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Image processing and interpretation of ground penetrating radar data

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27.1 Introduction

The application of ground penetrating radar (GPR) to archaeology has had mixed results. A recent editorial in *The Field Archaeologist* (TFA 16) suggested that GPR was discussed by two types of people: those who believe that GPR is the best thing since sliced bread, and those who believe that dragging pieces of sliced bread across a site gives equally useful results.

The use of radar to investigate structures beneath the ground surface has been known for around 80 years (Daniels 1988), but only with recent advances in computer technology and signal and image processing has the technique really become widespread. GPR is used in a variety of civil engineering applications – road and bridge surveys, for example – and can be used in conditions as variable as ice, fresh water, salt deposits, desert sand and rock formations. GPR has been used in archaeological applications in Japan (Imai *et al.* 1987) in York (Stove & Addyman 1989), Gloucester (Milligan & Atkin 1992) and at Sutton Hoo (Daniels 1988).

GPR has occasionally been discredited by overzealous interpretations, but it has produced good results in both archaeology and civil engineering. The technique is non-destructive and non-invasive and so can be used through the floor of a cellar to examine underlying layers, for example. The time spent on site can be kept very short. For road or bridge projects, the survey must be done during the few hours when the area can be closed to traffic. Data is then taken back to the office where it can be computer processed and interpreted while activity continues on the site.

This paper describes some recent archaeological projects undertaken by Geospace and the software used to process survey data.

27.2 Principles of GPR

The basic components of a GPR system are the radar unit, a power supply, and two antennas. The antennas may be mounted on a simple sled and drawn by hand or by a suitable vehicle. They may also be placed in a rubber boat for working through fresh water.

The basic principle in GPR is that a radar antenna transmits an electromagnetic pulse of radio frequency into the ground. When the pulse reaches a layer with different electrical properties, some of the energy will be reflected back while the rest is transmitted on. As transmitter and receiver are towed along the surface, images are built up showing the time elapsed between wave transmission and reflection.

The production of images is explored further by Fletcher and Spicer (1993), who describe a computer program to simulate GPR. Using this program, it is possible to visualise the returns produced by individual simple targets. As a learning tool, this is of great value as actual GPR images are not immediately interpretable to the untrained eye. Further work in using synthetic radar

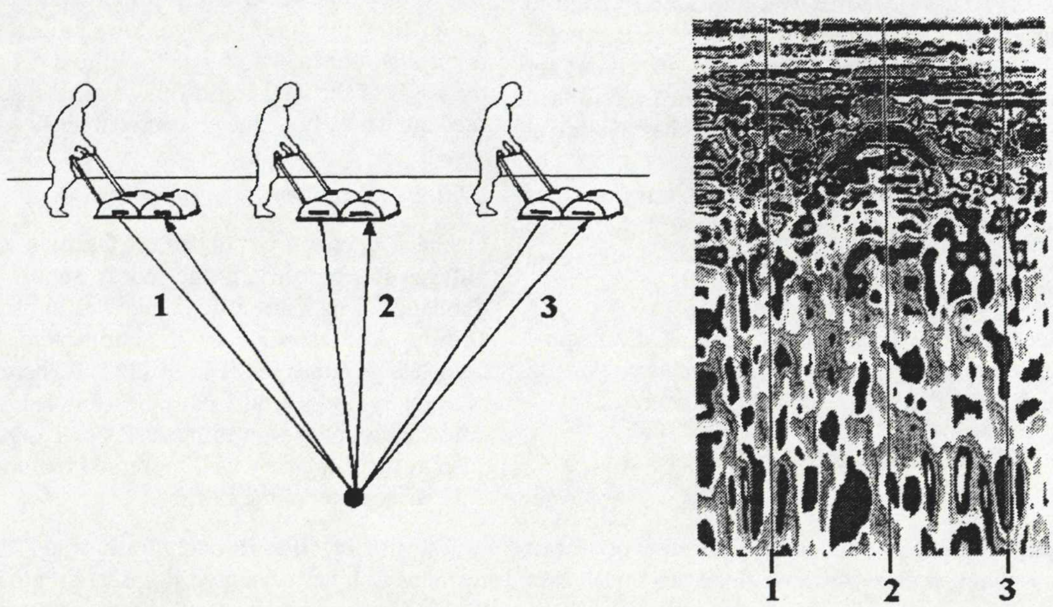

Figure 27.1: Point targets appear as hyperbolas on ground penetrating radar records.

