

Training Images for Weathered Type Deposits

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The mining industry has been unable to take advantage of the benefits of multiple point statistics (MPS) because of the lack of training images (TI). The methodology described here can be used to create TIs for weathered deposits such as nickel laterites or aluminum bauxites. The TIs generated are three dimensional models of the boundary between weathered and non-weathered layers. The methodology is based on an application of simulation to specially coded drill holes. Examples comparing the TIs to geological interpretations of weathered deposits and photographs of deposits show that the TIs contain many of the features seen in actual deposits.

Introduction

The benefits of MPS for reproducing curvilinear features in a deposit are well known (and discussed in *Methodology to Construct Training Images for Vein Type Deposits* in this CCG report). Traditional geostatistics largely ignore non linear features because SGS only uses the variogram to capture linear, two point relationships. Real deposits often display complex geological feature that, if included in realizations, would have a large impact on reserves. As discussed in *Methodology to Construct Training Images for Vein Type Deposits* there is a lack of TIs in the mining industry preventing the use of MPS to account for the curvilinear features seen in actual mineral deposits. This paper focuses on developing geologically realistic TIs for weathered mineral deposits using readily available tools such as SGS. Weathered deposits are characterized by multiple layers, corresponding to various degrees of weathering. The mineralogy of these layers are different, making it important to model this contact. TIs that contain realistic properties of this highly nonlinear contact will be created for use in MPS.

Background

TIs will be created for weathered deposits such as laterites, saprolites, and bauxites. The following discussion will give a brief overview of the processes that create the boundary between the weathered and non-weathered rock. Typical profiles for these types of deposits are presented to provide the necessary background to evaluate the geologic realism of the proposed TIs.

The overall process of weathering is the combined effect of physical, chemical and biological processes on a parent rock. The outcome of weathering can be to: erode away a potentially economical ore body; leach away a valuable mineral, reducing the economic worth of the deposit; concentrate a valuable mineral, increasing economic worth; or chemically alter the mineralogical makeup of the ore deposit (Guilbert and Park, 1996).

The chemical portion of weathering occurs because the original rock, formed under high temperature and pressure, is not in equilibrium when exposed to the low temperature, low

pressure, high humidity and variable pH at the surface. As water from the surface flows through these newly exposed rocks, the carbon dioxide rich and potentially low pH surface water chemically alters the rock. The processes involved in chemical weathering include hydration, solution, oxidation, reduction, hydrolysis and chelation, see Bland and Rolls (1998) for a detailed description of these processes.

Physical weathering is considered to be weathering that occurs without changing the chemical composition of the rock. This can take the form of dissolving, crystallization, freeze thaw cycles, etc, see Bland and Rolls (1998) for a complete list and description. Physical weathering may occur in tandem with chemical weathering, as the chemical weathering process often weakens the integrity of the rock, making physical weathering more effective.

Biological weathering is thought to be secondary to physical and chemical weathering (Guilbert and Park, 1996; Bland and Rolls, 1998) and is not critical to the understanding of the formation of the boundary between the weathered and non-weathered layers in an ore deposit. Therefore, the reader is referred to Bland and Rolls (1998) for a description of biological weathering.

When the combination of physical, chemical and biological weathering erode, dissolve and transport a mineral of interest such that the subsequent deposition increases the concentration of the mineral, the process is called supergene enrichment. If the concentration is increased sufficiently, a weathered type ore deposit is created. Supergene enrichment most commonly occurs with iron, aluminum, and manganese (Guilbert and Park, 1996) because of the chemical and physical properties of these minerals. These weathered deposits have a distinctive bedded profile consisting of a soil layer followed by layer of highly weathered rock, a layer of weathered rock and underlain by the original parent rock, see Figure 1. These layers form because of the interaction of the water percolating through the rock and its behavior once reaching the water table at the time of weathering. Each subsequent layer, moving downward in the horizon, is defined by a marked decrease in the degree of weathering, from the completely weathered soil to the intact host rock. The naming of the layers in the profile vary in the literature, hereafter the highly weathered layer will be deemed laterite and the less weathered layer saprolite (after Bardossy and Aleva, 1990). The boundary between the soil and laterite, as well as between the laterite and saprolite is continuous; however, the transition occurs over a scale of centimeters up to a few meters (Bardossy and Aleva, 1990). For mining purposes this boundary will be considered a sharp contact between layers and will be modeled as such.

Bardossy and Aleva (1990) describe the contact between weathered layers as an “irregularly shaped, downward attacking interface, with broad, retarded embayments and deeply penetrating and advancing tongues.” (pg. 48). What they mean by this description is shown by the irregular nature of the contact between the laterite and saprolite in Figure 1, specifically, the jagged nature of the contact and the pockets of material that appear. These are the types of features that will be important to reproduce in a TI.

