Improved variography using simulated annealing to adjust sample locations to align with diamondiferous linear beach structures

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Synopsis

At Namdeb, submerged beaches are earmarked for sampling and future mining and various sampling configurations are tested for optimality through the use of spatial simulations. For the creation of these virtual orebodies, basic statistics and variograms are needed, but in this specific instance no data exists from which the necessary parameters can be determined. The best that can be done is to use proxy data from onshore beaches, with adaptations where needed. The reworking of raised beaches during periods of rising and falling sea levels in some cases destroyed the internal beach structures, and it is very difficult to determine the variograms.

A method is proposed whereby simulated annealing is used to adjust the sample locations to align the data pertaining to beach crests or cliff lines, thus improving the variogram structure along the shoreline in the direction of the highest geological continuity.

Keywords
submerged beaches, simulated annealing, variography.

Introduction and geological framework

The diamondiferous linear beach deposits of Namibia's Sperrgebiet (Figure 1) form part of the world's greatest marine diamond-bearing deposit.

The onshore beach components, which are now mostly mined out, extend northwards along the coastline from the Orange River mouth for about 100 km. Six raised beaches, from 30 m above present sea level, are developed at different elevations and extend to the current day sea-level. Strong geological continuity governed by sea-level stands in a coast-parallel direction is evident for all six beaches. Continuity in the direction normal to the coast line is not so strong. The geological delineation of the six raised beaches is based on 1 m trenches comprising 1×5 m sample paddocks and mega-trenches comprising 10×50 m sample paddocks (See Figure 2).

Through a process of beach accretion (overburden sand resulting from the mining process used to extend the beach seawards) the linear beach deposits are currently mined to 25 m below sea level. With the onshore *in situ* deposits largely depleted, new resources below sea level are targeted for exploration, and a sample optimization study is required.

Since there is very little sample data available for the submerged beaches, the onshore data is the only information available that can be used as analogue data with which to design optimized sampling programmes to be applied in the exploration of the submerged beaches. This is deemed acceptable based on the results obtained from the -25 m mining results and geological understanding of the depositional environment. Over time, as sample information from the submerged beaches becomes available, the sampling programmes will be reviewed.

Data

Traditional trench sampling campaigns used to delineate raised beach deposits are not feasible in a submerged beach environment. Current mining at depths of 25 m below sea level has, however, yielded enough evidence to show that data collected from onshore beach sampling campaigns can be used as proxy information (with some modifications) in the sample optimization studies.

Data from the 1 m wide trenches provides information regarding the nature and elevation of the footwall, diamond content, and gravel occurrence on a 1×5 m scale. Cliff lines (which are not always visible due to sand cover) and internal beach morphology are governed by sea-level stands. The cliff lines are not equally well developed for all sealevel stands and internal beach structures are sometimes destroyed during multiple cycles of sea-level transgression and regression.

Based on the simultaneous interpretation of a series of adjacent trenches, the six beaches were delineated and split into geological zones, each with its own statistical characteristics which are analysed separately.

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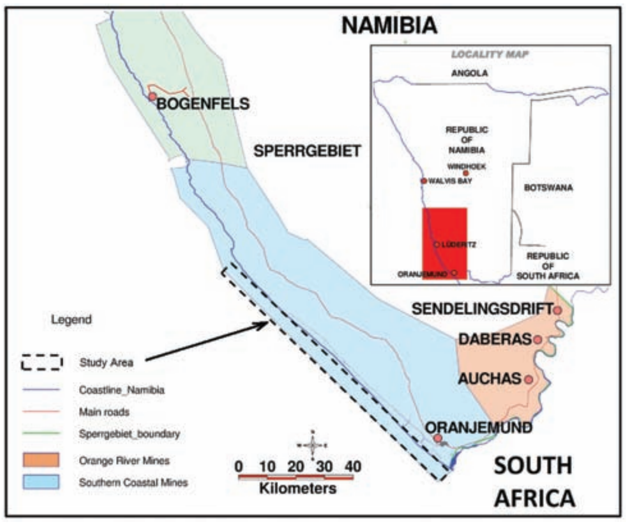

Figure 1—Location map showing the study area

Figure 2—An extract of the data showing delineation trenches sampled in 1×5 m (green) and 10×50 m (red) paddocks orientated perpendicular to the coastline

The outlines of the geological zonation are straight lines which have, due to the 500 m spacing of the data, inherent inaccuracies. Previous work (Jacob, *et al.*, 2006) showed that cliff lines are generally associated with zones of higher diamond concentration, and this feature of the depositional environment can be used to adjust data to align with the cliff lines. Adjustment of the data locations to align with the cliff lines (or beach crests) would result in the optimum variogram. This is equivalent to calculations along an unfolded structure, aligned to the underlying geological structures of the beach. The complexity of this method is underpinned by adjusting the data in such a way as to obtain the most robust structured variogram (clearly defined variogram type, range, and expected low nugget effect) through alignment of the higher grades in each sample line. To achieve this, a squared difference, weighted by the distance between the sample lines, is proposed while sample locations are adjusted through simulated annealing.

