Updating Probabilities for a Mineral Exploration Project

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Abstract

This paper describes a mineral exploration project conducted by a junior mining company within a probabilistic framework. In particular, it shows how beliefs about a project can be updated in response to a series of new pieces of information about the project associated with exploration activities using subjective probabilities. Several alternative frameworks are briefly mentioned as ways to improve on this simplified model.

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Bell Copper Inc. is a publicly-traded junior mining company that seeks to establish the existence of a large copper porphyry deposit in Arizona, USA. The company has conducted exploration activities at site for many years and established large body of evidence to support their thesis. This paper builds a probability model and shows how this model could be updated in response to new information as it became available. While the general theory of Bayesian updating for a probabilistic model of mineral exploration is relatively straightforward in theory, it can be quite tricky in practice.

The rigorous approach of establishing the appropriate prior distributions for key variables and then working through the sequence of exploration results to update these distributions based on geology is beyond the scope of this work. This article attempts to formalize the "exploration checklist" of things that could go wrong with Kabba exploration project and build a subjective probability model that moves the reader a few steps closer to understanding the key pieces of information regarding the potential for a meaningful geological discovery.

A landmark paper by Einstein & Baecher (1983) emphasizes the role of subjective probability, writing "Much of the uncertainty in geological exploration can only be expressed subjectively." (p.56) However, the paper focuses on questions in engineering geology where a great deal of information is already known and exploration is modelled as a stage in a decision tree. This unsatisfactory treatment of the problem facing exploration geologists by Einstein & Baecher leads me to describe a live example from the mining industry. Although there has surely been great progress in the literature since Einstein & Baecher, I believe there has also been a move towards a strict statistical empiricism that conflicts with the profound uncertainty in early-stage geological exploration and the need for expert opinion.

The paper proceeds a with blow-blow description of key geological facts established through exploration and a discussion of their significance for the exploration model of Kabba. These things are documented further in series of interviews with CEO of company, Dr. Tim Marsh here Bell, Peter (January 30, 2018).

Possible Approaches to a Probabilistic Model at Kabba

To begin, it is essential to determine what is in the model and what is outside of it. Since the Kabba project is at an early stage of exploration, many important facts about it are not known. However, it is still possible for a minerals exploration company to profit by simply establishing a broad understanding of the size and character of the deposit. This paper focuses on a probability model that matches the preliminary nature of the company's exploration activities, but briefly describes several other approaches.

In an effort to mimic the formal resource estimates that are critically important to the business of resource development by precisely describing a mineral deposit *in situ*, Model (i) in Table 1 below considers a pair of variables that are typically key for project valuation: size and

grade. While two projects with the same total size and average grade can be vastly different, these two data points are a starting point. Other variables can also be included, like "average depth" of the deposit. It's also possible to refine the model with smaller bin sizes for each variable, although the bin size should have some relationship to the modeler's ability to predict the deposit. A detailed understanding of the deposit is the purpose of a formal resource estimate and goes far beyond what Bell Copper is dealing with at the Kabba project, which is discovery.

In fact, it may be too much to guess at the average grade for a deposit at Kabba yet since the main mineralized body hasn't even been drilled yet! Model (ii) in Table 1 reflects this idea by simply modeling the size alone. It may well be possible for a geologist to give meaningful estimates for the size of the Kabba with corresponding probability values. However, that would require information beyond this paper and still wouldn't include important information about the economic potential of the potential discovery.

Model (iii) is a drastic departure from the other two by use of an imprecise definition of whether Kabba is "big enough" or not. The strength of approach is that "big enough" refers to something that has enough pounds of copper at sufficient grades that are not too deep so that a major copper mining company will be interested in developing Kabba immediately. The weakness of this approach is that it becomes much more difficult to pin down meaningful probability estimates for these outcomes.

Table 1: Possible Modeling Approaches

(i) "Size x Grade"	(ii) "Size"	(iii) "Big Enough"
Where *S* is defined as total size (million pounds copper equivalent) and *G* is defined as average copper grade (% Cu equivalent) at Kabba: $I_{i,j}\{^{1\ if\ S_i, G_j}_{0\ else}$ For all possible (*i, j*). Where possible sizes *S* are: $S_1: 0 < S < 250$ $S_2: 250 < S < 750$ $S_3: 750 < S$ And possible grades *G* are: $G_1: 0 < G < 0.5\%$ $G_2: 0.5\% < G < 1\%$ $G_3: 1\% < G$	Where *S* is defined as in (i): $I_1\{^{1\ if\ S_1}_{0\ else}$ For all possible (*i, j*). Where: $S_1: 0 < S < 250$ $S_2: 250 < S < 750$ $S_3: 750 < S$	Where *X* is defined as a deposit with sufficient size, grade, and depth to yield a project that will likely pass a major's hurdle rate at prevailing market conditions: $I\{^{1\ if\ X}_{0\ else}$