Figure 1 is an idealized view of a weathered contact. The exact nature of this boundary will vary by deposit. To obtain a better idea of some of the typical features seen in weathered boundaries, Figure 2 and Figure 3 show geological interpretations of weathered contacts and Figure 4 shows a photograph of a weathered contact. Note the irregular nature of the boundary and the presence of boulders in both the geological interpretations and photographs.

Proposed Methodology

Realistic TIs will be created by modeling the boundary between two weathered zones. The important geological features to reproduce include i) the erratic nature of this boundary as seen by the sharp changes in the boundary direction, often curling back on itself, see Figure 4, and ii) the pockets of laterite material that appear in the saprolite zone and the pockets of saprolite that appear in the laterite zone. The boundary modeling will be accomplished by using SGS to model fabricated data that represents the laterite and saprolite zones. Specifically, the methodology for generating TIs for weathered boundaries consists of the following steps, explained in greater detail below:

1. Generate synthetic drill hole data for the depth of the weathered contact
2. Assign a positive value to the laterite zone and a negative value to the saprolite zone
3. Perform SGS with the synthetic drill holes
4. Apply a threshold of 0 to the realizations generated in step 3 to define the laterite and saprolite zones; and
5. Use MAPS to smooth the contact and remove the randomness generated by simulation

Step 1: Synthetic Drill Hole Data for Control Points

An initial depth for the boundary between the laterite and saprolite layers below the topography is created by simulating a depth to contact variable on a coarse grid. Figure 5 shows an idealized initial grid and depth to the boundary.

These drillholes will be considered the control points for the weathered boundary. The drillholes are created by simulating a normal scored variable representing the depth to the boundary at each drillhole location. This depth variable is scaled so that each depth is positive and has the desired range. For example, multiplying the normal scored variable by 5 and adding a mean depth of 15 will generate a contact that will have an average depth of 15 and will cover approximately ± 10 . Changing these factors will change the depth over which the contact varies and can be used as a tuning parameter for generating a TI with the desired structure. Moreover, actual drillholes for a deposit of interest could be used as the control points to generate a site specific TI.

Step 2: Assigning Conditioning Data for SGSIM

The depth of the contact has been defined by the simulation described above. The remainder of the drill hole will be populated in such a way as to generate a realistic boundary. Features of a realistic contact include: maintaining a certain depth below the surface as it may be unrealistic to have the boundary outcropping; small scale irregularities are encouraged; and, pockets occurring with greatest frequency near the boundary. To reproduce these features the drill holes will be populated with values near 0 at the contact and will have increasingly negative values to the bottom of the drill hole and increasingly positive values to the top of the drill hole, see Figure 6. Once simulated, the boundary will be defined as the zero contact in the model. Arranging the drill hole values in this way will force the boundary to pass through the control points at 0 but also allow it to fluctuate between drill holes, generating the irregularities of the boundary and the pockets.

In addition to adding control points on the boundary in the form of pseudo-drillholes, the location of the boundary on the edges of the model can be fixed. This can be done by adding conditioning data around the model as a skin, see Figure 7. All edge values of the model can be assigned

positive and negative values, this will have two main effects: (i) the boundary will be forced to a user defined depth along the edges of the TI, and (ii) the high positive and negative values at the top and bottom of the model will tend to reduce the irregularities seen in the boundary.

The skin shown in Figure 1 would constrain the boundary at the edges of the TI. This may be undesirable, therefore, an alternative would be to include the skin on the top and bottom portions only. This would have the effect of limiting the irregularities in the boundary without constraining the edges, see Figure 8.

The magnitude of the positive and negative values added to the skin will effect the irregularities seen in the boundary. When higher values are added to the top and bottom of the model the boundary will be less irregular and tend to the center of the model.

An important implementation detail when using the skin around the drillholes has to do with the timing of when the data is normal scored for SGS as step 3 requires a normal scored set of data. If the skin is not used the drillholes can be normal scored and passed to SGS. However, if a skin is used, a constant value should be applied to the top and bottom edges of the model. If the skin and the drillholes are both normal scored, the resulting upper and lower skins will not have a constant value because most normal score programs break up spikes in the conditioning data and randomly assign them to different parts of the normal distribution. To correct for this, the drillholes should be normal scored and then the skin can be added as conditioning data. For example, the drillholes are normal scored and then a skin that has a value of +3 above and -3 below would be added to the drillhole conditioning data. The resulting distribution will not be normal but the goal of this simulation is not to reproduce a given distribution but to generate a realistic TI, therefore a perfectly normal distribution is not needed for SGS.

Step 3: SGS

SGS will be used to populate the model with positive and negative values. Conditioning data for this simulation could take many forms, as described in *step 2*:

- Drill hole data only
- Drill hole data and a skin on the top and bottom of the model
- Drill hole data and a skin around the entire model

Two important considerations when performing SGS is the choice of variogram and the search for conditioning data. Both of these will have a large effect on the look of the TI. A longer range, or greater correlation, imposed by the variogram will flatten the boundary and reduce the number of pockets. Moreover, using a larger search or more conditioning data from the search will have a similar effect. The effect of the variogram, search, and conditioning data options on the resulting TI will be discussed in the **Example** section below.