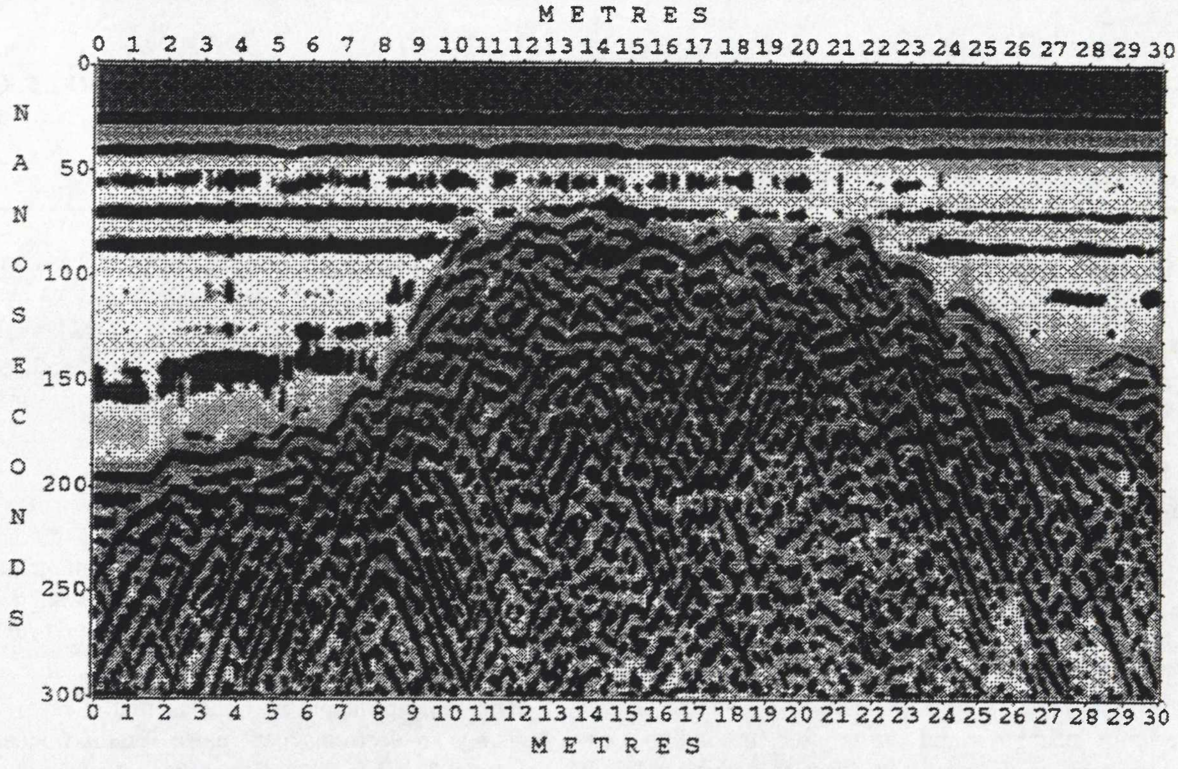

Figure 27.2: Ground penetrating radar record of Oakbank Crannog, Loch Tay.

images to aid interpretation is described in Goodman and Nishimura (1992).

An interface between soil and rock will show up clearly, and point targets or linear features such as pipes appear as hyperbolas. The hyperbola is created because the radar waves cannot just go directly vertically downwards through the ground in a narrow beam. The beam may be 90 degrees wide and so features are picked up when the antennas are directly overhead and before and after that point in the survey line. This is illustrated in Figure 27.1, where ray paths 1, 2 and 3 correspond to the positions marked on the radar trace. The vertical scale on the image is proportional to the two way travel time for the radar waves going from transmitter to receiver. When the antennas are directly above the target, the rays travel the shortest distance and this is shown as position 2. For positions 1 and 3 the distance, and therefore travel time, is longer. The return from the object appears further down the column of pixels representing that returned pulse and so creates the hyperbolic shape.