The goal for a minerals exploration company with a porphyry deposit like Kabba is typically to find something big enough to attract a partner, since these projects are typically very expensive to fully explore, develop, and mine. Although this imprecise term "big enough" will set the formalists on fire, it gives enough flexibility to be useful in this exercise. As always, it is possible to refine model to strike a different balance between precision and usefulness.

The Exploration Story at Kabba

This section describes a series of pieces of information or *Evidence* that have been established during exploration at Kabba so far. Since the company has been working on the project for many years already, it is possible to take the various pieces of evidence the company has already established for the project and offer a possible interpretation for the odds of a discovery after each piece of new information. Note that there is generally a reflexive relationship between what data the has company gathered so far and what questions they ask next, but this modelling approach will simply take the evidence for granted and not explore what should be done next.

Since the Model (iii) uses a single indicator variable, the relevant probability statement is whether Kabba is "big enough" or not. I start with 50-50 odds as the uniform prior distribution is always a good place to start.

$$Prob(X) = 0.50$$

There are many pieces of geological evidence known about Kabba, but I suppose that the first piece of evidence to consider is as follows.

Evidence #1: Large area of intense hydrothermal alteration in footwall at surface.

The intense hydrothermal activity seen in the footwall at Kabba reflects an intense volcanic system, but that only translates into a mineralized porphryry if the mineralizing fluids were trapped in the host rock because the volcano didn't erupt. The type and intensity of alteration seen in the footwall exposed at surface suggests that the volcano didn't erupt. For example, there are polymetallic veins seen at surface in the footwall that are typical of outer parts of mineralized porphryry. Also, it is very encouraging to see quartz magnetite veins as they correspond to copper-bearing chalcopyrite veins higher in the system.

In addition to the type of alteration seen in the footwall, the size of alteration zone is also encouraging. It's a little tricky to do any statistical comparison on the size of this footwall zone and associated pyrite shell with other known deposits because this part of the porphyry system is typically buried at great depths, maybe 2-3 kilometers below earth surface. To see it exposed at surface gives us a snapshot into part of the system that we wouldn't normally see, which makes it hard to find good comparables. Regardless, Bell Copper does see a very large pyrite shell in the footwall at Kabba – approximately 15 square kilometers – and can reasonably expect that to be associated with a very large copper shell.

Together, the combination of size and type of alteration provide strong indications that there is a large copper porphyry at Kabba. The interpretation of *Evidence #1* leads me to move the beliefs to 60-40 that it is "big enough".

$$Prob(X) = 0.60$$

It is somewhat arbitrary to move the beliefs to 60-40. This choice is made to reflect direction more than magnitude, in contrast with most probabilistic models that make great pains to get the magnitude of change correct in accordance with Bayes' theorem. There are difficult questions around how to properly interpret information in these models, whether concerning the objective aspects of the physical geology or the subjective aspects of the interpretation of the geology. As much as geology is a science, there is a great degree of subjectivity in exploration. Consider, for example, that Dr. Marsh refers to the exposed footwall as "Church" because it reaffirms his belief in the existence of a large mineralized porphyry at Kabba project.

Following *Evidence #1*, the question professional geologists often ask Dr. Marsh is whether upper part of porphyry just eroded away? Apparently, that would provide a much more simple explanation for the footwall exposure. This is relevant to our model because the size of the deposit could have been reduced by erosion. Part of the answer is seen in the first drill hole at Kabba, which provides the second piece of evidence.

Evidence #2: First drill hole K-1 shows stratigraphic inversion in the gravel pile.

A bit of geology is needed to understand this piece of evidence. A trough was created as the cupola or upper part of the porphyry as it moved to east and this trough was filled with eroded material from the exposed footwall after the movement. When Bell Copper drilled into the trough, the order of rocks in the gravel pile was the opposite order of what was sitting on top of footwall, however, it did not include any parts of the copper porphyry. This provides evidence to suggest no part of porphyry was left on top of footwall and subsequently eroded. Instead, the whole cupola moved down the slip fault together in one piece when it went.