Finally, a threshold of 0 will be applied to the simulations to generate the TI. Each image will be binary, with values >0 defining the upper oxidized layer and values <0 defining the lower less-oxidized layer.

Step 4: Smoothing

Even without using a nugget effect, the random nature of SGS will result in realizations that may be too pixilated to be realistic. An idealized boundary between weathered layers is often depicted as smoother than an SGS realization would generate (see **Background** for figures of weathered contacts). Actual deposits may show characteristics that are more similar to the pixilated

realizations generated by SGS, see Figure 12. However, MAPS (Deutsch, 1998) can be used to smooth the realization and create a boundary that is similar to an idealized weathered contact. Either the SGS realization or the MAPS (Deutsch, 1998) smoothed model could be used as a TI for multiple point simulation depending on site specific conditions.

Example

The proposed methodology is applied with an 80x80x30 block model to demonstrate the process. Images of a larger model follow the example.

Steps 1 and 2: Synthetic Drill Hole Data

Using SGSIM (publicly available in the standard GSLIB package, see www.gslib.com) an unconditional SGS was performed on a coarse grid to simulate the depth to the boundary for use as control points. 16 drill holes are generated 20 units apart with an average depth of 14, see Figure 9. Simulation was performed with the following variogram.

$$\gamma(h) = 0.2 + 0.8sph_{\substack{ah1=50 \\ ah2=50 \\ vert=30}}(h) \quad [1]$$

The drillholes are then populated by assigning positive and negative values increasing away from the depth to the boundary. A cross section for the first row of drillholes located at y=10 is shown in Figure 10.

The location of the zero value in these drillholes is determined by the control points shown in Figure 9. No skin will be added to this example, the effect of adding a skin is discussed later.

Steps 3: SGS

The boundary must be created in three dimensions between all drill holes. This is done by simulating the above drillholes without a nugget effect. The lack of a nugget effect is to ensure the 0 boundary is continuous. The parameters in simulation will control how erratic the boundary is and how many pockets appear. Simulation with the following arbitrary variogram is shown in Figure 11.

$$\gamma(h) = 1.0sph_{\substack{ah1=30 \\ ah2=30 \\ vert=10}}(h) \quad [2]$$

The ranges selected for the variogram to be used in simulation should be considered relative to the spacing of the pseudo drillholes. In this example the range is about 3/2 the spacing of the control points. A range shorter than the distance between control points will create a boundary that is more erratic.

Finally, a threshold is applied to obtain the boundary between the laterite and the saprolite layers, see Figure 12.

Step 5: MAPS Smoothing

The use of simulation to define the laterite and saprolite rock types introduces excessive randomness and may require smoothing. MAPS (Deutsch, 1998) is used to define a smooth boundary and only retain pockets of significant size.

Sensitivity

There are a number of parameters in this methodology that can be used to generate boundaries with different characteristics. These parameters include:

- Control Points – the number of control points used in the domain will control the global shape of the boundary. It must be remembered that many parameters interact to determine the final features of the TI. The number of control points must be considered relative to the number of blocks in the model, and the variogram/search parameters of SGS must be considered relative to the spacing of the control points.
- Conditioning data options – drillholes are used as control points for the boundary. In addition to this, conditioning data can be added to the edge of the model to flatten the boundary or to constrain it to a user defined depth near the edges of the TI.
- Variogram parameters – the range/anisotropy of the variogram used when simulating the distance function will either increase or decrease the erratic nature of the boundary. It is necessary that no nugget effect be used to keep the contact continuous.
- MAPS smoothing – The degree of smoothing will control the level of randomness in the final TI.

Showing TIs for different values of all of the above parameters would result in many images. Therefore, Table 1 will summarize the effect of all parameters and a few examples are shown in Figure 14, Figure 15, and Figure 16.

Table 1: Sensitivity analysis of weathered TIs to input parameters.

Parameter	Effect on Irregularities in TI	Other Effects on TI
Control Points	Increasing the number of control points – fewer pockets and a smoother boundary	The depth of the control points determines the global shape of the contact. The remaining parameters control behavior between control points (drillholes).
Magnitude of values in drillholes	Increased magnitude of positive or negative values – fewer pockets and a smoother boundary	
Applying a skin to the entire model	Reduces pockets and smoothes the boundary. Increasing the magnitude of the values assigned to the skin will further reduce pockets and smooth the boundary.	Constrains the boundary to edges of the model where the user has inputted the 0 boundary in the form of conditioning data.
Use a skin above and below the model	Reduces pockets and smoothes the boundary. Increasing the magnitude of the values assigned to the skin will further reduce pockets and smooth the boundary.	Does not constrain the boundary at the edges of the model
Variogram range	Increasing the variogram range will reduce pockets and smooth the boundary.	
Variogram anisotropy	Increasing the range in the vertical direction creates larger vertical deviations in the boundary	
Variogram structure	Higher correlation – fewer pockets and a smoother boundary	
Including a nugget effect	Increased number of pockets and a more erratic boundary.	Will result in boundaries that are not continuous.
Degree of smoothing: MAPS	More smoothing reduces the randomness generated by SGS.	
Number of MAPS iterations	More iterations – fewer pockets and a smoother boundary	