The equipment used by Geospace is a Georadar-I electromagnetic profiling system with antennas working at 175MHz or 600MHz and a TEAC data recorder.

27.3 Case studies

27.3.1 Soutra

Soutra, near Edinburgh, Scotland, is the site of a vast medieval hospital complex which originally extended over almost a square mile (Musty 1993). Currently, only one building is visible, and that is thought to have been built later from stones robbed from the ruins of the hospital. The remnants of walls and foundations of the many other buildings are completely invisible beneath farm land.

The prime objective of Dr Brian Moffat's excavation was to locate medical waste deposits, identify their constituents and determine their use. A variety of seeds of plants with medicinal properties have been recovered.

Geospace were called in to investigate two wells on the site, Trinity Well and Priory Well. The area of interest was at that time under a turnip field and in order to get a survey line, the antennas were towed along between lines of turnips. Radar waves penetrated to a depth of 12m and the walls of the well and layers of infill material could be seen quite clearly on the processed traces.

27.3.2 Loch Tay

Oakbank Crannog is situated off Oakbank Cottage in the village of Fearnan on the north shore of Loch Tay, Scotland. This man-made island was in use from the late Bronze Age through to the Iron Age, and is now completely submerged (Dixon 1981). There are few finds of pottery or metal, but the timbers used in the construction of the dwelling, and other organic materials such as seeds are very well preserved by immersion in the cold peaty water of the Loch.

The use of GPR through fresh water is an accepted technique. It has been used in research into river and lake systems to measure depth of water and to examine bottom sediments (Finnish Geotechnical Society 1992).

The survey took place in summer 1993. The radar antennas, together with data processing and recording units and power supply, were placed in a small Zodiac. In the time available, it was not possible to perform a complete survey, but a number of survey lines were followed. The site is subject to short, choppy waves, which troubled the preliminary excavation in 1978 and did not help in keeping a straight survey line. The survey was completed in less than 30 minutes on the water.

Figure 27.2 shows an example radar trace from a survey line over Oakbank Crannog. It is possible to pick out the interface between water and sediment quite clearly. It should be remembered that the image is a representation of returned radar signals and cannot be taken directly as an archaeological section drawing. However, the water forms a homogeneous medium and so the loch bed profile shown is its correct shape. Radar waves travel through water at 3.3cm/ns. The deepest water corresponds to a two way travel time of almost 200ns and so is $3.3 \times 200 / 2 = 330$cm or 3.3m deep. The water over the crannog is about 1m deep. The interface between the man made structure and the natural lake bed is less clear, but it is possible to pick out a number of small hyperbolas within the structure, which may be timbers or stones used in construction.

A side scan sonar survey of the site would show any targets protruding from the seabed, but would give no indication of buried material. A sub bottom profiler would be unlikely to detect the wooden piles of the crannog as the density of waterlogged wood is very similar to that of wet sand. It would also be difficult to operate such equipment in shallow water. The use of sonar is described further in Blake (1991) and McCann *et al.* (1988) compare seismic and GPR techniques.

As a preliminary trial, the exercise confirmed that ground penetrating radar can be used on archaeological sites submerged in fresh water. The results are promising, but it will be necessary to return to the Loch when the waters are calm so that the area can be resurveyed with accurate position fixing.

27.4 Image processing and interpretation

The Georadar system has a number of inbuilt signal processing features. These include integrated signal averaging and time varied gain (tvg) control. As a signal is attenuated with time, so tvg can be applied to compensate and ensure that the amplitude remains consistent across the image.

The data is recorded in analogue form on audio tape and as it is read into the computer it is digitised and formatted for processing. The signal received is converted into a column of pixels each with intensity between 0 and 255. When the image is displayed, the data pass through a look-up table (LUT) where intensity values are mapped to differing grey-scales or colours. The images presented here use a grey scale palette of 255 greys. There are a number of colour palettes available.

