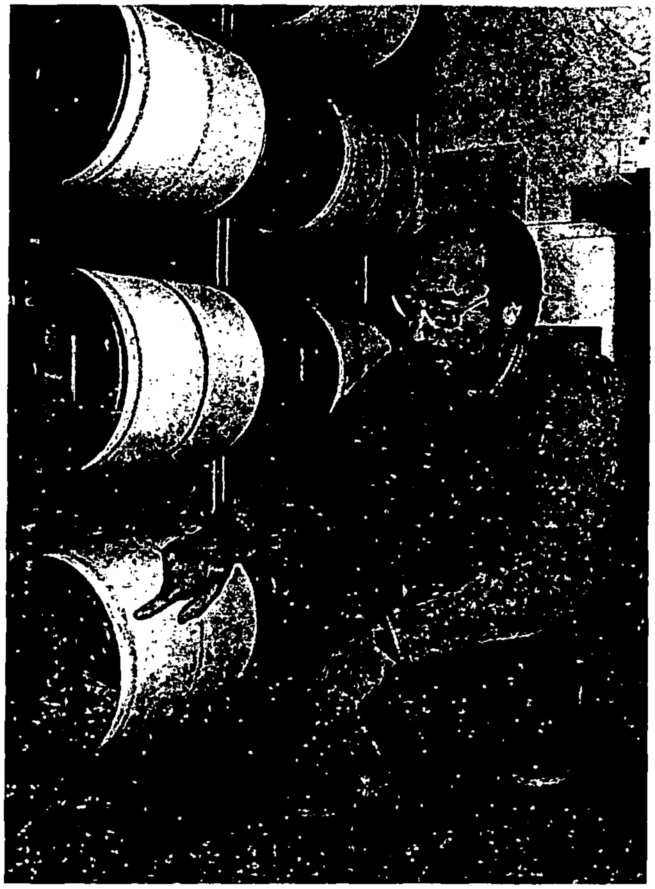
Investigation by William Bakun of the USGS and Thomas McEvilly of the University of California-Berkeley reveals another astonishing feature about Parkfield. The seismograms of the three events (1922, 1934, 1966) for which records are available are remarkably similar. "They are so alike that if you lay them on top of each other, the fit is almost perfect," says Bill Ellsworth, chief of the Branch of Seismology in Menlo Park. "A conclusion jumps out at you — the *same earthquake* is occurring over and over."

The discovery might have come about 15 years earlier, shortly after the 1966 shock, if the US had been as oriented toward earthquake research as Russia, China and Japan. But not surprisingly, America is a relative latecomer to the field; most of its vast territory is not earthquake-prone, and because the country has but recently become heavily populated on the seismically active west coast, it has suffered few shocks devastating to people — the kind that put earthquake research high on the governmental agenda. And the most seismically active state, Alaska, remains the nation's least populated area. Prior to the famous 1964 Anchorage cataclysm (9.2 magnitude, the second largest in the Western Hemisphere in this century and one of the mightiest ever) Alaska had only two regularly operating seismograph stations.

But post-World War II demographics did thrust a certain earthquake awareness upon the US. California, the second most seismically active state and one with a history of big tremors, became the most populous region of the country, making it a prime target for a major tragedy. A large rupture near Los Angeles, hardly an improbability, could kill tens of thousands.

Thus, in 1977 the US officially got into large-scale, unified prediction research with the *Earthquake Hazard Reduction Act*, an all-encompassing measure which also funded research in engineering, building standards, seismic analysis of nuclear power plants, and disaster relief. The US Geological Survey was given responsibility for prediction research. Its Branch of Seismology office in Menlo Park naturally inherited a major role.

The latter's initial efforts concentrated on expanding the limited earthquake knowledge — "developing", says Ellsworth, "an integrated picture of the seismic hazard and trying to learn the actual physics of the earthquake process." During the '70s, researchers became aware that other than long lists of dates, places, and magnitudes, few hard scientific facts were known about quakes. The only valid evidence comes from the events themselves but these do not marry easily to scien-



**Bill Ellsworth checking Menlo Park instruments.**

tific study; earthquakes arrive suddenly and are gone within minutes. Consequently, until quite recent times, precise observation and measurements of the actual physics of the temblor process right next to the source were quite difficult and due in large degree to pure chance.

To a great extent technological advances have solved this classic vicious circle. By the early 1980s, the USGS had erected a monitoring network, featuring about 800 seismometers, along California's major fault zones which has become so refined that quakes can be studied almost as they occur. Telemetry transfers field data almost instantly into the Menlo Park computer system. The latter is programmed to sift through the data and flag the most interesting for more detailed examination.

This system has already shown great life-saving potential, perhaps the next best thing to outright prediction; in 1982 Menlo Park experts were able to analyze quakes at Long Valley and in 1983 at Coalinga, soon enough to be of significant help. Ellsworth recalls: "We were able to make a rapid assessment of the state of affairs in the fault zone while the earthquake swarm was building up. We could pinpoint them within minutes. We were in contact with community officials and telling them what we were seeing.

"This allowed them to give much more sound judgment to the people in the area doing emergency work. There was great concern that the Coalinga earthquake had the potential to trigger a much larger one, but within a couple of days we developed a clear picture of what was going on. There was no indication in the strain data that one was imminent. Frankly, we have been rather surprised the system has been able to keep up with approximately 1,000 quakes a day. We've found that one analyst on a computer can do the work of four using traditional data processing procedures. And in the last 12 months we've moved into a full-scale monitoring program. The computers are always searching for something and we always have a seismologist on call. A number of us have graphics terminals in our homes so if something happens in the middle of the night, we can monitor the situation and make decisions from there."

In the early 1980s, the improvements in data collection methods came fully on line. This was just as Bakun and McEvilly were completing their comprehensive examination of Parkfield's earthquakes and concluding:

"The Parkfield section of the San Andreas fault zone is characterized by recurring earthquakes with predictable features."

Bakun has been studying Parkfield off and on since he was a graduate student. The theme of his first scientific paper was the 1966 earthquake. That shock drew more attention than its modest 5.6 magnitude would normally warrant because it put Parkfield back on a 22-year period. Its antecedent in 1934 had come 10 years too soon, flawing a sequence which otherwise had an almost military precision — 1857, 1881, 1901, 1922 and 1966.

Bakun and McEvilly began comparing the last two events, for which they had abundant and accessible records, and soon discovered striking similarities. The 1934 main shock, which propagated toward the southeast, followed a foreshock, which propagated northwest by 17 minutes 25 seconds. In 1966 the foreshock-main shock directions were identical and they came 17 minutes 17 seconds apart. Analysis of the wave travel times showed the epicenters of the main shocks could be separated by no more than six kilometers.

Initial comparison of the magnitudes indicated different sized shocks but when refigured to take the unilateral direction of rupture into account, they too showed remarkable congruence — 5.6 for the main shocks, 5.1 for the foreshocks.

Limited instrumental data from the 1922 earthquake and descriptive historical records from earlier events hinted they were of comparable size and fractured at approximately the same location as the two most recent temblors. It goes without saying that the remarkable consistency invited detailed inquiry.

Although quakes generally have been quite successful in hiding their traits from scientists, they have one which makes certain data plentiful; seismic waves from even medium ruptures travel for immense distances, in and around the earth, generating records wherever there is a working seismograph. In 1981 Bakun and McEvilly requested seismograms from 25 stations around the world which had documented more than one Parkfield earthquake. Over the following year the records arrived steadily, and confirmed suspicions that the 1922 quake was almost a carbon copy of its two successors.

The most striking evidence came from De Bilt in the Netherlands. This was the only station recording the last three Parkfield earthquakes with the same seismograph, in the same location. Its seismograms for '22 and '34 are an almost trace-for-trace match. The 1966 earthquake had very similar waveforms and was only slightly larger.

"All the data suggests Parkfield earthquakes are periodic, with similar properties," says Bakun. "We think we're looking at a characteristic earthquake that repeats. There is no reason to think the next one will be different."