The following TIs were generated with the above methodology to show the variety of features possible in the final TIs. Many of the parameters described in Table 1 are redundant and are used to control the smoothness of the boundary: this can be visualized with Figure 14 for changing the variogram range. Figure 15 shows the effect of adding a skin of conditioning data to the

simulation. Figure 16 shows how the smoothing can be varied to generate TIs that have more randomness.

Only XZ slices that show the boundary in cross section will be shown to conserve space. The TIs shown in Figure 14, Figure 15, and Figure 16 are 200x200x40.

Discussion

The geological realism of the TIs will be judged by a visual comparison with the photograph of a weathered contact presented in the background, see Figure 4.

The similarities between the TI and the coded photograph in Figure 17 are encouraging. The irregular nature of the contact and the distribution of pockets throughout both layers is apparent. The vertical fingers of laterite creeping into the saprolite, and vice versa, are also captured.

Figure 14, Figure 15, and Figure 16 give some examples of the versatility of this technique. There are many controls that allow for different types of boundaries to be defined. This gives the geostatistician a large degree of freedom when generating a TI. Moreover, it is possible to incorporate exploration data into this process. Rather than using pseudo drillholes as control points, actual exploration drillholes can be used. This would generate TIs that match the known site specific depth to contact at each drillhole location.

Conclusions and Future Work

The lack of TIs is a serious problem preventing the use of multiple point statistics in the mining industry. Due to the use of multiple point statistics in the petroleum industry there are emerging solutions to many of the implementation problems facing the use of multiple point statistics. Therefore, the only obstacle preventing the use of multiple point statistics to capture curvilinear geological features of mineral deposits is the absence of TIs. The simple methodology proved here for weathered deposits shows that the generation of geologically realistic TIs for mineral application is possible with the tools currently available, such as SGS. It should be noted that SGS is only used to generate TIs and that these TIs contain the desired nonlinear features that can then be reproduced in multiple point simulations using algorithms such as presented by Lyster (2006).

Multiple point statistics is a relatively new way of quantifying the uncertainty in reserves and still requires solutions to implementation problems; however, before a successful application of multiple point statistics, TIs that contain the desired curvilinear features of mineral deposits are needed. Future research should not only be focused on solving the problems facing a successful workflow for multiple point statistics, but also directed at generating TIs that contain desirable features.

References

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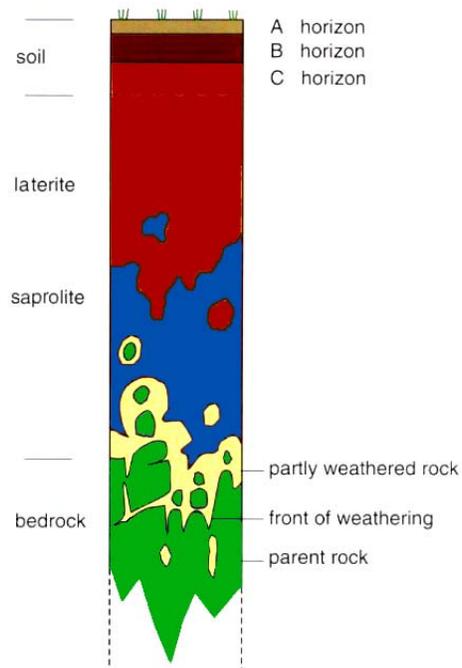


Figure 1: Typical horizon of a weathered deposit. Modified from Delvigne (1998). NTS.

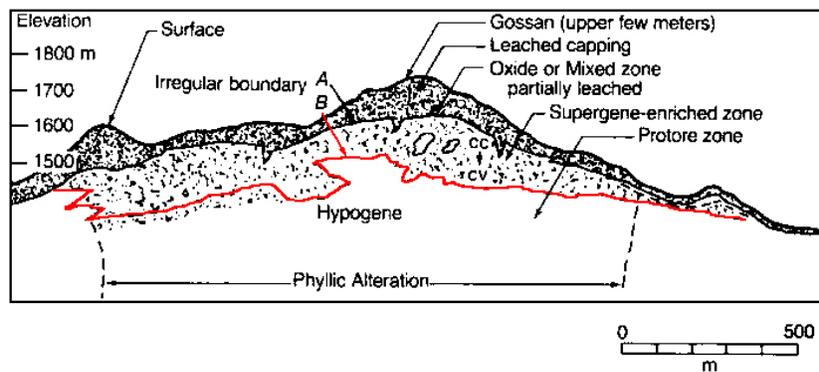


Figure 2: Geological interpretation of a laterite profile at La Caridad, Sonora, Mexico (modified from Guilbert and Park, 1996). Scale shown on figure.

