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On the feasibility of detecting potholes and limestone pinnacles in alluvial mining areas by gravity surveys

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Abstract: Bedrock topography buried under alluvium causes Bouger gravity anomalies. Anomalies over large potholes (radius greater than 20 metres) should be detectable by surface measurements but anomalies over limestone pinnacles will be too small (by up to an order of magnitude) to detect.

INTRODUCTION

To date geophysical methods have seldom been used in exploration for alluvial tin deposits within Malaysia because they do not directly indicate the presence of tin and because for shallow deposits Banka drilling provides a cheap source of information not only on the structure of the deposit but also directly of the tin grades. However as the shallow deposits are exhausted exploration will become more problematical and more expensive and geophysical surveys may well prove viable particularly for offshore or for deep deposits for which the drilling costs are liable to be very high. The geophysical methods which will probably prove most valuable in positioning boreholes and in correlating between holes in exploration for onshore alluvial deposits are seismic refraction and resistivity surveys, but as a quicker and cheaper method gravity surveys may provide valuable auxiliary information and in cases of extreme bedrock topography or at granite contacts gravity surveys themselves may prove sufficient in locating areas of probable deposits. Two particular possible applications of gravity surveys to alluvial tin exploration are investigated here: the detection of potholes which might hold rich tin concentrates (for example see Aw, 1981) and the detection of limestone pinnacles which might cause problems for dredging operations. Both structures represent local lateral density variations which effect the value of gravity measured at the surface while the ability of gravity surveys to locate the structures depends on the reduced measurements being sensitive enough to detect these variations.

GEOPHYSICAL MODELS AND EXPECTED ANOMALY AMPLITUDES

Geological bodies are usually irregular in shape and to compute their gravity fields analytically if their exact shape and position are known is quite a complex problem, but the amplitude and general form of the anomalies can be more easily calculated if the bodies are approximated by geometrically simple forms. As limestone is denser than alluvium a suitable geophysical model for a limestone pinnacle surrounded by alluvium is a vertical cylinder of excess mass, and similarly that for a pothole is a vertical cylinder of deficient mass (see figure 1). The gravity anomaly is positive over the pinnacle and negative over the pothole and in both cases the peak values occur over