If part of the porphyry had been eroded, then that would detract from confidence that the porphryry was "big enough". Refuting a question that would detract from your confidence in the idea implies greater confidence in the idea. Before that question was answered, it was a source of uncertainty to the answer, "is it big enough?" After it is refuted, it takes away a possible sequence of events that would lead to it not being big enough. It also reduces the set space of possible outcomes where it's not big enough. If your probability measures are weighting those spaces in some way, then refuting it must decrease the probability that it's not big enough and increase the probability that it's big enough.

The size of effect of resolving this question on the probabilities is subject to debate, but I suggest five points. That brings us to 65-35 odds that the deposit is big enough.

$$Prob(X) = 0.65$$

This first hole provides additional pieces of evidence that are relevant to our considerations.

A key part of the geological model for Kabba is that Basin and Range Extension created an opportunity for cupola to move eastward. Bell Copper drilled their first hole in place where they expected to see the cupola if it had slid at a 40-60 degree angle. They were surprised when the first hole hit the footwall rather than hangingwall, which suggested the body moved much further than expected. They were also surprised to see that the angle was much softer than expected, which was further supported by seismic reflection work that established the slip fault was less than 30-degrees.

Evidence #3: First drill hole K-1 shows a low-angle slip fault.

If the first hole had found the cupola moved much further than expected at a steep angle, then it would have ended up much deeper than a shallow angle and that would be reduce the probability of "big enough" significantly. If it was found at too great depth, then it could prove to be a fatal flaw for Kabba. However, that wasn't the case, so it eliminates the possibility of a really long, steep slip fault and corresponding catastrophic implications for the exploration thesis. We don't have to worry about that at this point as a possible fatal flaw, which increases the probability that it's big enough, although it is still possible that the cupola is still buried to great depth just by sliding along the low angle slip fault; that uncertainty will remain a key question until Bell Copper finds the thing!

Eliminating the possibility of great movement along a 60-degree angle is a good thing because it eliminates a big possible negative and correspondingly increases probability that it's big enough. I suppose it is now 70-30 odds.

$$Prob(X) = 0.70$$

Following the first hole, Bell Copper has drilled a series of holes around the edges of the system and established that it appears to be richly mineralized as seen in the footwall. They have seen typical zonation with the base metals in the outer edges of the system in holes that missed the heart of the system. The company has also completed some pretty sophisticated work on mineralogy, such as comparing the temperature gradient as seen in deep drill core versus the exposed footwall that shows a substantial heat source was in place at historically. All this provides very important evidence to suggest that the cupola is a well-mineralized system, which provides further encouragement that it will have sufficient grades to prove big enough.

Evidence #4: Encouraging mineralogy.

In addition to the mineralogy established around the cupola, the company has established that there is evidence of pathfinder elements in water wells located above where the cupola is believed to be located. Without holes in the porphyry, the grades are still uncertain, but

Evidence #4 provides important facts to suggest this thing is big enough. I increase the odds by another five points, which takes us up to 75-25.

$$Prob(X) = 0.75$$

There are certainly other pieces of evidence that have not been included in this discussion, but this discussion has hit several of the key points. These 4 pieces of evidence are very important for supporting the exploration thesis even though the 75% probability value that I have offered here is not based on rigorous geological understanding of the exploration results.

Discussion

In addition to the 4 significant pieces of geological evidence described in this paper, many drill holes were expected to hit the deposit but failed to do so. Although these holes are discouraging, they don't necessarily answer the question "is it big enough?" It may be arrogant to dismiss drill holes that missed by saying that they didn't disprove the geological thesis, but it may be the most fair statement. Many exploration geologists get accused of wearing rose-colored glasses and it's necessary to keep sense of curiosity in face of apparent failure.

What's more, all the prior misses at Kabba now put Bell Copper in a position where they have focused the target zone for the next rounds of exploration. They have confidently identified where the deposit isn't located, which helps increase the probability that one of these next holes will find it. The question of where to drill next is or whether the next hole will lead to discovery is an interesting problem but is much more sophisticated questions than I've been trying to grapple with here.

Even after Bell Copper gets their first holes into the Kabba porphyry, it will take several more years and millions of dollars to get a definitive determination of whether it is big enough or not. If one of the next holes hits and shows high-grades, then it might increase the odds by a further 5 or 10 percent but it will not settle the issue until it goes through the resource-definition exercise. Regardless, a junior can create value in the exploration stage of mining business just by getting in the ballpark for a large exploration project.

References

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