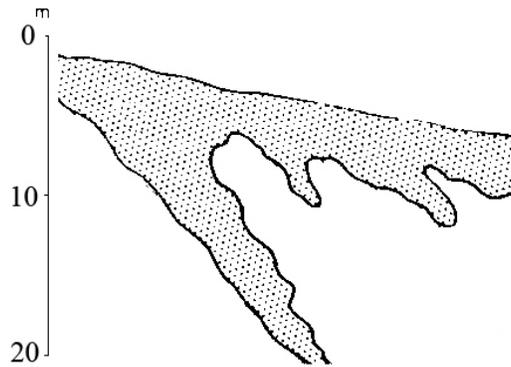


Figure 3: Geological interpretation of a laterite profile near Poços de Caldas, Brazil (modified from Bardossy and Aleva, 1990). Scale shown on figure.

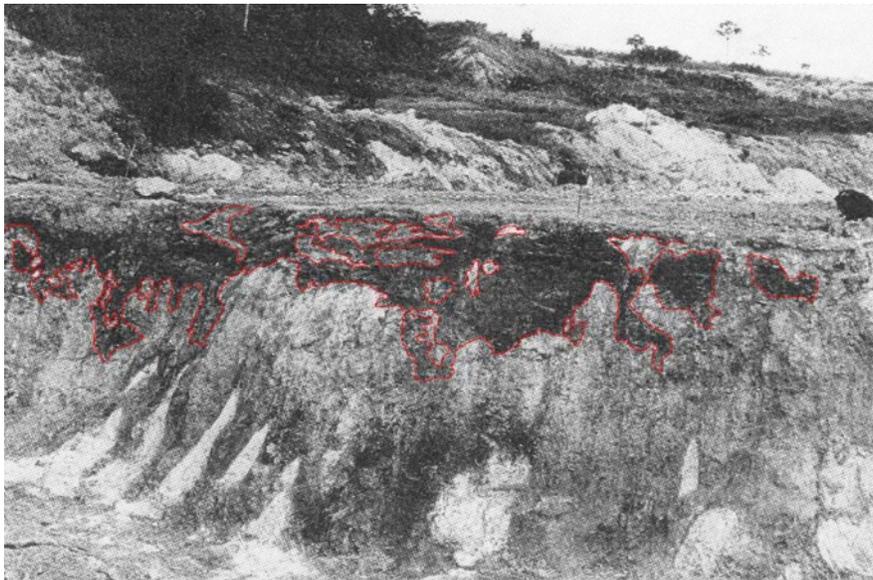


Figure 4: Photograph of an iron bauxite contact on a mined bench (modified from Bardossy and Aleva, 1990). Red highlights added to show the irregular nature of a weathered contact. Unknown scale.

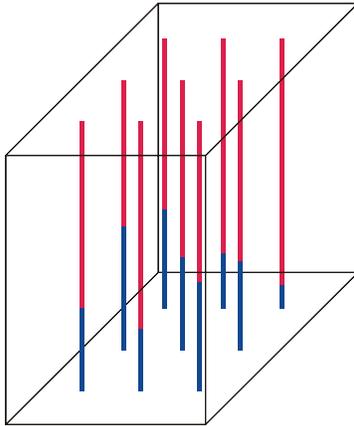


Figure 5: Coarse grid for simulation of the initial depth of the boundary. Red – laterite. Blue – saprolite.

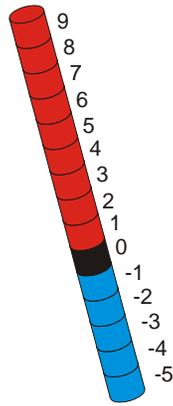


Figure 6: Example drill hole showing the assignment of positive and negative values.

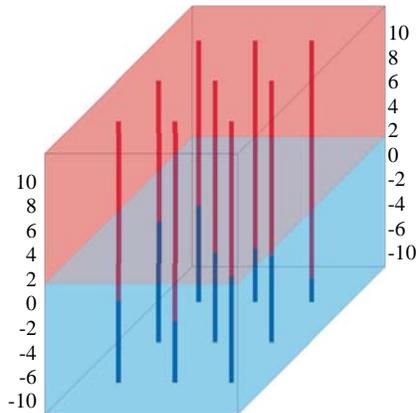


Figure 7: A skin of positive (red) and negative (blue) conditioning data can be added to the edges to control the boundary.