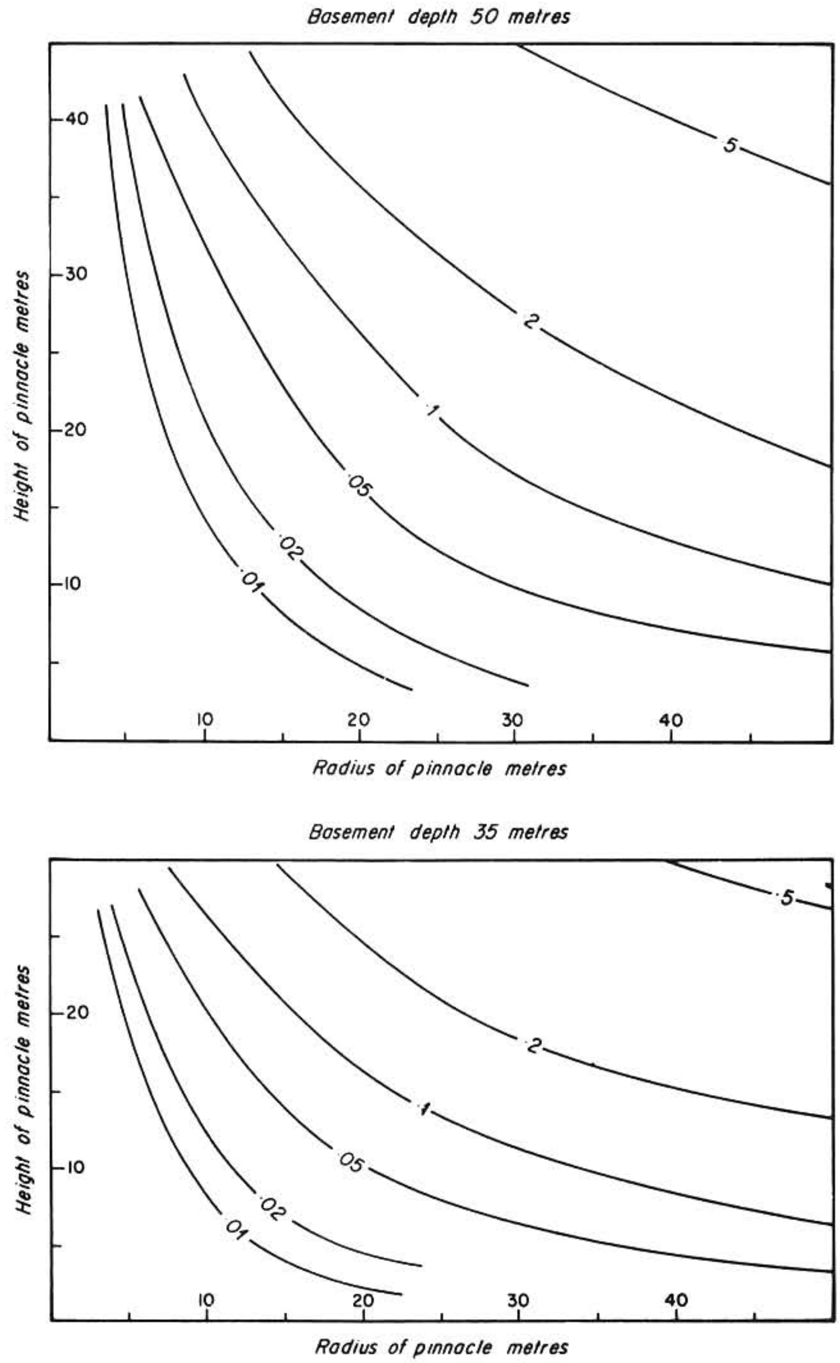

Fig. 1. Representation of gravity anomaly profiles over a pothole and a pinnacle modelled as vertical cylinders of anomalous density extending from the bedrock alluvium contact.

the axis of the features (see figure 1) and depend on the radius and length of the cylinder, the depth to its top and the density difference between the limestone and the alluvium. This relationship is expressed mathematically by the equation:

$$\text{anomaly amplitude} = 2\pi \text{ GP}[L + (Z^2 + R^2)^{\frac{1}{2}} - ((Z + L)^2 + R^2)^{\frac{1}{2}}]$$

(See Telford *et al.* 1976, p. 61–62)

where G is the gravitational constant
P is the density contrast
R is the radius of the cylinder
L is the length of the axis of the cylinder
Z is the depth to the top of the cylinder.

Anomaly values at points on the surface which are away from the axis are more difficult to compute but they decrease smoothly with distance from the axis equally in all directions, and from a map of the gravity anomaly it is possible to identify the source in terms of depth of burial and its vertical and horizontal dimensions although the solution to this inverse potential problem is not unique and a range of possible source bodies could be proposed.

In considering the problem merely of the detection of potholes and pinnacles it is the peak amplitude of the anomalies which is the most significant factor. The relationship expressed in the equation above has been contoured in a space of L/R and Z/R for values from 0.1 to 10 and the peak value of the gravity anomaly can be determined from this diagram by reading the contoured value at the relevant L/R and Z/R values and by multiplying by the density contrast in units of gm/cc and by the scale factor of the radius R in units of kms. As an example the value of the gravity anomaly over the pothole near Pusing described by Aw (1981) can be determined: an average value for the bedrock depth (Z) of c. 12 metres is reported with an average radius of the pothole (R) of c. 43 metres (giving a radius scale factor in kms of .043) and the depth of the pothole (L) in excess of 45 metres (it is unbottomed and I have arbitarily chosen a value of L = 50 metres). Plotting L/R and Z/R in figure 2 gives point 'A' with a contour value of c. 18. Alluvium densities vary with the degree of compaction and sorting as well as with the average density of the material of which it is composed and with the degree of water saturation but have typical values around 2.0 gm/cc while a reasonable estimate of the limestone density is 2.7 gm/cc, which gives a density contrast of 0.7 gm/cc. Multiplying 18 by 0.7 and by .043 gives a predicted peak anomaly value of .54 milligals. Over a pothole of only half the radius (point 'B' in figure 2) the contour value is roughly the same but the scale factor is decreased by a factor of 2 and the resultant anomaly amplitude is .27 milligals; a pothole the same size as that described by Aw (1981) but buried under 50 metres of alluvium (represented by point 'C' in figure 2) would have an amplitude of only .23 milligals. Similarly the amplitude of an anomaly over any pothole or pinnacle which can reasonably be considered as a buried vertical cylinder can be determined from this figure. Figures 3 and 4 display the peak anomaly values over pinnacles rising from particular bedrock depths. For a region with a mean bedrock depth similar to one of the values chosen for figures 3 and 4 these diagrams can be used to indicate the horizontal and vertical dimensions pinnacles would have to have in order to cause gravity anomalies of a specified amplitude.