The Bakun-McEvilly recurrence model is supported by such compelling evidence that the USGS has made it the subject of its most advanced earthquake research project — the Parkfield Prediction Experiment, a high-tech attempt to capture as much geophysical data as possible before and during the next Parkfield earthquake. At present the carefully deployed instrument network includes:

- A two-color laser system to monitor the shape of the crust as it is deformed by the continually building stresses which will ultimately generate the next quake. The system can measure deformation to an accuracy of 1 millimeter in 10 kilometers.
- Dilatometers at the bottom of two, 200-meter holes to continuously measure strain.
- Portable lasers which measure distance changes every three months.
- Eight creepmeters, stretched across the fault, to measure strain released without causing seismic activity.
- About 20 seismometers to record the release and redistribution of strain by seismic action.
- Magnetometers to measure stress induced changes in the magnetic field.

(The experiment is an ongoing process and other kinds of instruments will probably be added. However, the project is unlikely to be concerned with such possible earthquake precursors as changes in the flow of natural springs, soil radon emission, or animal behavior. A few years ago these were thought to rank among the most promising routes in the development of prediction models. They are still being researched, but as yet results have not given solid indications these measurements will be significant aids to prediction.)

"Parkfield looks like the best of all worlds," says Bakun. "We have time to get ready; it's not a crash program. It's in a convenient spot. We know a lot about it. It's not in an area where it will cause death and major destruction.

"Since we know about what happened in '66, we know exactly where to focus our efforts. We don't have to have instruments everywhere. We've been monitoring carefully since 1966 so we have a good idea of normal seismicity and activity. Now, we've got a very accurate, very fast system that will tell us instantly if the activity is starting to pick up in the critical area.

"We've looked very carefully at the information available, and we have a time estimate and a remarkably detailed estimate of what will happen. We've done everything in the world to make sure our equipment is right on top of things. We think we've done what can be done. We're ready."

The prediction implications of an on-schedule Parkfield earthquake are obvious; it will provide dramatic support for the hypothesis that earthquakes are repeating phenomena, plus mountains of data from which seismologists will attempt to extract, needle-in-the-haystack-like, geophysical clues that signaled the shock.

There is, of course, the negative side — the chance that Parkfield will come and go as expected and yet prove scientifically unrewarding because it turned out to be uniquely anomalous. Ellsworth admits this is possible. However, he feels the odds strongly favor the scientists.

"If you have a good geologic record, you can go back and see similar quakes in the same area — a strong suggestion that the process has some repeatability to it. Even over a relatively short time you can see repeatability. Southern California is a prime example. There's evidence of 10 major quakes about 150 years apart over the last 1,500 years. The last one was in 1857 so the next should come by the end of the century — we may even be overdue for it now.

"This average recurrence interval gives you some idea of how long it takes the earth in a certain area to store the strain of a major earthquake. If you know the time frame, you know where and when to watch for the subtle changes that indicate a major shock is imminent. These slight changes are the things we hope to start learning from Parkfield.

"The experiment there might not lead all the way to earthquake prediction, but it should tell us if it is possible." LE

*(Editor's Note: In late April, after this article was in the final stages of editing, a 6.2-magnitude earthquake occurred near San Jose, California, approximately 50 kilometers from Menlo Park and 75 from San Francisco, both of which reported significant ground shaking. The cupola of the San Francisco City Hall may have been slightly damaged.*

*The earthquake epicenter was in an area the USGS monitors monthly. "Very fortuitously, we had made geodesic measurements there just a week and a day before the earthquake," says Ellsworth. "They showed no changes. This might be disappointing at first glance but actually it's really confirmation of our conviction that the strain changes are very small."*

*Early analysis of the recent quake has reinforced the repeatability hypothesis. "We're fairly certain it is a recurrence of one in 1911," says Ellsworth. "There was also an earthquake in 1979 that seems to have been a repeat of one in 1897. So now we are beginning to define a repeat time for the Calaveras fault. Bill Bakun discussed the possibility of a repeat in a paper in 1980 so in a long-term sense he predicted this earthquake.*

*"The latest quake fits into what we think is the cycle of temblor behavior for this area. We interpret it to support the observation that strain is building back toward what it was at the time of the great San Francisco earthquake of 1906 but that a great quake in northern California is still several decades off.")*

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IN REPLY REFER TO:

10/3/84

To: J. Keaton, M. Wright, C. Taylor

From: Rus Wheeler

Subject: Enclosed draft of the report arising from a discussion group that we all attended, at the hazards meeting in Salt Lake City in mid-August

The discussion group was asked to treat the application of geological, geophysical, and engineering data to hazard evaluation and mitigation. Walt Arabasz moderated the discussion and I have prepared the enclosed report, with Walt's help. It must be received by Walt Hays, who organized the meeting, in Reston, Va., by 10/19. The report will be published in the proceedings volume of the meeting, which will appear as a USGS Open-File Report in the so-called "red book" series.

You three are the only ones who responded to Walt's request for any written communications to be included in the report. In each case, I have edited and condensed your communication as seemed appropriate, and attached it to the end of the report as Appendix 1, 2, or 3. Please let me know if I have done violence to your intent or meaning, omitted anything important, or included anything inappropriate.

Because I have about 2 weeks to get this report ready to transmit to Walt Hays, it is entering an abbreviated version of USGS internal review as I mail copies to you. Also, if you want me to make any changes in your contribution, please telephone me at 303-236-1592 (direct), 236-1629 (messages), or 477-1372 (home). I will interpret no response as either acquiesence or indifference.

I apologize for the hurried way I must handle this. I have been in the field, on leave, or otherwise unable to attend to this since the meeting in mid-August. Thanks very much for what you sent to Walt. As you probably realized, in such a diverse group no two people are likely to be able to properly represent all perspectives and needs.

Rus

# SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 1: SYNTHESIS OF GEOLOGICAL, GEOPHYSICAL, AND ENGINEERING DATA FOR EVALUATION OF EARTHQUAKE HAZARDS

Moderator: Walter J. Arabasz, University of Utah

Recorder: Russell L. Wheeler, U.S. Geological Survey

## FORWARD

(by W. J. Arabasz)

A primary charge given to this discussion group was to "identify achievable actions that can be taken within the next 2 years to foster an environment for implementation for loss reduction measures in Utah", from the viewpoint of a synthesis of geological, geophysical, and engineering data for evaluating earthquake hazards. For a number of reasons, the scope of discussion was much broader. In particular, the group included a large number of participants working on fundamental studies of earthquakes and fault behavior in the area of the Wasatch Front, and this was their first forum for open discussion within the framework of a new USGS Wasatch Front initiative. Given strong convictions about how much we do not know about earthquakes and fault behavior in the Wasatch Front area, there was a natural hesitancy to address only short-term, implementation-oriented programs and plans.

Recommendations reported here reflect, in part, the participants' many-sided scientific and engineering interests. Participants were invited to submit correspondence to form part of this report, and edited versions of three such submissions are appended. However the group recommendations listed in the summary below are more than a patchwork of individual interests. The recommendations represent first-order concerns of experts who are directly involved in earthquake problems in the area of the Wasatch Front.

## SUMMARY

(by R. L. Wheeler)

### INTRODUCTION

The discussion topic is broad, covering many disciplines, diverse activities, and a complex of challenging problems with varying susceptibilities to being solved. Accordingly, to lend coherence and brevity to this report, recommendations are divided according to whether they apply to the long or short term. For each of the two time scales, most discussion and recommendations are concentrated around one problem or goal. Because of the scope and diversity of the topic, some useful suggestions put forth during discussion are omitted here.

Short-term efforts cover fiscal years 1985 and 1986 (Oct. 1, 1984 to Sept. 30, 1986). Our general recommendation is that adequate priority be given during the next two years to filling gaps in the base of data and understanding that is needed for probabilistic risk assessment. The reason for that recommendation is that experience elsewhere demonstrates that the results of probabilistic risk assessment are likely to have considerable technical and societal impact, can provide a focus and guide for later work, and probably can be produced using data and understanding that are available now or can be obtained in the next two years. We recognize the need to produce implementation-oriented products in the short term; the focused work just recommended will increase our ability to produce such products.

Longer-term efforts should start now, but extend beyond FY 1986. Such efforts should aim at increasing understanding of earthquake occurrence and of the earthquake process. A useful and challenging focus for such work is anticipation of the most likely area for the next large earthquake in Utah.

Short- and long-term efforts are equally necessary, and it is important not to concentrate resources unduly on either to the detriment of the other. Short-term work can quickly provide a foundation for planning and preparedness; long-term work is necessary for refinement and specification of hazard estimates, and for eventual forecasting and prediction. The short-term work will allow some actions to be taken soon, but the longer-term work will eventually allow the most focused and therefore cost-effective mitigation of hazard and reduction of risk.