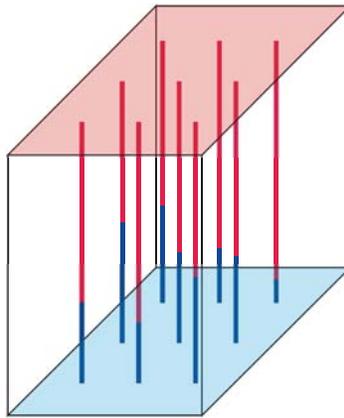


Figure 8: A skin of positive (red) and negative (blue) conditioning data can be added to the top and bottom to control the boundary without constraining it at the edges.

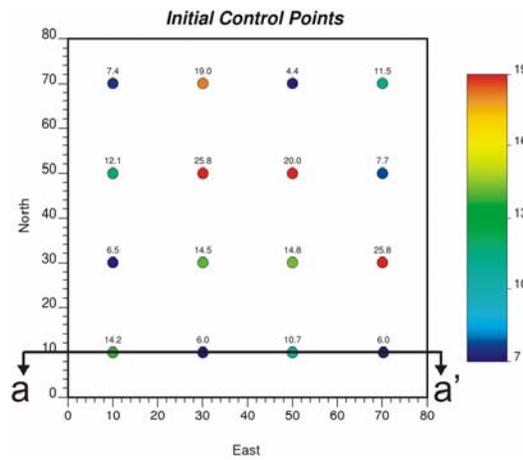


Figure 9: Drill holes showing the initial control points for the depth to the boundary. Section aa' can be found in Figure 10.

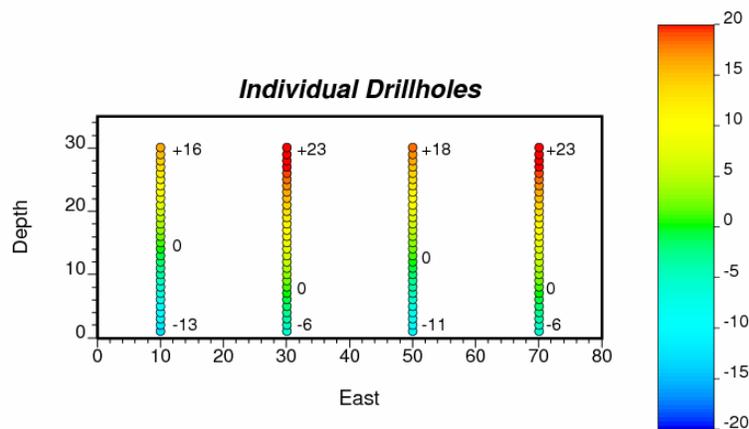


Figure 10: Section aa' - drill holes assigned positive and negative values, increasing away from the boundary. Minimum, maximum and the boundary (zero value) is shown for each drillhole.

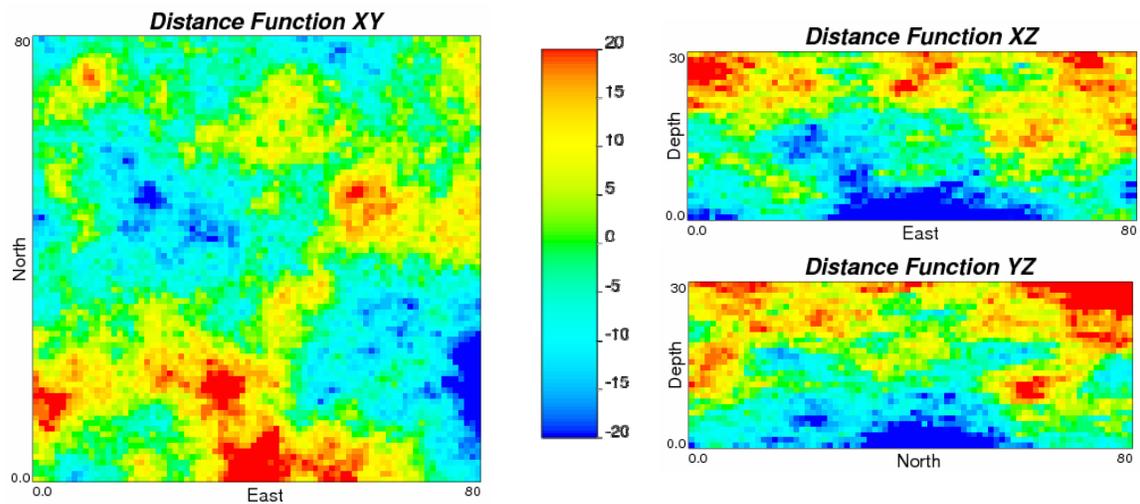


Figure 11: Simulated positive and negative values.