The images are first horizontally rectified to correct for variations in data collection speed. There are then a number of image processing techniques available to enhance the image. Images may be filtered or contrast stretched and they need to be converted from a time scale to depth. Most of the processes are standard techniques, more details of which may be found in textbooks such as Gonzales and Wood (1992).

Filtering is a general term for transforming image intensities in order to enhance or improve the quality of an image prior to interpretation. There is no general theory of image enhancement. The radar images are processed for visual interpretation which is a highly subjective process. The software is sufficiently flexible to allow the user to try different processes which may bring out different features in datasets.

The filters used with the radar data are background removal, low pass or smoothing filters and high pass or sharpening filters.

Background removal attempts to remove slowly varying background intensities by first approximating them, and then subtracting this approximation from the original image. This is done by taking a mean value for a section and subtracting an amount proportional to this from each value along this section. The smoothing filter achieves noise reduction and reduces spikes. A kernel size is specified by the user and for each point in the data the surrounding values within this kernel, including the point itself, are summed. The arithmetic mean replaces the data point. The high pass or sharpening filter highlights fine details and enhances detail that has been blurred during image acquisition. Each data point is replaced by an amount proportional to the difference between the point and the mean of its neighbours. Low contrast images can be improved by contrast stretching which increases the dynamic range of the grey levels in the image being processed.

Figure 27.2 showed a GPR image of a crannog where the vertical scale was a measurement of time in nanoseconds. For water, the radar wave velocity is known and depth could be calculated easily. Where the material properties are not known, a calibration procedure known as a WARR (Wide Angle Reflection and Refraction) is used.

Transmitting and receiving antennas start together, and are then moved apart, as shown in Figure 27.3. As distance between the antennas increases, the time taken by the signal to travel from transmitter to receiver increases. The additional delay, ΔT, or normal move-out for a receiver with offset X compared with one at offset zero is given by:

$$\Delta T = (To^2 + \frac{X^2}{V^2})^{\frac{1}{2}} - To$$

where V is velocity and To is the initial two way travel time.

The curves labelled (a) and (b) in Figure 27.3 show idealised normal moveout curves. When interfaces are

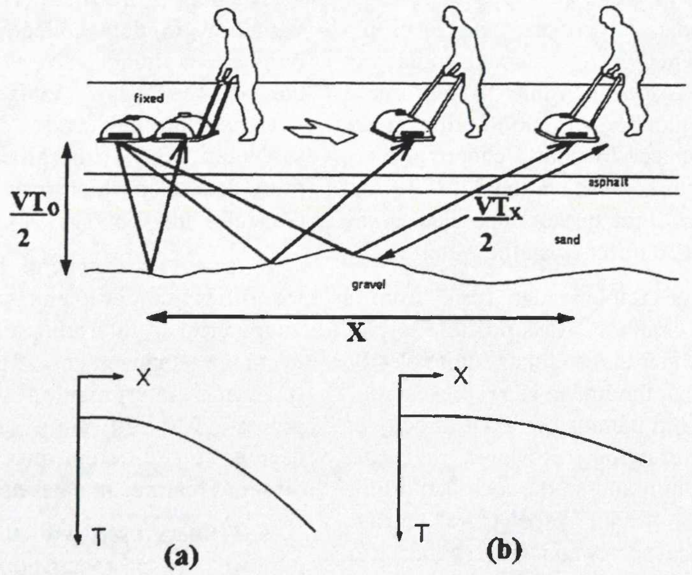

Figure 27.3: Wide Angle Reflection and Refraction.

deeper or velocity increases, the curve is flatter, so (a) represents a low velocity or shallow reflector and (b) a high velocity or deep reflector. For a real example, each interface between materials of differing electrical properties will generate such a curve. The software allows the user to pick out these curves on the WARR image, from which it can calculate the depth of each interface and interval velocity. These values are then applied to the image to convert the time scale to depth.