RECOMMENDATIONS

The following investigations are considered likely to produce the most effective results.

Short term (next 2 years)

1) Expanded geodetic studies: these include collection of new data and investigation and extension of existing data sets.

Coordination and development of a rapport with the National Geodetic Survey (NGS) would increase the usefulness of their results for our purposes. Two or three decades ago the Civil Engineering Department of the University of Utah, together with the NGS, established local geodetic networks in the area of Salt Lake City; the feasibility of reobserving these networks is worth investigating. Expected results of geodetic studies include characterization of present deformation on active faults, possible detection of preseismic deformation, and ability to model strain. Costs of such work would be comparatively low, returns should appear quickly, and results would guide other work.

2) Accelerated investigations of active faults:

a) Detailed investigations of the Quaternary record, to determine elapsed time since the last large earthquake, and to estimate the average interevent time for such earthquakes.

b) Shallow reflection and other geophysical work to determine subsurface fault geometries and properties, and to extend the results of work on the Quaternary record.

c) Evaluation of proposed segmentation of the Wasatch fault.

Longer term (but to start now)

3) Investigations of subsurface fault geometries throughout the seismogenic layer of the crust; activities can include drilling, designed reflection surveys, reprocessing of existing reflection data, and geological investigations of exposed

analogues.

4) Accelerated seismological research:

a) Stable support for seismograph networks and for the analysis and application of their data.

b) Proposal to IRIS/NSF for a large experiment to image the upper crust at the Wasatch fault. Some U.S.G.S. support could improve the proposal's chances of success.

5) Attention to the needs of investigators of ground failure (see appendix 1).

OPTIONS

The following are some of the other investigations that were suggested and questions that were asked by participants in the discussion group. See also the appendices.

1) Are the spatial and temporal distributions of small earthquakes guides to the occurrence of large earthquakes, as has usually been assumed? An answer to this question will involve, but not be restricted to, an evaluation of the hypothesis of characteristic earthquakes.

2) How much attention should be paid to faults other than the Wasatch that are capable of producing moderate but still damaging earthquakes?

3) Ground shaking, its spatial variability, and attenuation are poorly characterized along the Wasatch Front urban corridor. Design and evaluation of engineered structures requires better

characterization of those variables.

## APPENDIX 1:

## GROUND FAILURE

The draft of this appendix was prepared by a subgroup concerned with ground failure and methods for assessing its hazard.

PRIORITY

Most important and urgent is the development of a comprehensive model that synthesizes characteristics and hazards of the several kinds of ground failure. To assess hazard from specific kinds of ground failure, and to combine them into an overall assessment, requires consistent criteria, data formats, and map scales.

TASKS

1) Improve the methodology for the probabilistic assessment of ground failures such as liquefaction-induced failures and seismic slope failures.

2) Develop a basis for estimating the amount of displacement resulting from liquefaction-induced ground failure and from seismic slope failure.

3) Assess the implications of the unique characteristics of local soils for liquefaction potential and for ground failure.

4) Assess the hazard from tectonic subsidence (ground tilting) and from any resulting flooding at lake margins.

5) Assess the hazard from earthquake-induced snow avalanches.

6) Assist in developing realistic damage estimates based on studies of ground failure, especially for lifelines.

## APPENDIX 2:

## GEODETIC AND SUBSURFACE STUDIES

What follows is condensed from a memorandum sent to W. J. Arabasz by M. Wright of the University of Utah Research Institute.

GEODETIC STUDIES: Even with the enthusiasm shown at the meetings for precise surveying, the potential contribution of such work may be understated. With the work of Arabasz, that shows strike-slip components of motion on certain faults in central Utah that were previously believed to be normal faults, and with the confirmation of this seismological evidence through field geological studies by Anderson, the need for precise horizontal surveys to supplement the leveling surveys is evident. Documentation of the extent of east-west extension along with vertical motions could help us choose among various models of deformation in the Basin and Range province. Knowledge of north-south relative strains would be valuable in visualizing possible strike slip on the north-south faults that predominate in the area.

Precise surveying has the potential for measuring current strain rates in a relatively short time, and additional information might even be available before 1986. Certainly with vertical rates of 4 mm/yr, surveys could be repeated in 5 to 10 years with expectation of valuable information. The same would be true of horizontal surveys.

The surveying should not be restricted to merely releveling the Spanish Fork profile, as was implied at the meeting. We should consider spending on the order of $250,000 to establish precise horizontal and vertical networks for at least 5 carefully selected locations along the Wasatch Front. Networks should extend far enough east of the Wasatch fault itself to detect movement on the more seismically active faults. These networks would provide very valuable data in the years to come as they are resurveyed. There is no other way to obtain this kind of information.

SUBSURFACE STUDIES: An interdisciplinary group should be identified to help determine subsurface configuration and conditions, not only of faults, but of the rocks between major faults. Integrated interpretation of interdisciplinary data would be the strategy for this group. At least the following efforts can contribute to such an effort:

1) Structural studies. Geologic mapping and structural studies should be part of the funded effort. We actually know little about the subsurface structure of the area of interest. For example, the Wasatch fault itself is a complex structure not all of whose many strands have been identified either in the alluvial areas or in bedrock.

2) Microseismic studies. Detailed microseismic studies

have the potential of mapping active faults at depth in selected areas.

3) Reflection seismic studies.

4) Gravity studies. The start made by M. L. Zoback should be encouraged. We should upgrade the gravity data base.

5) Magnetic studies. Detailed aeromagnetic surveys can reveal pertinent details such as fault boundaries of magnetic bodies and subsurface configurations. Publically available data may not be of the quality needed. Flying detailed surveys over selected portions of the Wasatch Front would be comparatively inexpensive.

6) Electrical studies. The magneto-telluric (MT) method has great potential to contribute to knowledge of subsurface structure using modern modeling techniques. Dipole-dipole resistivity surveys would be needed to constrain interpretations of the MT data at shallow depths.

A workshop on subsurface studies should be convened to help define the state of knowledge and availability of data, and to recommend studies. This workshop should include representatives from industry, the USGS, the UGMS, and universities. Oil companies would have motivation to participate in and contribute to such a workshop, and perhaps to provide some funding support. The first day of such a workshop could concentrate on invited, half hour reviews of specific topics. A following half day could concentrate on defining potential contributions, in disciplinebased discussion groups, and on a concluding plenary session to integrate results.

## APPENDIX 9:
## NEEDS OF DAMAGE MODELING

What follows is condensed from a letter sent to W. J. Arabasz by C. Taylor of National Technical Systems.

I have reviewed briefly with our staff and others some potential needs in examining seismic risk problems in Utah. Some of our initial findings may be worth reflecting in the report of the discussion group.

First, we do not currently know how important the seismic ground failure issues are in the Utah environment. They may turn out to be the major risk issues. We shall be examining expected pipeline failures in various Wasatch Front environments. But, the full significance of the ground failure problem is unlikely to be known unless efforts are made also to assess ground failure potentials in canyon corridors. Based on studies of other lifeline networks, however, I expect the liquefaction problem to be far more severe for most Wasatch Front networks than the fault rupture problem.

Second, additional trenching studies and/or scientific knowledge of normal faulting behavior could be useful in resolving the issue of how to distribute larger magnitude earthquakes within the energy release zone. The standard Der Kuireghian and Ang model implies that fault rupture is more likely to occur in the middle of a segment than at its ends. Other models can be devised if this standard model is physically or historically inaccurate. Any model selected will have significant implications for site response values, as well as for how to interpret the trenching results at a given site in terms of magnitude return intervals.

Third, modeling of expected damage to lifelines and buildings relies on parameters whose values may be uncertain, and on strategies whose effects may vary. Reduction of uncertainty in values of some parameters and scientific exploration of views that greatly transform the total picture would consequently appears to be worthwhile program goals.

# GEOPHYSICAL METHODS FOR THE INVESTIGATION OF LANDSLIDES

V. A. BOGOSLOVSKY* AND A. A. OGILVY*

Landslides occur extensively in all countries of the world. A landslide is a complex geologic body composed of a combination of layers having contrasting and gradational physical properties. In assessing the danger of landslides, it is of prime importance to investigate the structure of the landslide slope and its water saturation as well as the properties and status of the soils comprising the slope. The investigation and full evaluation of all these problems by traditional methods of engineering geology are sometimes impossible.