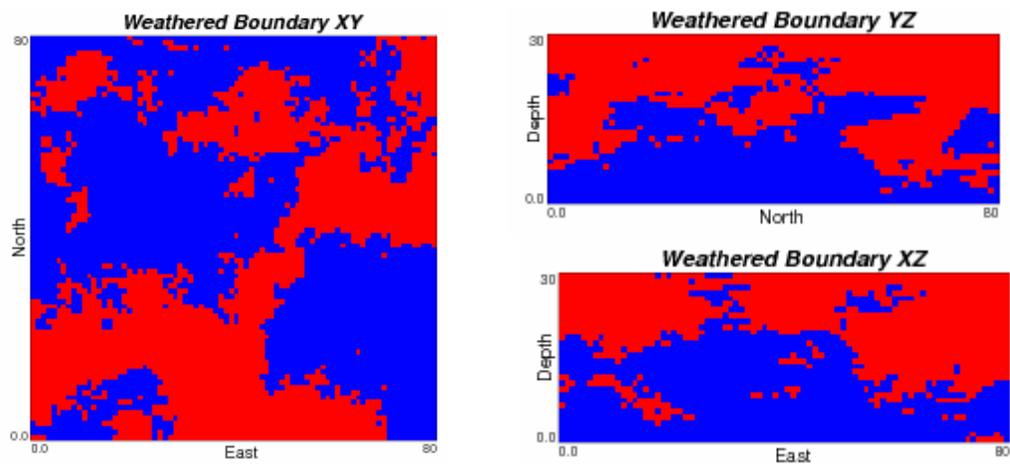


Figure 12: Simulated values with a threshold of 0 applied to define the boundary. Red – laterite. Blue – saprolite.

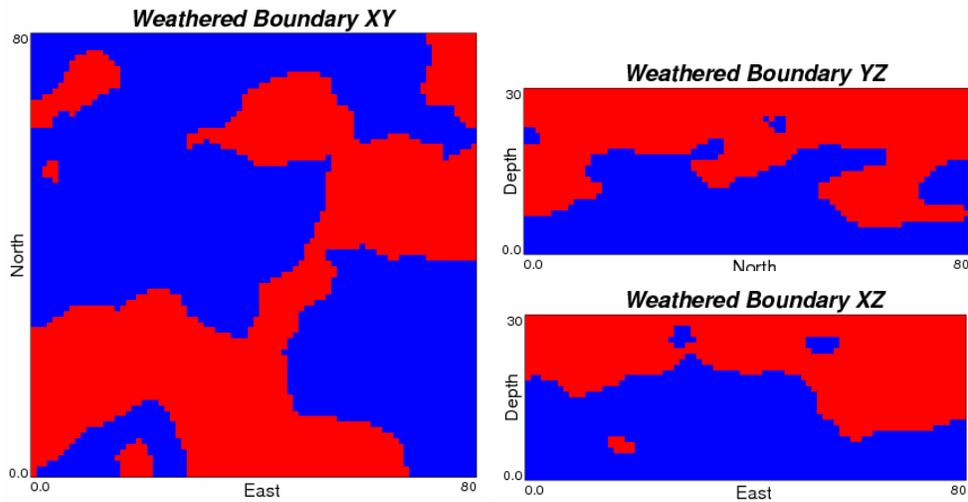


Figure 13: Smoothed Figure 12 using MAPS (Deutsch, 1998).

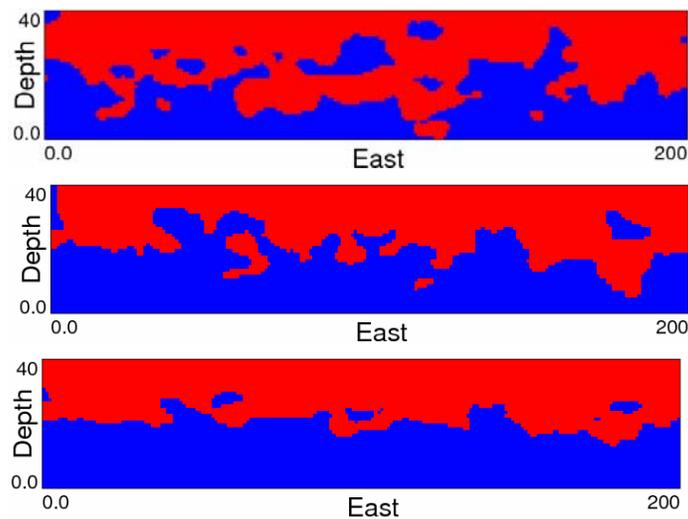


Figure 14: Effect of increasing the variogram range on weathered TIs. Control points have a spacing of 20 units. Above – $ah_1=ah_2=10, avert=5$. Middle – $ah_1=ah_2=20, avert=10$. Below – $ah_1=ah_2=60, avert=20$. The search distance for each direction equals the range parameters. A minimum of 4 and maximum of 16 conditioning data were used in the simulation with 12 simulated nodes.