Figures 27.4, and 27.5 show the same example dataset. Figure 27.4 shows the raw data which has only been horizontally rectified. Figure 27.5a shows the data after processing. It has undergone smoothing, a high pass filter and conversion to depth scale by a WARR. Figure 27.5b shows the interpretation. The example shows a mineshaft in the centre of the image. With changing land usage, disused mineshafts are a continuing problem for developers. Records may have been lost, or plans may

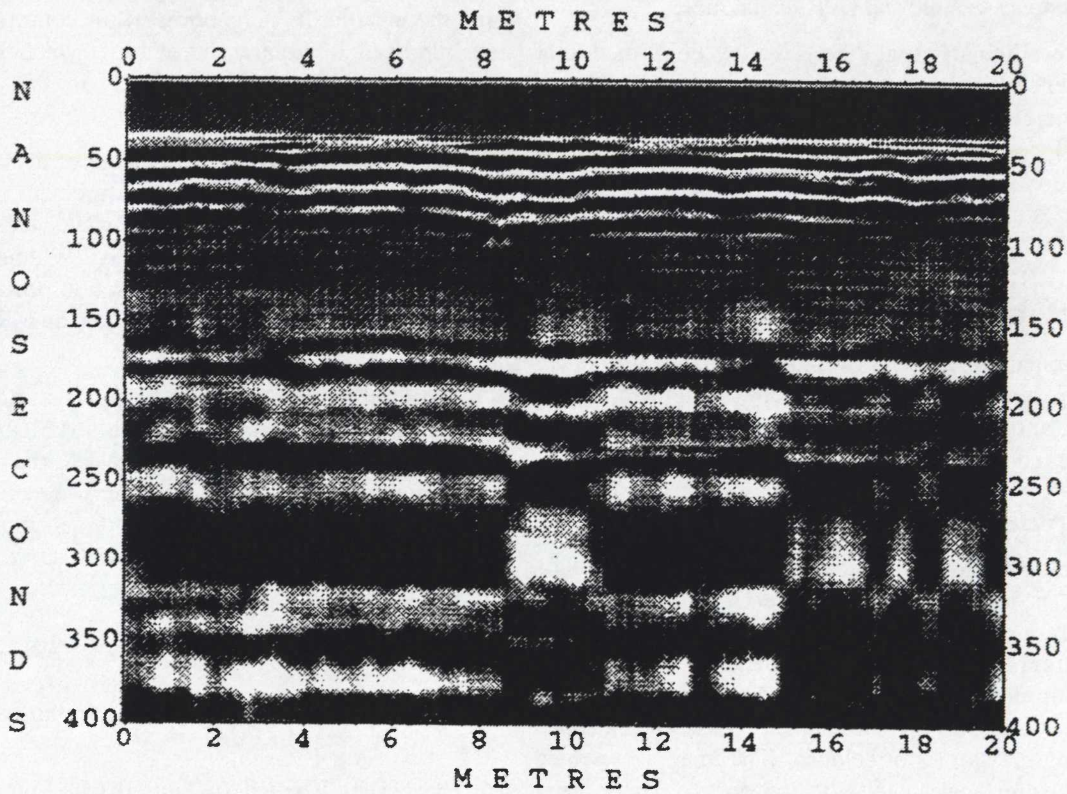

Figure 27.4: Raw data.