Electrical and seismic methods are used to obtain the information needed to determine slope stability. Experience has been gained from long-term investigations carried out in various regions of the Soviet Union. Applications include evaluating geologic and hydrologic conditions related to the occurrence of landslides. Primary attention is devoted to the study of landslide slopes proper. The geologic structure of a landslide is considered in modeling it and determining the thickness of both the landslide body and the slip zone. The methods of self-potential, resistivity, and temperature measurement are analyzed for characterization of the seepage flow through the landslide body. Self-potential, resistivity, and temperature anomalies are associated with sites of increased landslide activity.

Useful engineering properties of soils may be obtained from field and laboratory geophysical measurements. Measurement of changes of geophysical parameters with time are significant in assessing changes in the states of landslide soils.

Observation of the direction and velocity of landslide movements is possible with magnetic and electrical methods.

Examples of geophysical investigations of landslides in the Crimea, on the Black Sea coast of the Caucasus, and in the Volga River Valley are presented.

## INTRODUCTION

The term "landslide" implies a sudden or gradual rupture of rocks and their movement downslope by the force of gravity. Landslides may occur in many settings: on the banks of rivers, lakes, reservoirs, and seas as well as on mountain slopes. They often affect extremely valuable areas of economic development and endanger engineering structures. Where they occur on the edges of quarries and on the slopes of open pit mines, landslides menace the exploitation of mineral deposits.

Landslide control is enormously expensive and labor-consuming and is not always effective. Sometimes the intensity of deformation even increases after control procedures are initiated.

A valid assessment of landslide hazard requires the solution of specific problems concerning the structure and composition of the slope as well as the status and properties (e.g., thickness and water content) of individual layers of rocks. Data on the groundwater regime should also be developed. Estimates of slope stability must be based on the results of these investigations, supplemented by data on the climatic and hydrologic conditions of the region, the economic activity of man, and the history of local landslides.

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areas, producing data with increased accuracy from a larger number of sample points than is possible by the use of geologic engineering techniques. As an additional advantage, the determination of the mechanical properties of the wet and dry soils is not made on single samples of limited volume, but is based on measurements of large volumes of rocks directly involved in the processes occurring in the slope under investigation. Thus, the parameters measured automatically reflect the combined geologic and hydrologic characteristics, which sometimes cannot be identified separately. Moreover, the potential value of regime[1] observations increases significantly because geophysical measurements can be repeated any number of times without disturbing the environment.

We shall delineate the major problems of the investigation of landslides by geophysical methods and deal with certain aspects of the data interpretation.

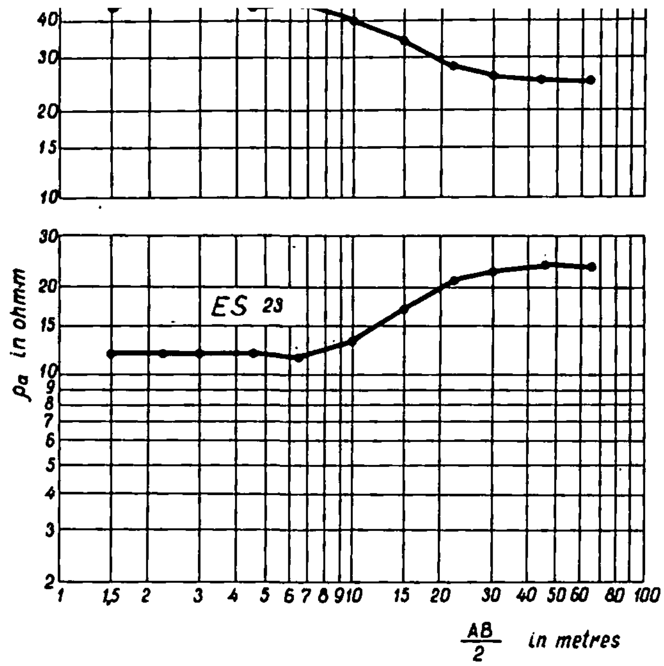


FIG. 1. Vertical electrical sounding curves measured at a landslide site on the southern coast of the Crimea.

## INVESTIGATION OF THE GEOLOGIC CONFIGURATION OF A LANDSLIDE

Landslides are characterized by a combination of layers oriented in different directions and having varying degrees of physical property contrasts and gradients.

The complexity of the geologic configuration of landslides makes it necessary to investigate them in detail. The rapid variation with distance of geoelectrical conditions in landslide slopes is illustrated by the comparison of the two electrical sounding curves obtained at measurement stations 100 m apart at a site on the southern coast of the Crimea (Figure 1). It is most probable that the landslide deposits at electrical sounding station ES 23 are heavily saturated with water which causes the relatively low apparent resistivities (about 12 Ω-m) seen on this curve at values of AB/2 less than 15. Naturally, under such conditions, a single sounding cannot provide very representative data. It is not an exaggeration to say that a sparse network of measurement stations on a landslide is sure to lead to failure of the investigation.

When it is not economically and technically feasible to establish a uniform grid of observation points, the landslide investigation should be conducted by use of a system of profiles. In such cases, it is recommended that three profiles be located along the axis of the landslide, i.e., approximately along its direction of flow. Then a number of profiles should be oriented across the landslide body. Both the longitudinal and transverse profiles should extend beyond the landslide boundary to make it possible to compare the measurement values obtained within the displaced landslide mass and those associated with the stable slope.

In addition to the use of a sufficient density of measurement stations, one should use techniques designed to cope with the specific problems expected. Frequently, the electrical sounding curves and refraction traveltime graphs turn out to be difficult to interpret because the interfaces to be detected are discontinuous and closely spaced, and the layers are thin, often with gradual or small changes in the rock properties. For instance, a slip zone in homogeneous soil may be so thin that it does not affect the geophysical measurements at the ground surface despite a strong contrast of physical properties within the zone.

An important phase of the interpretation of electrical soundings consists of simultaneous consideration of entire groups of curves, with the

[1] The term regime is used to include the boundaries and parameters of the system.

general shapes of the curves, minor flexures should be noted if they reoccur systematically in a particular group of curves, and are not caused by roughness of the terrain.

When interpreting electrical soundings, it is important to consider a gradient in the conductivity of an intermediate layer which, in the majority of cases, is representative of the slide zone. According to recent investigations (Zhigalin, 1973), the three-layer curves calculated for sections with an intermediate layer of continuously changing conductivity differ significantly from those plotted for models with constant resistivities. For flowing landslides characterized by a three-layer section of $H$-type ($\rho_1 > \rho_2 < \rho_3$) where the intermediate layer conductivity changes exponentially with depth, a formula has been obtained to calculate the apparent resistivity curves

$$\rho_a = \rho_1 \left[1 + 2 r^2 \int_0^\infty R \, J_1(m r) \, m \, d m\right],$$

where $R = \{[(2T)/(P - S) - 1]e^{2mh} - 1\}^{-1}$, $T, P, S$ are coefficients depending on the section parameters. The curves calculated from this formula make it possible to interpret the soundings more accurately than is possible with curves for simple beds. The divergence may amount to 20–100 percent, depending upon the value of the conductivity gradient and the intermediate layer thickness.

The interpretation of seismic recordings obtained in areas of considerable seismic wave attetudinal and transverse waves. The spread-shotpoint layout used in making seismic observations must always provide for obtaining direct and reverse traveltime curves.

Statistical methods of distinguishing useful signals from background noise are also very significant in interpreting data from both electrical and seismic surveys. In each case, it is necessary to apply filtering techniques in order to enhance signals useful for solving specific problems.

For example, in mapping landslide bodies it is frequently difficult to detect $\rho_a$ anomalies associated with the contact zone because of considerable noise associated with strong and nonuniform weathering of the slope rocks. Our experience indicates that in such cases it is most expedient to smooth the observed $\rho_a$ values with a filter of the form (1 + cosine), which effectively reduces the high-frequency noises and makes it possible to distinguish weak anomalies (cf., Ilyina, 1973).

There are numerous examples of successful applications of electrical and seismic prospecting methods to the investigation of the geologic configuration of landslide bodies. Some of these are presented in the following paragraphs.