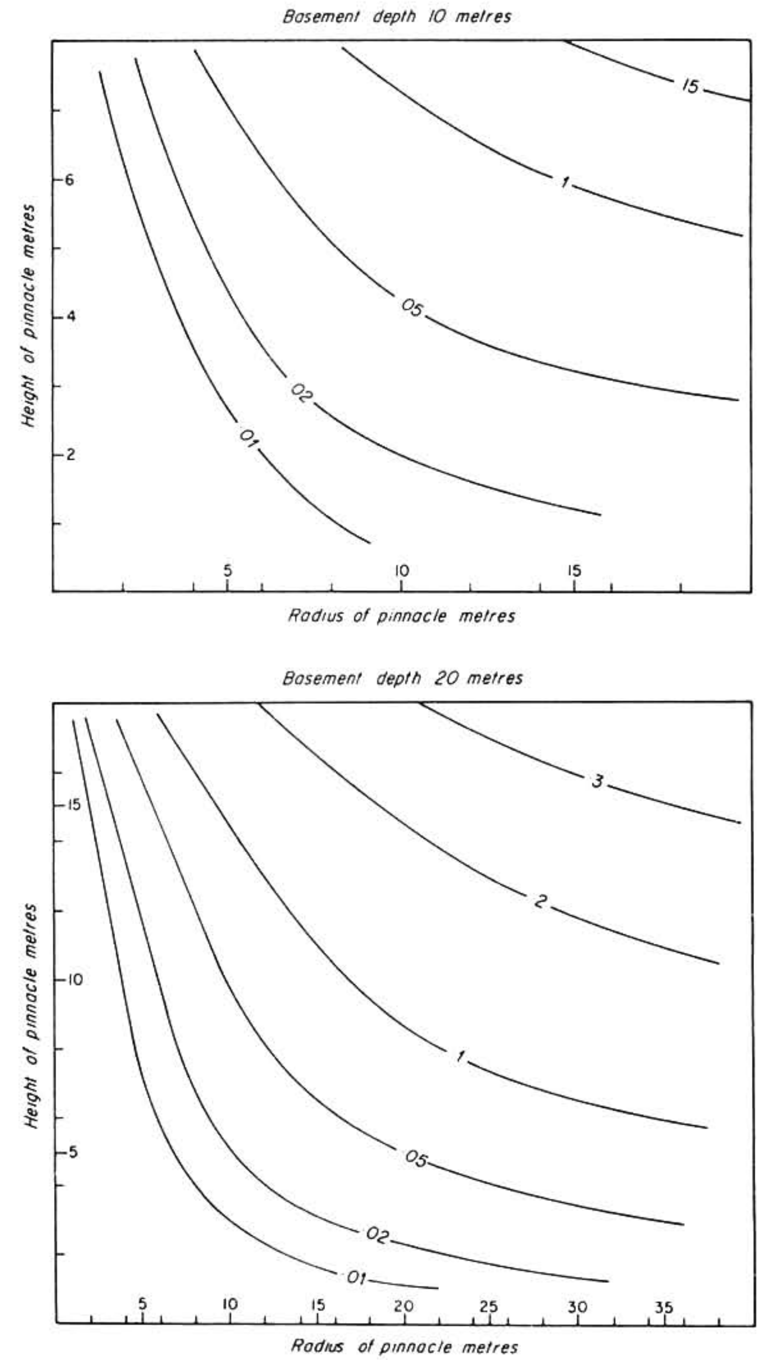

Fig. 2 Milligal contours of peak Bouger anomaly amplitudes over vertical cylinders. For explanation see text.

FEASIBILITY OF DETECTION OF ANOMALIES

Gravity meters used in exploration work have sensitivities of c. 0.01 milligals (for example the Worden Prospector) or as high as 0.001 milligals for temperature stabilised meters (for example the Lacoste-Ramberg) but these sensitivities do not represent the resolution limits for anomalies because there are problems of constraining various other causes of gravimetric variation. One such cause is the variable influence on the gravity field throughout the area of any steep nearby topography, but this will not be a major problem for exploration in the large alluvial plains except in immediate proximity to deep mining pools or tailings tips. The major source of imprecision in a small scale gravity survey in these areas will be the height

