Mem. Natl Inst. Polar Res., Spec. Issue, **56**, 1–4, 2002

A review of high-altitude drilling

Bruce Koci

Ice Coring and Drilling Services (ICDS), University of Wisconsin-Madison, 1225 West Dayton Street, Madison, WI 53706, U.S.A.

Abstract: In 1979, we began a program of retrieving ice cores from glaciers located at high elevations in low-latitude locations for use in past climate research. The high-resolution records of past climates obtained from these cores provide a unique link to past climates outside the Polar Regions.

Since 1986, coring has been successful at various locations in South America and across the Tibetan Plateau using a combination of electromechanical and thermal drills to reach depths of up to 309 m and working altitudes of up to 7200 m. The wide variety of environmental and ice conditions including 'brittle ice' has resulted in the development of a drilling system that can use a variety of power sources and drill ice that varies from −20°C to near 0°C. Because of the brittle ice phenomenon, we have experimented with ways to improve core quality in the brittle ice zone. We also developed shelters, core processing equipment, and shipping containers capable of returning ice core to the lab in a frozen state. Lessons leaned from these excursions are discussed.

1. Drill development

The current wisdom in 1976 was that a helicopter was the transport vehicle of choice because it was considered impossible to carry a drill across mountainous terrain, reassemble it, and drill a core. However, our first attempt to transport a standard electromechanical drilling system to the 5600 m Quelccaya Ice Cap in Peru ended in failure because the helicopter could not safely fly above 5500 m. The drill was a standard electromechanical drill having a heavy steel armored cable and required a heavy generator to power it. There was no choice but to postpone the project until a more portable drill could be developed.

In the period from 1980–1983, we established that it was possible to build a drill that could be assembled from parts having a maximum weight of about 30 kg and that solar panels would deliver power at a level of 25% greater than at sea level. We returned to the Quelccaya Ice Cap in 1983 with a newly designed 2-kW solar-array-powered electrothermal drill developed at the University of Minnesota, which featured a Kevlar electromechanical cable. Despite having to walk to the summit every day, we were able to drill two cores to bedrock, one to a depth of 163 m and the other to a depth of 154 m, at a rate of 14 m per day. The two continuous cores were melted and returned as water samples for analysis. They were the first deep ice cores ever obtained from the tropics.

2. Other drilling projects

Our next site was the Dunde Ice Cap in north central China at an altitude of 4636 m. Drilling during the monsoon season made the use of solar panels impossible. We chose using a two-cycle snowmobile engine to power a standard 5 kW alternator. Two-cycle engines have a high specific power making them ideal for high-altitude operation. We were able to provide the full 5 kW with an engine weighing 20 kg. However, the specific fuel consumption of this type of engine is high resulting in transportation of additional fuel (about twice that of a diesel). Three cores were drilled to bedrock at 145 m in ice that was -4 to -2°C. Hole closure at this depth was not a problem. We experimented with returning ice cores in a frozen state by using boxes designed by Insulated Shipping Containers and a eutectic mixture of propylene glycol and water designed to freeze at about -5°C. Two of the three cores were returned in a frozen state and one was melted and returned as water samples. The boxes were able to keep the cores frozen for several days without refrigeration. Each box holds six 4-in cores and is transportable by horse or yak.

In 1992 we journeyed deeper into Tibet in the Western Kunlun mountain range at an altitude of 6100 m. Our only addition was a 6-m geodesic dome, which permitted drilling at night despite cold temperatures. We used an electromechanical drill to get to 200 m, followed by a thermal drill supplied by Victor Zagarodnov to reach a final depth of 309 m. This thermal drill allowed us to inject a water-ethanol mixture to make up for material removed by coring. At this altitude, the single-cylinder Rotax engine was at its limit of power production for thermal drilling. Fuel consumption was nearly 3 *l* per m during the thermal drilling phase. The high fuel consumption was a result of running the engine at full throttle. Cores from this project were returned in a frozen state. They were transported across the Tarim Basin over a three-day period. This is one of the hottest places on earth.

In the following years we continued to drill other ice caps in Peru, Bolivia, and Tibet. Equipment did not change much but the altitude increased to a maximum of 7200 m. At this altitude we found it necessary to use a twin-cylinder Rotax engine that could deliver 45 Hp at sea level. This engine weighed 30 kg and was fully capable of delivering the full 5 kW at this altitude. Increased engine weight was offset by greatly reduced fuel consumption. The solar array was increased from the original 2 kW to 3.6 kW, which was more than adequate to provide thermal drilling power on Huascaran in Peru.