*Examples*

The investigation of a landslide slope in the Volga River Valley, where $H$-type curves prevail

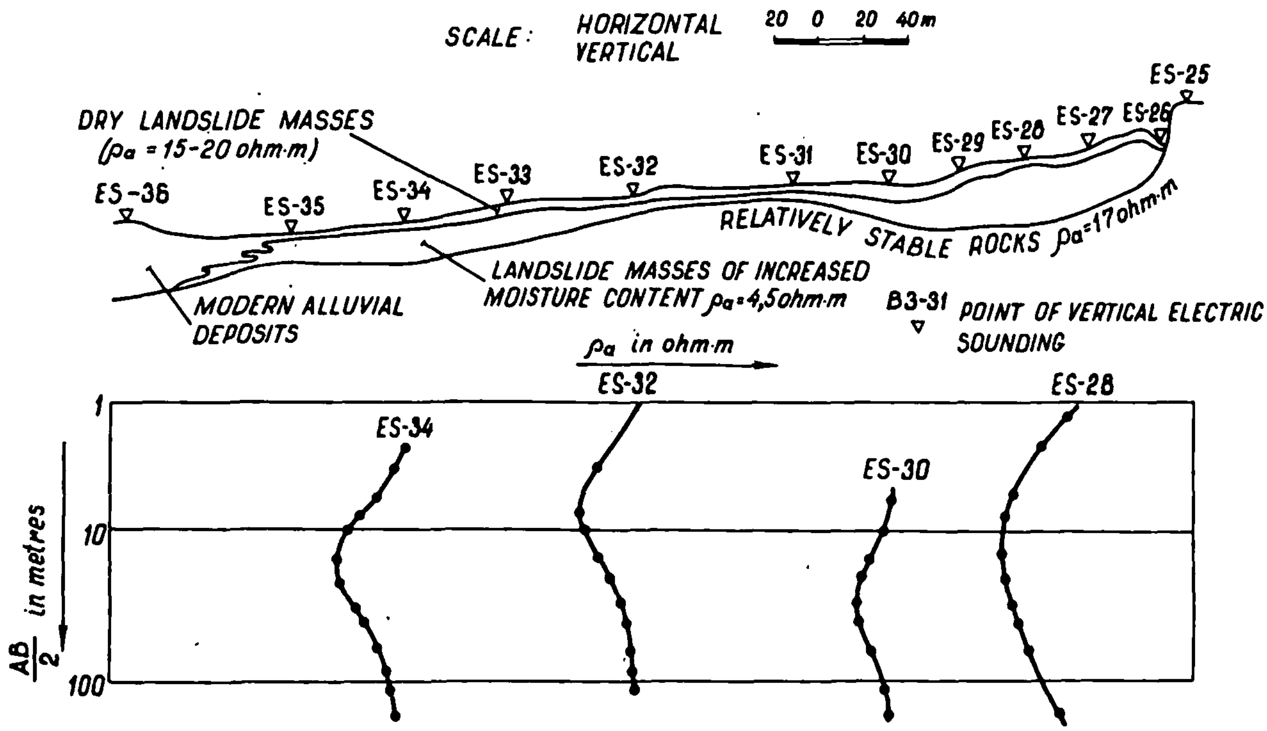


FIG. 2. Geoelectric section of a landslide slope in the Volga River Valley.

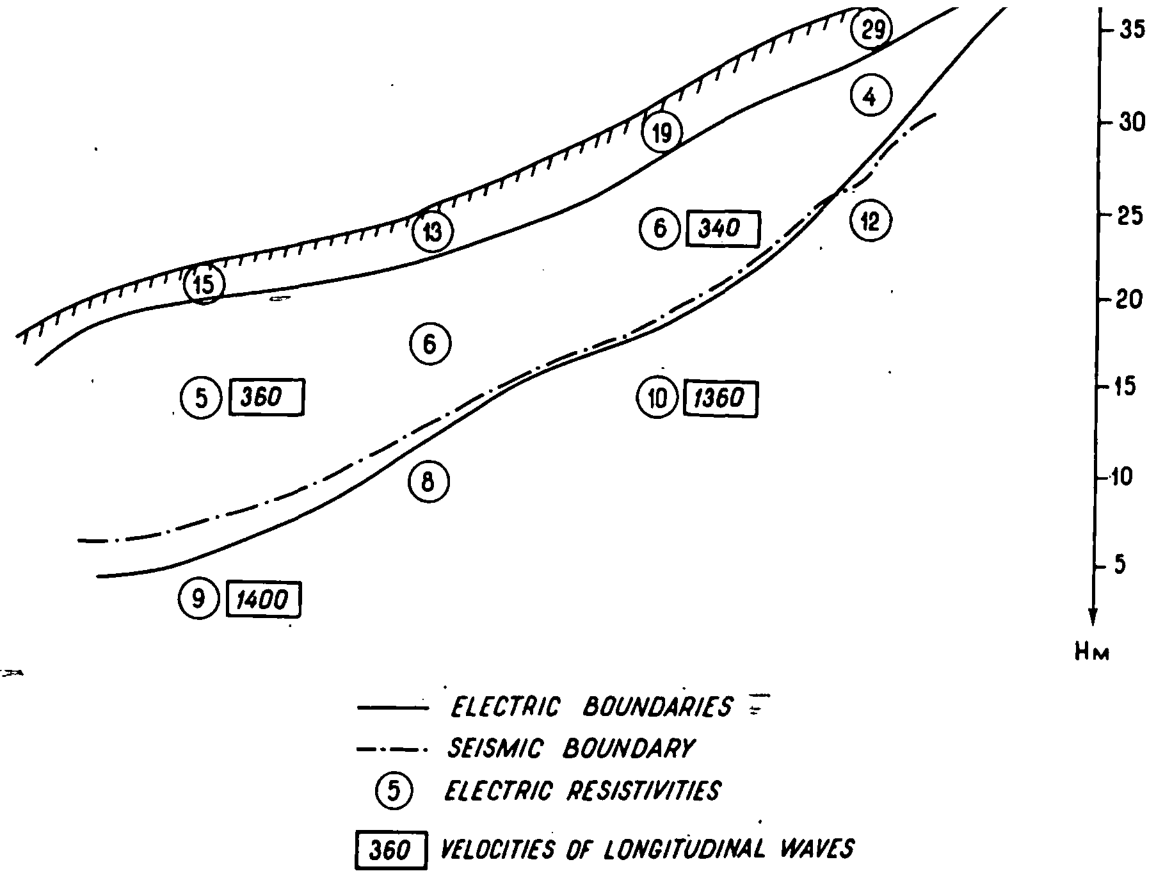


FIG. 3. The electric and seismic boundaries of a flowing landslide near the town of Sochi.

($\rho_1 > \rho_2 < \rho_3$), produced the cross-section shown in Figure 2. The upper layer, composed of comparatively dry landslide deposits, has a resistivity $\rho_1$ of the order of 20 Ω-m. The second layer, the main part of the landslide mass, is characterized by an increased moisture content (34–37 percent) and, consequently, by a reduced resistivity $\rho_2$ of 4–5 Ω-m. The third layer, consisting of clayey rocks undisturbed by landslide processes, has a moisture content of 25–28 percent and displays resistivities of the same order as the first layer. The layering interpretation shown in this cross-section was later confirmed by drilling.

Figure 3 shows the results of geophysical investigations carried out on one of the flowing landslides on the Black Sea coast of the Caucasus near the town of Sochi. The body of this landslide is composed of loamy rocks underlain by a weathered crust of argillites. Electrical surveys have distinguished the following three layers in the slope: the upper layer ($\rho_1$ = 13–29 Ω-m) corresponding to the landslide body, the middle layer ($\rho_2$ = 4–6 Ω-m) corresponding to the slip zone and coinciding with the most weathered part of the argillites, and the lower layer ($\rho_3$ = 9–12 Ω-m) corresponding to undisturbed argillites comprising the base of the landslide.