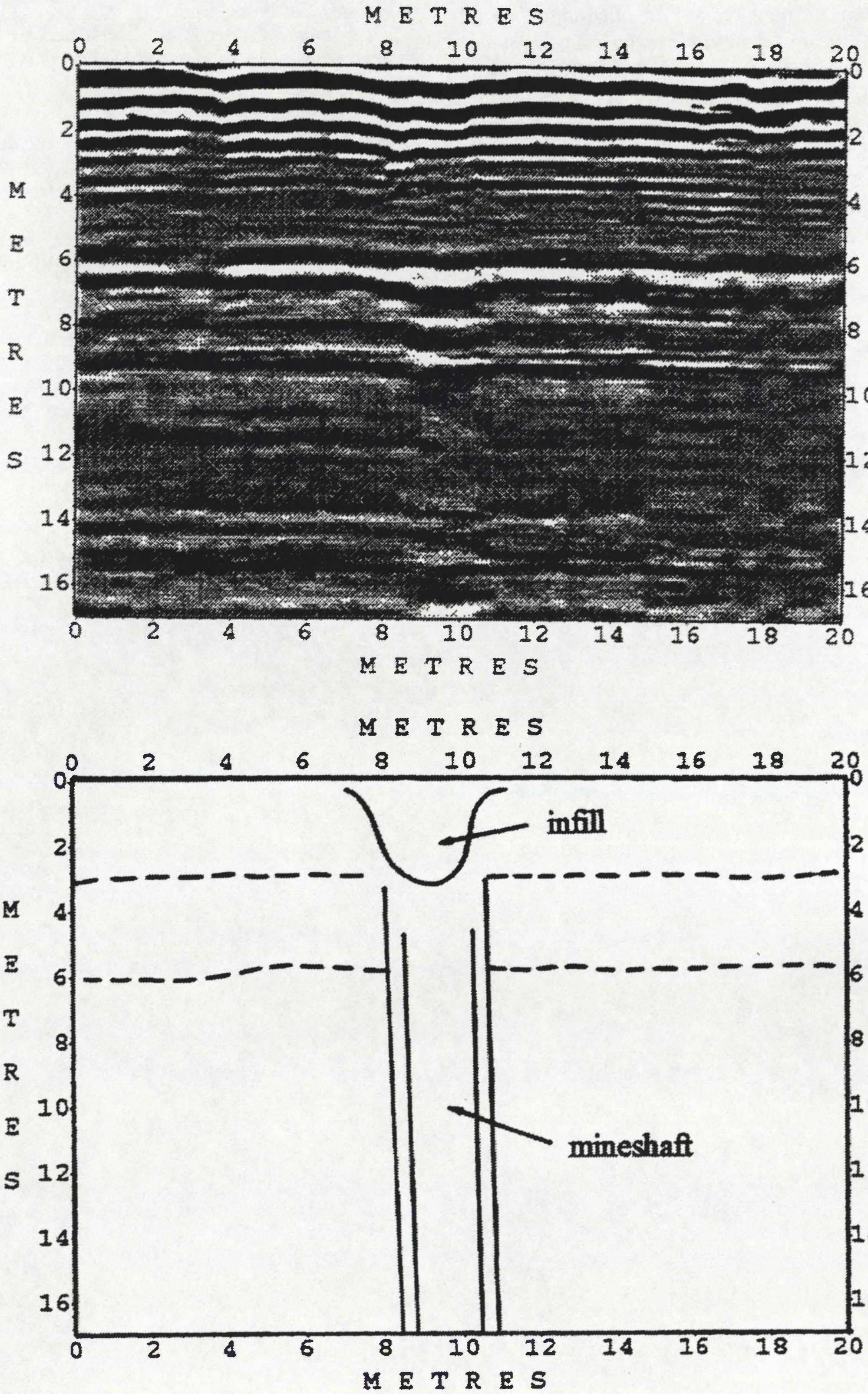

Figure 27.5: (a) Processed data, and (b) Interpretation

relate the mineshaft position to features which no longer exist. A mineshaft may have been partially filled with material which will show up on the radar trace as different to that surrounding it and dipping strata over the shaft can also be seen on the image.

27.5 Conclusion

Ground penetrating radar has been used successfully in archaeology, geology and civil engineering, and for the identification of grave sites, for murder enquiries or archaeology. The techniques have occasionally been discredited where results have not matched unrealistically high expectations or where overzealous interpretations have not agreed with the stratigraphy found by excavation. It must be remembered that the image is a representation of returned radar signals and is not a section drawing. The image processing techniques described here enhance the image greatly and bring out features which can then be interpreted, using experience and a knowledge of radar principles. An archaeologist cannot expect to hire a set of equipment for the afternoon and get detailed results on the spot, but used correctly, GPR is a valuable tool.

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