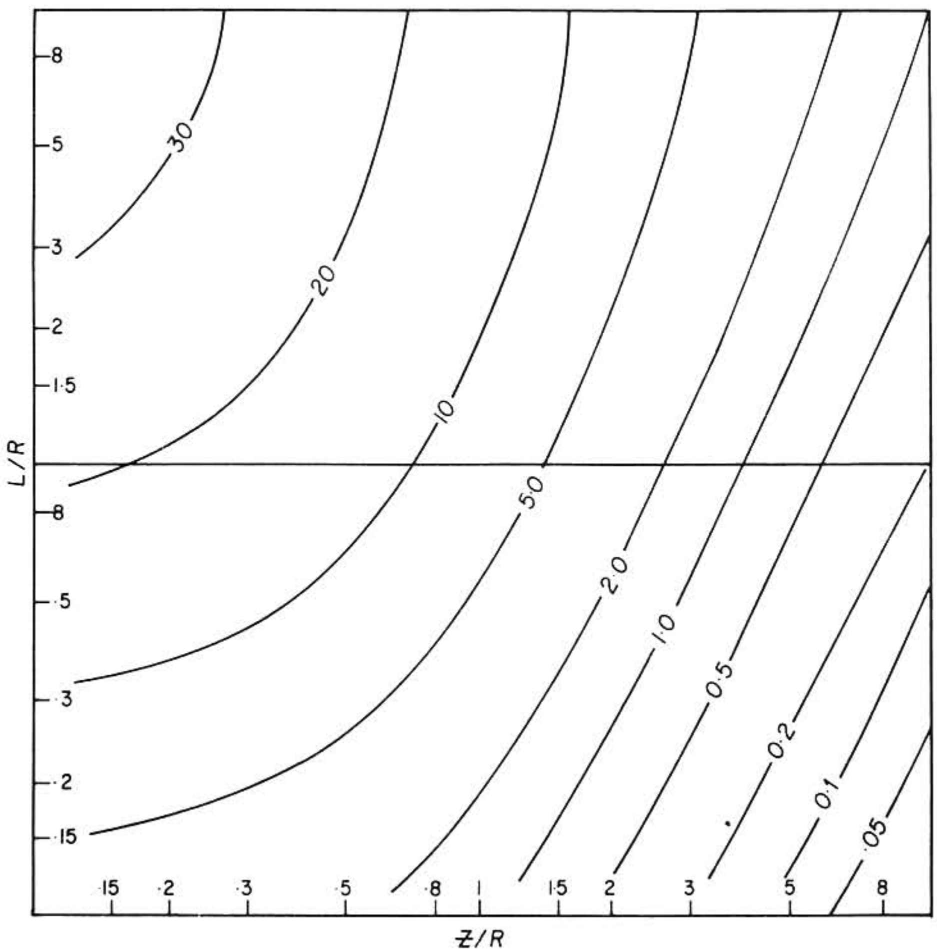

Fig. 3. Milligal contours of peak Bouger anomaly amplitudes over pinnacles rising from basement depths of 10 and 20 metres. A 0.7 gm cc density contrast is assumed, for different density contrasts the amplitude is changed proportionately.

control of the measurement points; an elevation error of 1 metre causes an error in the reduced gravity (Bouger) anomaly of just less than 0.2 milligals. For surveys of areas no larger than 100 square kilometres pressure sensitive altimeters can be used to rapidly determine relative heights to within 2 metres (repeat measurements at each point are necessary) but to detect the anomalies expected over bedrock irregularities in alluvial tin mines theodolite controlled elevation surveys are necessary which should have errors of less than 10 cms with associated Bouger gravity errors of less than .02 milligals. Although surveys with sensitivities of 0.01 milligals and less have been reported (Arzi, 1975) these are surveys of construction sites which are small and for which there are detailed surveys not only of the measurement locations but also of the surrounding terrain. Considering elevation errors, imprecise drift corrections and local density and terrain variation, a reasonable estimate of the sensitivity of a carefully conducted gravity survey over an alluvial tin mining prospect is between .05 and .1 milligals according to the instruments used and the care taken over the survey.

The minimum amplitude of anomalies which would be expected to be detected at a given degree of sensitivity depends on the spacing of the measurements as they will not generally be made exactly over the axis of buried features to record the peak amplitude. The areal extent of gravity anomalies depends on the size and shape of the source body and its depth of burial and, although there are no hard rules to link the detectability of anomalies to measurement spacings, anomalies over equidimensional bodies of