Seismic measurements identified a single boundary that divides the landslide slope into two distinct masses of rock. The upper one (with $V_1$ = 340–360 m/sec) comprises the landslide body and the slip zone, and the lower one (with $V_2$ = 1360–1400 m/sec) corresponds to the upper surface of the argillites. There is good agreement between the seismic boundary and lower electrical boundary in the upper portion of the slope, whereas near the landslide toe the seismic boundary is higher than the electrical one by 1.0–1.5 m. This may be explained by the considerable fracturing in the upper part of the nonweathered argillites which allows an increase in their moisture content; the abrupt increase in the velocity of longitudinal waves from 360 to 1400 m/sec occurs along the top of the fractured zone, but the increase of resistivity occurs only at its base. Thus, the discrepancy between the seismic and electrical landslide process.

If there is a need to study the geologic configuration of submarine extentions of landslides, this can be done by seismic methods. Some techniques which tentatively may be called "shore-to-sea" methods are also applicable. In this case, a sledge hammer is used to produce a seismic signal by striking a steel plate placed on the shore, and measurements are made by use of seismic receivers lowered to the sea bottom. This makes it possible to survey the offshore area out to a distance of several dozen meters, which is frequently sufficient for studying the landslide tongue protruding into the water; such tongues are rather characteristic of the landslides developed along sea shores. If these measurements are combined with the determination of electrical resistivities, then it is possible to get an impression of the composition and properties of the rocks in such protrusions. Electrical investigations carried out by us have shown that such measurements can be made most successfully by special arrays attached to a cable; these are analogous to logging probes used to investigate boreholes. Arrays of different dimensions are moved along the bottom when the cable is wound in by a winch. It should be borne in mind that geometric factor $K_S$ (in the $\rho_a$ formula) of an array placed on the bottom of the sea depends not only upon the array dimensions, but also upon its depth. For instance, the geometric factor of a three-electrode array $AMN$ submerged to a depth $h$ is determined from the following formula:

$$K_S = 4\pi r^2 \frac{r^2 + 4h^2}{2r^2 + 4h^2},$$

where $r$ is the array spacing; it is equal to $A0$ where 0 is the middle of the $MN$ interval. For $r/h \leq 7$ the factor for an array placed on the bottom is practically equal to that of the same array located on the water surface. For $r \ll h$, the resistivity value measured by the given array is $\rho_{a_S} \rightarrow \rho_0\rho_1/\rho_0 + \rho_1$, where $\rho_0$ is the resistivity of the water layer, and $\rho_1$ is the resistivity of the first layer of bottom deposits.

The location of submarine landslide protrusions can also be determined by conducting observations of submarine springs within the protrusion. These springs are detected by an increase in the electrical resistivity of sea water, anomalous water temperatures, and anomalous values of nat-

## INVESTIGATION OF GROUNDWATER AS A FACTOR IN LANDSLIDE FORMATION

Slope stability and, consequently, the entire landslide process is significantly affected by the groundwater contained in the landslide body. The level of groundwater determines the weight of the landslide body as well as the supporting hydrostatic pressure which, together with the hydrodynamic pressure of seepage flow, are factors which affect the landslide body stability. Therefore, a geophysicist is always confronted with the task of determining the level of groundwater and its fluctuation with time.

The presence of clay layers in the geologic section of the majority of landslides hampers the application of electrical prospecting for determining the depth of groundwater. However, the level of groundwater often can be accurately established from the change in seismic velocity associated with a change in saturation of soil or rock. The ratio of the longitudinal wave velocities in water-saturated and nonsaturated rocks depends upon the lithology, density, porosity, and depth of the rocks. Experience has shown that this ratio usually exceeds 1.4, which means that refracted waves propagate well along the groundwater surface. However, it is not a good refractor of shear waves since the velocity of transverse waves is only slightly dependent upon the degree of water saturation.

It should be noted that there is no distinct groundwater table in those areas where a landslide body is fully or partially composed of heavy clays. In such areas it is possible to speak of different degrees of wetting of the landslide soils.

Of great interest are observations of the fluctuation of the boundaries and parameters of the groundwater table because it affects slope stability. Seismic surveys made for this purpose should be systematically repeated along the same profiles, with absolutely identical arrays and measuring techniques. It is most significant to observe the fluctuations between periods of maximum and minimum precipitation. Sometimes one may succeed in detecting the change in the depth of groundwater after heavy rains. Comparison of contour maps of the groundwater table compiled at different times makes possible an assessment of the dynamics of groundwater table fluctuation

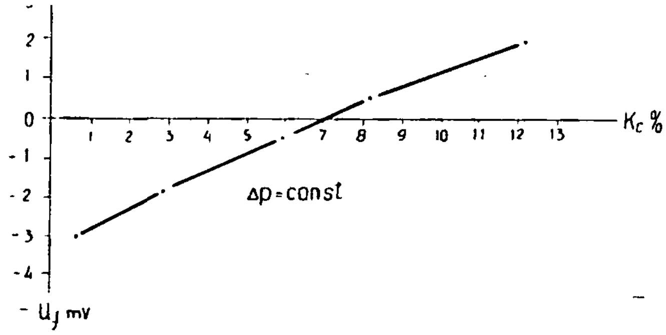


FIG. 4. Dependence of streaming potential $U_f$ on the clay content $K_c$ of a sandy medium. The data are from laboratory measurements by the authors. The pressure drop $\Delta p$ was held constant.

which is a function of groundwater supply and the area of recharge.

A landslide frequently acts as a large drainage basin, collecting groundwater from a well-defined and sometimes very large area. On the other hand, some parts of a landslide serve as barriers preventing water flow and causing waterlogging of some portions of this landslide.

*Use of self-potential and temperature measurements*

The application of the SP method (method of natural electrical potential measurements) to groundwater seepage investigations is based on the measurement of potentials induced by water flow through rock. Under natural conditions, the magnitude of these potentials may reach dozens of millivolts.

Maps showing contours of equal values of streaming potentials compiled for homogeneous soils often reflect the pattern of water table contours. These maps contain data on the spatial configuration of the seepage flow, its direction, and its intensity.

The distribution patterns and polarities of electrical potentials are influenced not only by hydrologic factors, but also by the lithology of the soil. For example, zones having high clay content are indicated by positive anomalies similar to those observed over areas of flowing water. Figure 4 contains a graph demonstrating the dependence of streaming potential $U_f$ on the clay content $K_c$ of a sandy medium. The data are from laboratory measurements obtained by the authors. For clay contents $K_c \geq 7$ percent and constant pressure drop, the streaming potential values are positive. Therefore, reliable interpretation of SP contour maps requires comparison of those maps with

tion was used extensively by the authors for studying landslides of the Black Sea coast of the Caucasus and the Crimea.

In certain cases, the locations of areas of groundwater discharge where landslide movement is imminent are indicated by a change in the intensity of the natural electric field. Under such conditions it is useful to measure the superficial potential density

$$\sigma_{uf} = \frac{\Delta U_f}{S_a}.$$

Here $\Delta U_f$ is the maximum increment of the potential within the detected positive anomaly; and $S_a$ is the area of the anomaly.

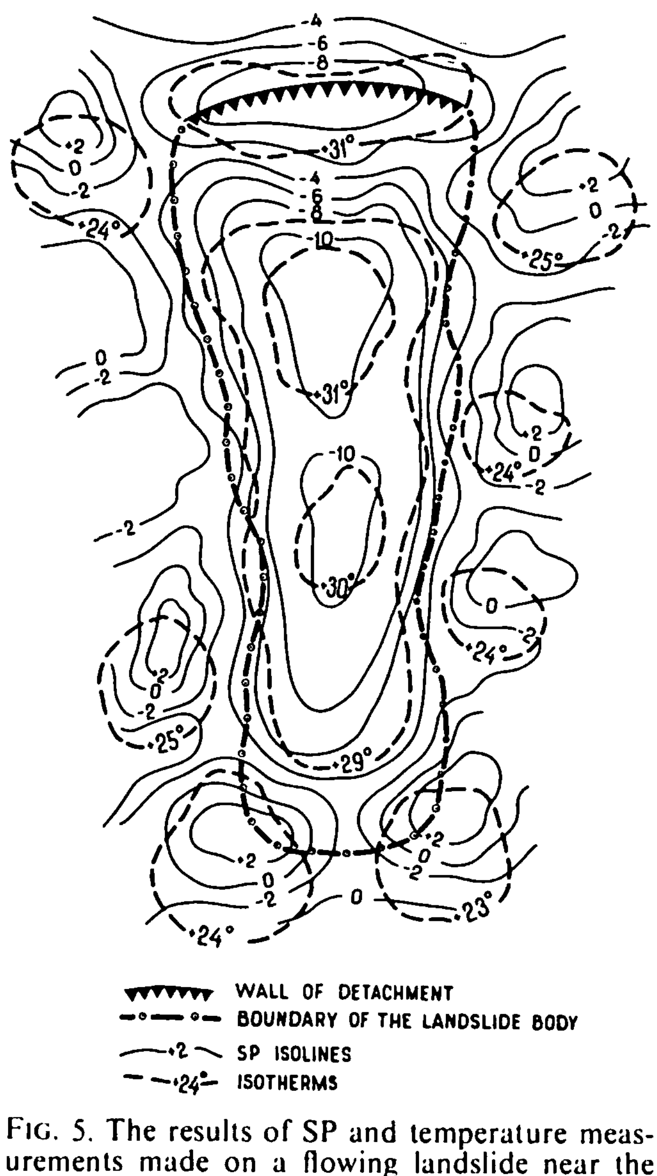


FIG. 5. The results of SP and temperature measurements made on a flowing landslide near the town of Adler. SP contours are marked in mV; temperature contours are labeled in °C.