Problem statement

In order to create virtual orebodies for use in sample optimization studies, spatial simulations with associated variograms are used, calibrated to the statistics of each beach deposit. High ratios of anisotropy in the direction parallel to the current shoreline exist, but reworking of raised beaches during periods of rising and falling sea levels in some cases destroy the internal beach structures. The expected strong spatial correlation is thus not clearly visible in the data. This could also be a function of the data spacing, which is wide relative to the expected ranges for variograms of diamondiferous beach deposits, or else the jagged nature of the coastline. This makes the determination of variogram parameters challenging.

A method is proposed whereby simulated annealing is used to adjust the sample locations to align the data pertaining to beach crests or cliff lines, thus improving the variogram structure along the shoreline in the direction of the highest geological continuity. Figure 3 shows schematic trench positions on a Google Earth backdrop. The middle trench needs to be aligned to the cliff line.

The sample data is migrated onto a 1×5 m grid with the aim of aligning the highest data values per trench with the adjacent trenches subject to constraints and minimizing an objective function. The problem statement is illustrated in Figure 4.

By iterating the sample data locations (constrained to a -2 to +2 block movement in a north/south direction), the weighted grade difference between the lines can be

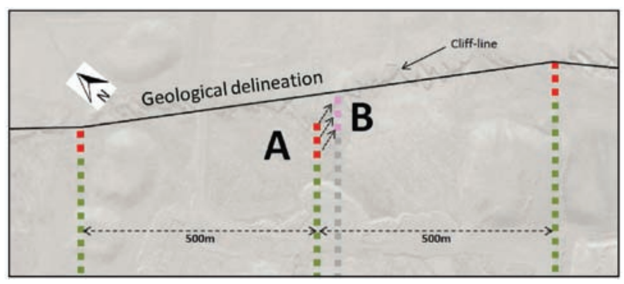

Figure 3—A well-developed cliff line with superimposed 1 m wide trench results. Schematically, higher grade samples (red) associated with the cliff line are shown in line A, with the pink and grey sample line (B) representing the two-step data shift needed to align the higher grades with the geological delineation

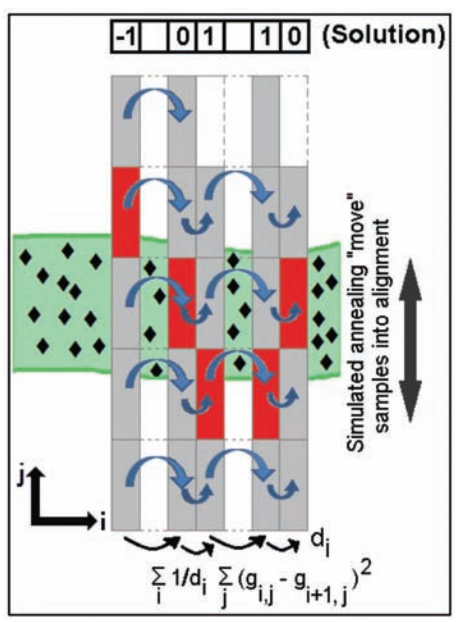

Figure 4—The high-grade blocks (red) must be aligned to the underlying geological structure (green) through sample location adjustments

minimized, implying alignment of the data to the underlying geological structure. The solution to the problem illustrated in Figure 4 shows how the high-grade (red) blocks need to be adjusted in order for the grade data to honour the underlying geological structure.

Adjusting sample locations using simulated annealing

Simulated annealing is a perturbing search method, whereby a change in the system causes it to deviate slightly, which is used for finding a best outcome within a solution space. In this study an objective function is minimized using simulated annealing by changing one factor at a time. The deviations are evaluated and solutions accepted that reduce the objective function. This is done repeatedly in a structured manner until a best solution is found.