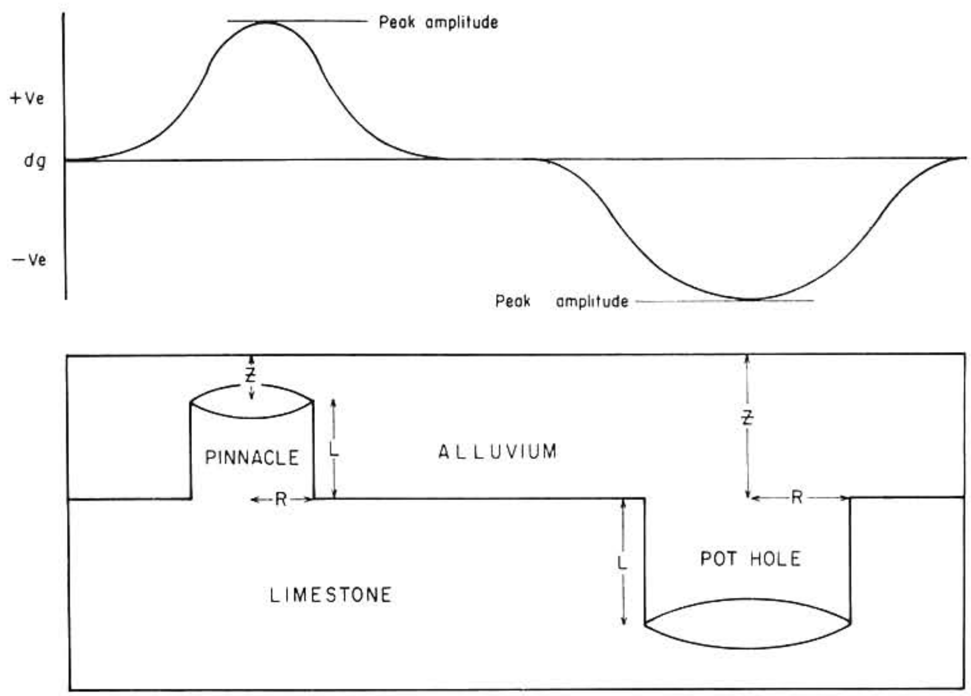

Fig. 4. Milligal contours of peak Bouger anomaly amplitudes over pinnacles rising from bedrock depths of 50 and 35 metres. A 0.7 gm cc density contrast is assumed.

shallow burial which have amplitudes greater than about three times the level of measurement error should be detected if the measurement spacings are no larger than the diameter of the body. Such a survey would not be sufficient to prove the existence of the anomalies and therefore of the source bodies but those measurements which suggest apparent anomalies can be checked with follow-up surveys of more closely spaced measurements. In flat featureless areas measurements are most easily made on a regular grid but this is not necessary and it is more important to keep measurement locations away from any sharp topographic features.

With an estimated sensitivity of between .05 and .1 milligals and a resulting expected detectability of anomalies greater than .15 to .3 milligals it can be predicted that the pothole described by Aw (1981) should have been detected by a gravity survey with measurement spacings as large as 80 metres but only surveys with the highest expected precision could be relied on to detect a similar sized pothole buried under 50 metres of alluvium, or a pothole buried at the same depth but of only half the size. Although the gravity method does seem to be applicable in exploration for these large potholes the horizontal and vertical dimensions of bodies to produce anomalies above .15 milligals as indicated by the position of that contour in figures 3 and 4 demonstrates that gravity exploration cannot be used to detect many pinnacles which are liable to be hazards to dredging operations since some significant pinnacles will have anomalies as much as an order of magnitude less than this detection level (for example from figure 4 a pinnacle of 6 metres height and 3 metres radius rising from a bedrock depth of 10 metres or from figure 5 a pinnacle of 10 metres height and 10 metres radius rising from a bedrock depth of 35 metres only have peak anomaly values of .015 milligals).

If a number of pinnacles are closely grouped (particularly in areas of deeper alluvium cover) their anomalies at surface will overlap and give rise to a broader and larger amplitude anomaly which will appear to be due to a general basement high with amplitude less than the heights of the individual unresolved pinnacles. It is because of such ambiguities in interpretation and because the gravity method in small scale surveys is sensitive only to the lateral changes in a generally layered structure that some control points are necessary on basement depth, either from drilling or from another geophysical method such as seismic refraction, before the ground structure can be interpreted from the results of the gravity survey.

CONCLUSIONS

The gravity method should be applicable in exploration for large buried potholes which have been shown to hold economic tin deposits but it does not have the resolution necessary to detect pinnacles which are significant at a much smaller size. These conclusions are based on estimates of detectability which are partially subjective and a far more reliable indication of the potential of the gravity method would be obtained by trial surveys preferably over structures proved by drilling.

Detection of potholes and pinnacles are only two possible applications of the gravity method in alluvial tin mining, two other obvious applications are the detection of buried granite contacts and buried major river channels which cut into bedrock. In both of these cases anomalies of larger amplitude from those over most pinnacles would be expected and furthermore detection limits would be improved because these are linear features and smaller fluctuations in the gravity values become significant if they can be traced from profile to profile.

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