rate of water inflow per unit of area. The area $S_a$ of the anomaly is indicative of the size of the region with excessive moisture content; therefore, the measurement of this parameter and its change with time may draw attention to sites on a slope where the rocks are becoming less consolidated. Thus, sets of detailed maps compiled at different times of the year reflect some concealed processes in the life of a landslide.

Data obtained from measurements of the thermal field effectively supplement data from SP measurements, since they also reflect the details of groundwater flow and the degree of water saturation of the landslide body. Temperature measurements are made by the use of an auger of special design with a thermistor on its tip. Temperatures are measured at a fixed depth below the zone of diurnal fluctuation. In the conditions of the Black Sea coast of the Caucasus, this zone extends down to a depth of 1.0–1.5 m.

*Examples.*—The effective use of both methods may be illustrated by the results of investigations carried out in 1972 on a small flowing landslide near the town of Adler (Figure 5). The position of the landslide body is indicated by distinct negative anomalies. The equipotential contours generally follow the landslide boundaries and the minimum gradients are in the direction of groundwater flow. The potential minima occur along the landslide axis and reflect the character of seepage flow which is controlled by the undulations of the underlying impermeable bed (or layer) and the change in water permeability of the landslide body. The negative anomaly at the head of the landslide is associated with water infiltration through the fractures located near the wall of detachment.

The landslide body is characterized also by increased temperatures reaching +31°C. These anomalies are associated with heating of the upper soil strata in those places where groundwater level is at a greater depth. At the sites of seepage outflow (in the peripheral parts of the landslide and near its toe) the temperature drops to +23°C.

*Resistivity measurements*

In addition to the use of the SP method, seepage flows in a landslide body can be investigated by the resistivity method. In homogeneous rocks, $\rho_a$ maps may also indicate the degree of water saturation. Figure 6 shows a resistivity map com-

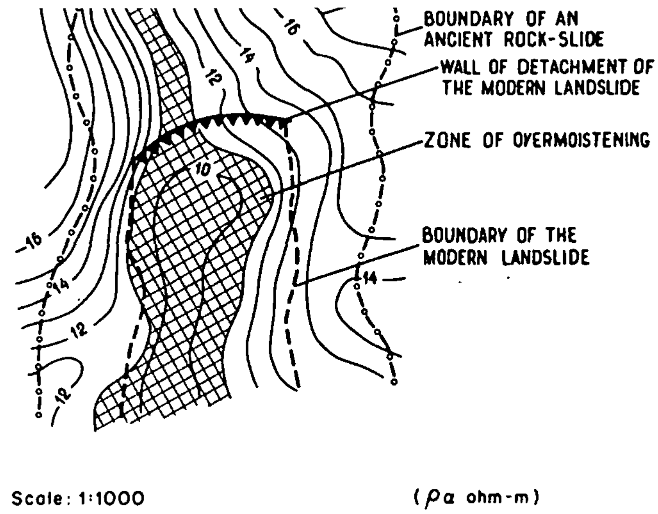


FIG 6. Resistivity contour map of a landslide near the town of Gagra.

piled from soundings run on a shallow landslide near the town of Gagra. The decreased resistivity values in the central part of this landslide correspond to the area of greatest water saturation of soils. The narrow zone of low resistivity in the northwestern part of the site indicates an underground canal bringing water to the central part of this landslide where the new wall of detachment has been formed.

## STUDY OF THE PHYSICAL PROPERTIES AND STATUS OF LANDSLIDE DEPOSITS AND THEIR CHANGE WITH TIME

Even though the use of geophysical methods for studying the properties of landslide soils is relatively new, it is already possible to draw some general conclusions regarding the results obtained.

The natural structure of rocks undergoes change primarily in the slip zone where the rocks are actually broken, their mineralogical composi-

**Table 1. Comparison of electrical resistivities of bedrocks and rocks in the landslide body. (Data from measurements made on the Black Sea coast of the Caucasus and the Crimea.)**

| | Electrical resistivity, Ω-m | |
|---|---|---|
| Rocks | Bedrock | Rock in landslide body |
| Argillites | 60–100 | 30–45 |
| Clayey sandstones | 30– 80 | 20–30 |
| Shales | 30– 80 | 10–20 |
| Clays | 6– 10 | 4– 6 |

result in a decrease in electrical resistivity. The resistivity of water samples taken in the slip zone may be 1.5 to 2 times lower than the average resistivity of groundwater in the site under investigation.

The most pronounced rise in electrical conductivity is exhibited by relatively high strength rock with rigid bonding such as argillite, shale, and clayey sandstone occurring in the slip zone. The rise in conductivity is considerably less in clay with high plasticity (Table 1). The properties of soils in the slip zone change more and more with every successive movement of the landslide, resulting in the development of a medium with gradients of physical properties within the slip zone, e.g., electrical and seismic parameters.

Sliding downslope also alters the mechanical properties of the rocks: the rocks are broken, their resistance to displacement decreases, and they become less stable. Various combinations of zones of compression and deformation develop, and these zones are characterized by corresponding variations in elastic properties.

Investigations near the town of Kafan (Armenia) carried out by Grigorian (personal communication) in 1970–1972 showed that surficial rocks of different lithologic types (ranging from light loam to clay) are characterized by a smaller range of variation of seismic parameters when they occur in landslides than when they occur in bedrock (Table 2). At the same time, a decrease in the velocities of both longitudinal and transverse waves is observed in the unstable part of the slope, and the $V_s/V_p$ ratio for the rocks composing the landslide body is higher than for the same rock types in the stable slope.

The difference in the seismic properties of landslide rocks and bedrocks is also seen in measurements of the effective coefficient of attenuation of seismic waves. This coefficient $\alpha$ is found from the following relation:

$$A(x) = A(0)e^{-\alpha x},$$

where $A(0)$ is the wave amplitude (near the source) and $A(x)$ is the wave amplitude at a distance $x$ from this source.

The effective coefficients of longitudinal $\bar{\alpha}_p$ and transverse $\alpha_s$ wave attenuation in landslide rocks are higher than in similar bedrock. For the rocks in these measurements, the greatest changes of elastic characteristics are observed in loams.