During the process, over and above accepting the solutions that improve the objective function, rejected solutions are randomly tested against the Metropolis criterion to occasionally accept less favourable solutions. This avoids the solution becoming entrapped in a local, sub-optimal solution. The probability of acceptance of a worse solution is determined as follows:

$$P(accept\ worse\ solution) = e^{-(obj_{new} - obj_{old})/T} > uniform(0,1)$$

where a temperature value (T) and the new and old objective function values are used. As the number of iterations increases, the temperature is reduced according to an annealing schedule, and combined with a smaller difference between the two objective functions, it becomes less likely that worse solutions will be accepted. The annealing process eventually converges to a ‘best’ solution.

The simulated annealing algorithm as implemented by Goffe *et al.* (1994) was modified so that each random adjustment can contain only integer values.

To take cognisance of the distance (d_i) between sample lines, the objective function includes a weighting based on the inverse distance between two adjacent sample lines. The objective function to be minimized is:

$$min\left[\sum_{i=1}^{\#sample\ lines} 1/d_i \times \sum_{j=1}^{\#samples\ per\ line} (stone\ grade_{i,j} - stone\ grade_{i+1,j})^2\right]$$

The movement for each sample line is initially set to zero and after running the annealing process inspection of the results shows that the most logical solutions are obtained when the movements are not allowed to deviate too much from zero. These slight movements of the sample locations were thought to be realistic, as the geological boundaries are not expected to be radically misaligned with the underlying beach crests/cliff lines. The constraints of the annealing process thus allowed only relatively small adjustments to the sample locations and were restricted to not more than 20 m in the cross-beach direction.

Case study

The F beach is the oldest, highest grade, and most eastward of the six raised beaches. The samples covering the beach are spaced at 500 m in the north-south and 5 m in the east-west directions. With the samples closely spaced across the beaches, the east-west direction should be more representative in terms of the modelling of the nugget effect of the variogram.

Figure 5 shows the variograms before and after the data locations were adjusted.

The variograms are plotted using two different scales on the x-axes, as the anisotropy along and across the beach cannot otherwise be shown in a single graph. It can clearly be seen that after the sample locations were adjusted, the nugget effect of the along-beach variogram is in agreement with the nugget effect determined from the across-beach data.

Similar results (although slightly less impressive than from beach F) were obtained from some beaches, but not in all cases. The reason for this is thought to be the reworking of beaches during the multiple transgression and regression cycles of sea level stands, which destroyed so much of the beach structures that it is very difficult to reconstruct the linearity of the beach based on the sample grade only.

Examples of before and after data adjustments within sample lines are shown in Figure 6.

Results and conclusion

Through inspection of the example in Figure 4, an alternative solution of (-2, -1, 0, 0, -1) can be proposed. Similarly, the results after annealing the sample locations of the beaches must be contextualized within the framework of the more complex data configurations and the possibility that the annealing probably does not converge to a unique solution.

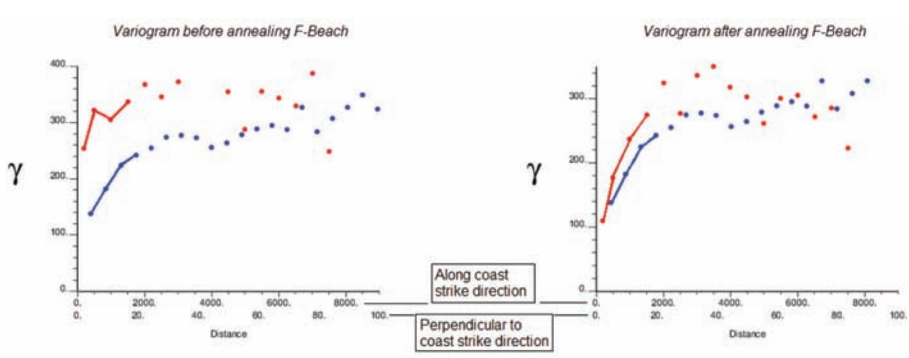

Figure 5—Variograms before and after simulated annealing, highlighting the modelling of the nugget effect. Strong anisotropy along (red) and across (blue) the coast strike directions is evident

Figure 6—Examples showing the alignment of samples before and after annealing

The multiple outcomes of annealing runs are therefore analysed and a range of variogram parameters determined, leading to an array of simulations for use in the sample optimization studies. In the inspection of the output to determine if cliff lines or beach crests can be identified from the data, the minimized objective function and variogram parameters are used to establish the acceptability of the results. The outcomes thus far have been promising.

The research is ongoing and is focusing on eliminating outliers from the data, testing the effect of different constraints on sample movements, as well as testing the effect of using multiple random starting points in the annealing.

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