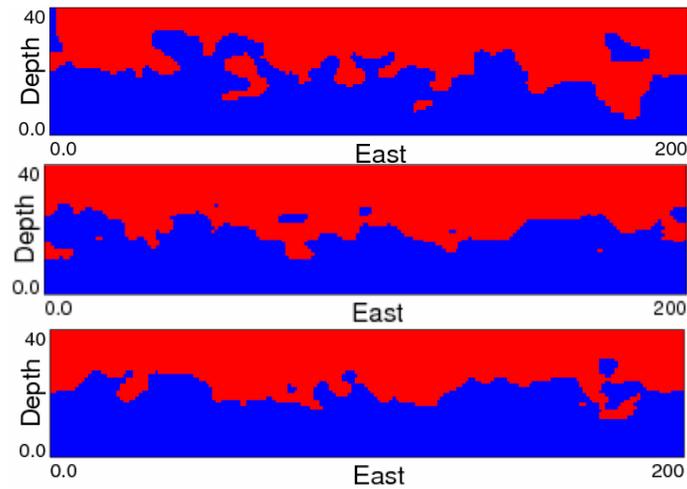


Figure 15: Effect of using different conditioning data options on the weathered TIs. Conditioning can be added around the edges of the model. Above - no boundary conditions (taken from Figure 14). Middle - normal scored data of magnitude 5 is added to the top blocks and -5 to the bottom blocks smoothing the boundary. Below - a skin around the entire model increases smoothness and constrains the boundary at the edges of the model.

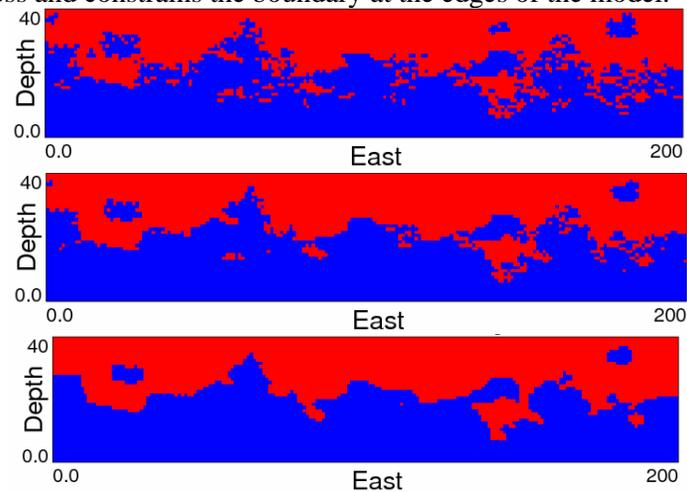


Figure 16: Effect of different smoothing options on weathered TIs. Increasing levels of smoothing from the upper TI to the lower.

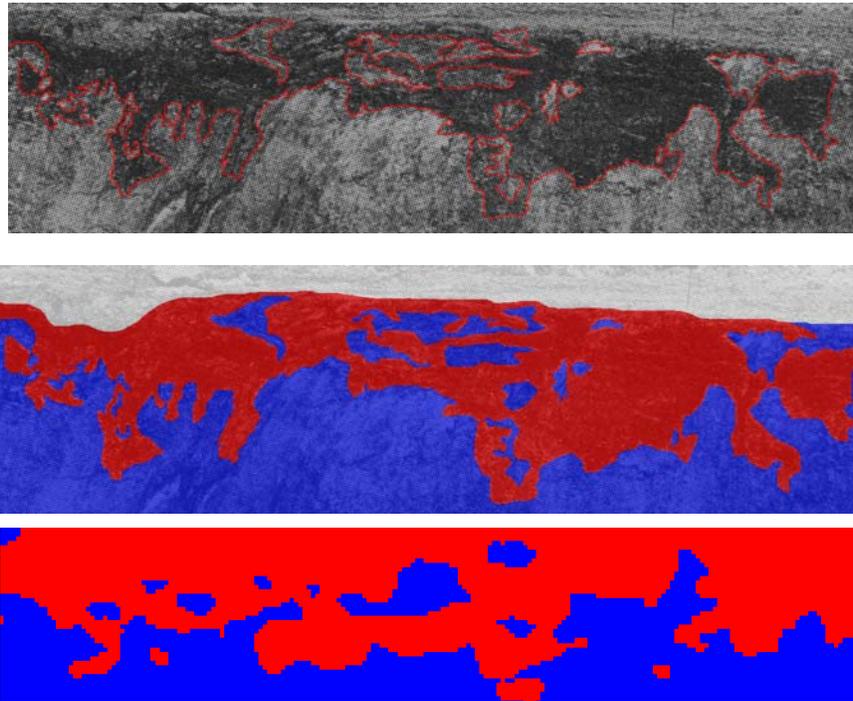


Figure 17: Comparison of a TI with a weathered contact. Above – photograph of a weathered contact with the authors interpretation of the contact, see Figure 4 for the original image (modified from Bardossy and Aleva, 1990). Middle –Photograph of the weathered contact recoded to laterite and saprolite categories to aid in comparison. Below – TI generated using proposed methodology.