**Table 2. Seismic parameters of bedrock and rock in the landslide body using the hammer seismic method (after M. Grigorian). $f$ = 50–80 cps.**

| Type of rock | $V_p$, m/sec | | $V_s$, m/sec | | $\bar{\alpha}_p\left(\frac{1}{m}\right)$ | | $\bar{\alpha}_s\left(\frac{1}{m}\right)$ | | $V_s/V_p$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bedrock | Landslide rock | Bedrock | Landslide rock | Bedrock | Landslide rock | Bedrock | Landslide rock | Bedrock | Lan[illegible] r[illegible] |
| Light loam | 370–400 | 200–300 | 200–210 | 150–190 | 0.09–0.12 | 0.45–0.48 | 0.08–0.12 | 0.39–0.43 | 0.52–0.54 | 0.6[illegible] |
| Medium loam | 490–580 | 240–390 | 230–250 | 180–220 | 0.06–0.1 | 0.43–0.44 | 0.05–0.11 | 0.38–0.40 | 0.43–0.49 | 0.5[illegible] |
| Heavy loam | 620–780 | 420–650 | 240–260 | 190–230 | 0.04–0.08 | 0.44–0.45 | 0.05–0.07 | 0.40–0.42 | 0.39–0.40 | 0.4[illegible] |
| Loamy sand | 310–370 | 250–270 | 190–210 | 150–190 | 0.11–0.15 | 0.55–0.58 | 0.14–0.17 | 0.50–0.52 | 0.60–0.62 | 0.6[illegible] |
| Silty clay | 340–880 | 530–690 | 250–280 | 200–230 | 0.3 –0.31 | 0.33–0.34 | 0.12–0.16 | 0.30–0.32 | 0.30–0.32 | 0.3[illegible] |
| Clay with sand | 890–950 | 600–740 | 280–300 | 210–250 | 0.09–0.11 | 0.32–0.34 | 0.10–0.12 | 0.29–0.33 | 0.30–0.31 | 0.3[illegible] |
| Clay | 1600–1750 | 830–980 | 310–380 | 270–290 | 0.03–0.06 | 0.28–0.31 | 0.02–0.05 | 0.24–0.27 | 0.20–0.22 | 0.28[illegible] |

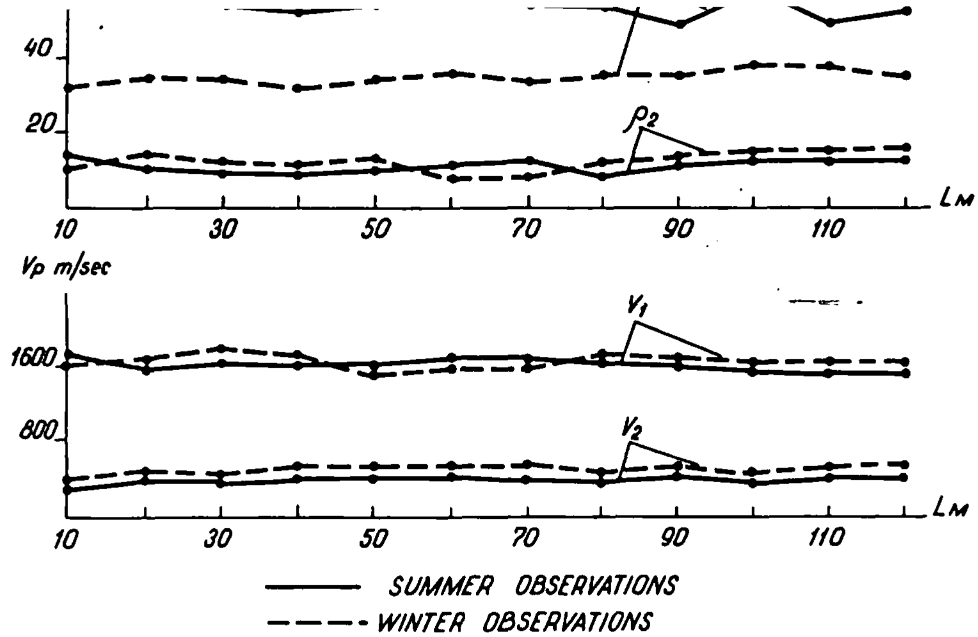


FIG. 7. Variation of $\rho_a$ and $V_p$ values obtained from regime observations made on a landslide near the town of Adler.

The variation of seismic properties within the landslide body and the conditions governing these variations are also of interest. Measurements of the velocities $V_p$ and $V_s$ give lower values at the head of a landslide, i.e., at higher elevations where the effects of linear deformation prevail, than in the landslide tongue. It is of interest to consider this finding in the light of the observation that the landslide toe occurs in the zone of compaction which accounts for the consolidation of soil in this area. (In addition, $\alpha_p$ and $\alpha_s$ decrease along the landslide axis in the downslope direction. At the lowest elevation of a landslide the values of these parameters may turn out to be even smaller than on the stable slopes.)

The variation of physical properties of soils with time is a phenomenon frequently encountered when geophysical methods are applied to landslide investigations. Time variability is most evident in the zone of aeration. Electrical resistivity, natural electric potential, elastic moduli, and other parameters are strongly affected by fluctuations of moisture content and temperature. This fact allows one to draw some conclusions concerning the causes of observed variations in the physical properties of soils in different seasons of the year.

To illustrate this point, the following example is presented with the data obtained from one of the landslides near the town of Adler. Winter and summer observations established that the resistivity values characterizing the landslide body ($\rho_1$) and the slip zone ($\rho_2$) do not change equally with time (Figure 7). The resistivity of the lower layer $\rho_2$ is practically the same in winter and summer, which indicates that the moisture content of rocks in the slip zone does not change. On the other hand, the resistivity $\rho_1$ of rocks in the upper stratum increases considerably in the summer because of the seasonal change in the moisture content of landslide soils. It is characteristic that the velocity of longitudinal waves in the landslide body ($V_1$) is practically the same in the winter and summer. Therefore, in this case, the resistivity method provides a more effective means of studying the moisture content variations of landslide deposits.

## INVESTIGATION OF THE LANDSLIDE MASS DISPLACEMENT PROCESS

Reliable data on soil displacements can be obtained from measurements of both the deviation of wells lined with special flexible casing and the displacement of casing in the observation wells. But these methods are technically complicated and expensive and provide a means of investigating only small displacements. However, in many cases, especially those involving the investigation of flowing landslides, one has to deal with comparatively large soil movements. In such instances, it is recommended that position markboreholes represent the simplest type of self-powered position marker.

Very strong magnets should be used. Otherwise, the anomaly produced on the surface will not exceed the background noise, even if the magnets are lowered to a depth of only 4–6 m. The authors' investigations have shown that it is most expedient to employ composite magnet dipoles consisting of 4–6 cylindrical magnets with a total length of no more than 0.5 m.

Position markers should be located far from iron structures, electric power transmission lines, and other sources of man-made magnetic fields. Magnetic observations should not be made in areas affected by electric railways and haulage systems.

Magnetic field observations are made in a radial or rectangular grid network with station spacings of 0.25–0.5 m. The observation points must be precisely located. The emplacement of magnetic markers should be preceded by a normal background magnetic field survey. In order to improve the accuracy of measurements, observations are made simultaneously with two magnetometers, one of which is located at a base station. As a result, an average measurement accuracy of 3–4$\gamma$ can be achieved.

The results of every repeated magnetic survey are represented graphically in the form of a magnetic intensity contour map whose maximum corresponds with the position of the projection of the position marker on the ground surface. Displacement of the marker can be determined by triangulation from immovable points on the slope. The appropriate time interval between successive surveys depends upon the landslide activity of a certain slope and may vary from 0.5 months to 12 months. Using the results of such surveys, one compiles maps of differential displacement $\Delta Z$ from which can be determined the horizontal displacement of position markers. When interpreting observational results one should consider both the vector displacement $L$ of the magnetic marker and the vector displacement $l$ of the position of the orifice of the well into which the marker was lowered. The ratio of these vectors $L/l$ is an index of the landslide body mobility. For block landslides this ratio can be used to distinguish the sites of maximum landslide displacements.

in a well. Then displacement can be observed from the change of the maximum values of the electric potential measured at the earth's surface.

## CONCLUSIONS

Application of geophysical methods to the investigation of landslide phenomena makes it possible to solve several problems, the most significant of which are: (1) determination of the geometry of landslides and their water saturation, (2) assessment of the physical properties and states of the rocks comprising the landslide, and (3) the study of the motion of the landslide mass.

The geophysical investigations which are carried out directly on landslides should include:

1) Combinations of self-potential, resistivity, seismic, temperature, and magnetometer surveys. Some special methods not mentioned in the text include borehole inclinometer measurements, and analysis of microseismic noises occurring in the soil strata of slopes.
2) Detailed measurements sufficient to reveal significant peculiarities of geometry, physical properties, and wetting of the slopes.
3) Systematic repetition (partial or complete) of regime observations at times of the year that are most meaningful in terms of water inflow and landslide activation.

It should be pointed out that the data of reconnaissance and detailed geophysical surveys can be employed directly in planning landslide control procedures. Geophysical measurements that are made to determine the effectiveness of artificial landslide control techniques constitute a specific and rather unique application of the methods of exploration geophysics. The authors plan to write a special paper on this subject.

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