We have demonstrated over the past 17 years that it is possible to transport a drill to remote areas by animals and/or humans through difficult terrain. There has been little effort until recently to use light equipment other than the introduction of Kevlar electromechanical cables and solar panels to generate electricity. The important factor has been the ability to break the drill into smaller components with a weight of about 25 kg. It is also important to recognize that one or two pieces weighing up to 50 kg are ceptable.

3. Drill power systems

Solar power is certainly my preference for generating power. While internal combustion engines can provide power at night, they are not permitted in some national parks, which are often drilling locations, because of their noise and pollution. Improvements in solar power efficiency are reducing the volume and weight of panels required to produce adequate power. The introduction of thin films and flexible backing makes it possible to cover large areas with a relatively light roll of solar cells. The efficiency of amorphous solar cells is not as great as the polycrystalline or single-cell type but the absence of a glass front and heavy frame helps. The mean time between failure for solar panels is at least 10 times that of any internal combustion engine. Solar power requires more set up than an engine-driven generator so it is probably is not very useful if many holes are to be drilled to a depth of 50 m or less.

The choice of an engine to drive a generator is a matter of personal preference. The two-cycle engines are light and powerful with a single engine providing enough power to run a thermal drill at 5 kW. However, they are notoriously bad mannered and inefficient. Diesels have a low specific power suggesting two or more are required to power a thermal drill at 5 kW. They too are not easy to start under high-altitude cold conditions. Generally, we have found that it is necessary to bring at least one spare generator when using engine driven power plants. The addition of a turbocharger to either type of engine would improve their capabilities considerably but the likelihood of being able to use one in the near future is small. Without this addition, the efficiency of internal combustion engines will remain stagnant while that of the solar cells continues to increase.

4. Drill site structures

Geodesic domes have proven to be the shelter of choice because of their ability to resist high winds. Large tents have shredded at wind speeds exceeding 90 km/h. The metal frame may also act as a Farady cage when lightening is present.

5. Brittle ice

We have encountered brittle ice many times as the drill depth usually goes beyond the 100 m below the firn ice transition rule. One way to counteract the negative effect of drilling is to slow the penetration rate by using finer penetration shoes. This technique is limited by the production of fine chips which jam in the barrel or which can stick the drill. It is important to remove all the chips from around the core during drilling and this becomes more difficult as finer chips are produced. We know from observations of the drilling process in clear ice that the cutter geometry currently favored produces cracks in front of the cutters. The ice fails in tension with the current geometry and the cracks propagate several cm in front of the cutters. Square corners on the inside of the cutters causes an additional stress concentration further enhancing the crack propagation into the core. A prediction of the stress field in front of and at the corners of the cutters can be found in Guyen Minh Due *et al.* (1972), Miller and Cheatham (1971) and Li and Schmitt (1997). Further experiments and modeling should be done to investigate the effects of changing the cutting geometry. It should be noted that the transition to thermal drilling produced perfect core through the entire hole depth beyond where mechanical drilling caused fractures. The ice was still brittle and very fragile. It should also be noted that we have not used a thermal drill in ice colder than -10°C.

We have used thermal drills having a long and short heated area. Those with the heating elements in direct contact with the ice are the most efficient and potentially least damaging to the ice. Exposing the ice to heat for the shortest time reduces the thermal stresses imposed during the melting process. Since the outer ring of ice is heated, it is loaded in compression which can lead to fractures from the inside out. This requires removing melt water from behind the drilling head, something that can be accomplished by injecting a cooled antifreeze mixture behind the heating elements. Note however that injecting excessive cooled antifreeze slows drilling progress. This approach was used on the Barnes Ice Cap in the '70s and probably has been used by others.

6. Summary

In general, we have used a systems approach to designing equipment used for drilling, logging, and returning of continuous cores from surface to bedrock in remote high-altitude locations throughout the world. The drilling system and crew have evolved through several iterations while maintaining a 100% success rate. Each new project has provided a unique set of challenges requiring a variety of equipment and schemes to assure successful completion. Recent development of a light drilling system by Victor Zagarodnov at OSU has continued the record with drilling on Kilimanjaro in Africa and the Tibetan Plateau. I believe this type of development can be carried over to intermediate and deep coring projects.

References

Guyen Minh Due, N., Cholet, H. and Tricot, P. (1972): Stress concentration induced in elastic rock under a diamond bit tooth. 47th Annual Fall Meeting of the Society of Petroleum Engineers of AIME, SPE 39.

Li, Y. and Schmitt, D. (1997): Well-bore bottom stress concentration and induced core fractures. AAPG Bull., **81**, 1909–1925.

Miller, T. and Cheatham, J. (1971): Rock/bit-tooth interaction for conical bit teeth. 45th Annual Fall Meeting of the Society of Petroleum Engineers of AIME, SPE 3031.

(Received February 14, 2001; Revised manuscript accepted April 9, 2001)