

## A Program to Analyze the Nature of Boundaries

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*The decision of stationarity is an important one in geostatistics. One aspect of stationarity is determining whether geologic boundaries exist, and, if they do, determining the nature of these boundaries. Geologic boundaries are typically classified as hard or soft. A tool for determining the nature of boundaries is presented. This tool allows a practitioner to quickly and easily create contact plots of the grade levels between the rock types or facies of interest. An indication of the type of boundary is given based on linear regression of the grade-distance relationship near the boundary. An example application of the tool to lead-zinc data is presented.*

### Introduction

A five step process has been proposed to deem reasonable the decision of stationarity (McLennan, 2008). The five steps are: 1) choose the number and type of domains, 2) model the boundaries of the domains, 3) quantify the nature of transitions across the boundaries, 4) quantify trends within the boundaries, and 5) ensure the trend is reproduced in prediction. This work is primarily concerned with step 3. Conventional geostatistical practice is to populate petrophysical properties within distinct geological domains enclosed by modeled boundaries. The models resulting from the pasting together of these independent models are not geologically realistic when smoother transitions are indicated by geological interpretation and/or sample data. The solution is to quantify the nature of the transition near the boundaries to reproduce geologically realistic transitions.

Domain boundaries are often referred to as either 'hard' or 'soft' (Larrondo and Deutsch, 2004). Hard boundaries are found when there is an abrupt change in the mineralogy or grade without a transition at the scale of observation (Ortiz and Emery, 2006). They do not permit interpolation or extrapolation across domains. Contacts where the variable changes transitionally across the boundary are referred to as soft boundaries. These allow selected data from either side of a boundary to be used in the estimation of each domain (**Figure 1**).

This work documents a program which analyzes the boundaries between domains and determines whether the boundary is hard or soft. The results are summarized in a postscript file. A contact plot for each combination of domains is shown as well as an indication of the boundary type.

### Contact Analysis

Domain boundaries can be either hard or soft, depending on the nature of the geological transitions across the boundary. A contact analysis is undertaken to detect hard and soft boundary transitions as well as different types of hard boundary transitions. The corehole data with rocktype or facies information is required for this analysis. McLennan (2008) proposes two types of contact analysis: expected value contact analysis and covariance function contact analysis. Cuba and Leuangthong (2009) show how the variogram can be used to identify non-stationarity in the local variance in addition to the local mean. The work presented here is less quantitative and more qualitative in nature than those methods mentioned. The tool creates plots of the boundaries between rock types with some basic identification of the type of boundary. The user is left to interpret the nature of the boundaries. Identifying the type of boundary is important as it affects how the modeling is performed near the boundaries. There are two general categories for modeling the nature of boundaries: implicit and explicit (McLennan, 2008). The first refers to the conventional method of pasting together domains predicted from separate stationary random functions and conditioning data sets. This is appropriate for hard boundaries. For soft boundaries, a near-boundary model describing how separate stationary random functions interact is needed to build in realistic geological transitions explicitly.

### Contact Plot

**Figure 2** shows the general form of a contact plot for a soft and hard boundary. This type of plot is useful for determining the nature of a boundary separating two domains. Sample data values  $z$  are plotted against their

distance inside either the left domain 1,  $d_{12}$ , or right domain 2,  $d_{21}$ , from the boundary. Expected values are represented with the solid lines. Notice the transition zone bound by the vertical dotted lines on the left. The size of the transition zone may vary, but this zone will be present for soft boundaries. The stationary random function (SRF) to the left and right of the boundary are denoted by  $Z_1(\mathbf{u})$  and  $Z_2(\mathbf{u})$ . In contrast to soft boundaries, the  $Z_1(\mathbf{u})$  and  $Z_2(\mathbf{u})$  SRFs are applicable all the way through their respective domains up until the hard boundary. There is no transition zone present.

An example of the contact plot generated by the tool presented herein is shown in **Figure 3**. The sample data values are plotted against their distance from the boundary. The x-axis is the distance from the boundary. The user specifies the maximum distance from the boundary they are interested in considering. The y-axis is the value of the variable they are interested in considering, in this case, porosity. The number of points within the distance limit for each rock type is posted at the top. The red line is the linear regression of the sample data on their distance from the boundary. The black lines above and below parallel to the red line indicate the 5<sup>th</sup> and 95<sup>th</sup> percentiles, that is, 5% of the points fall above the top black line and 5% of the points fall below the bottom black line. The gray shaded region represents the 90% probability interval. When there are fewer than 200 points, the 90% probability interval is determined by calculating the mean squared error (MSE) of the regression and multiplying the square root by 1.645. This comes from the Gaussian distribution where 90% of the distribution is within 1.645 standard deviations from the mean. These black lines outlining the 90% probability interval are used to determine the nature of the boundary.

### Boundary Types

This work utilizes four boundary classifications: none (N), soft (S), hard stationary (HS) and hard non-stationary (HN). These classifications are based upon the slope and position of the black lines representing the 5<sup>th</sup> and 95<sup>th</sup> percentiles, or P5 and P95 respectively. A hard boundary is present when there is significant change in the grade level at the boundary. This is identified when the P95 value at zero distance,  $P95_k(0)$ , for one rock type is less than the mean value at zero distance for the other rock type,  $M_k(0)$ , or when the mean value at zero distance,  $M_k(0)$ , for one rock type is less than the P5 value at zero distance for the other rock type,  $P5_k(0)$ . This is illustrated in **Figure 4a** where  $M_1(0) > P95_2(0)$ . A hard non-stationary boundary meets this same criteria with the additional constraint that for at least one rock type a significant trend is present. A significant trend is identified in two ways: either the P95 value at  $d$  distance is below the P5 value at 0 distance,  $P95_k(d) < P5_k(0)$ , or the P5 value at  $d$  distance exceeds the P95 value at 0 distance,  $P5_k(d) > P95_k(0)$ , as illustrated in **Figure 4b** where  $P95_2(d) < P5_2(0)$  and  $P5_1(0) > P95_2(0)$ . A hard stationary boundary has no significant trend. There is effectively no boundary when neither P95 value at zero distance exceeds the other mean value at zero distance,  $M_k(0) < P95_k(0)$ , and when no significant trend is present in either rock type. This is illustrated in **Figure 4c**. Finally, a soft boundary is present when the grade level in at least one rock type shows a significant trend ( $P95_k(d) < P5_k(0)$  or  $P5_k(d) > P95_k(0)$ ), but there is no significant change in grade level at the boundary as shown in **Figure 4d** where  $P95_2(d) < P5_2(0)$ ,  $P5_1(0) < P95_2(0)$  and  $P5_2(0) < P95_1(0)$ . All boundaries can fit into one of these four classifications.

### Calculation Methodology

The most straightforward application of this tool is when there are drillhole(s) along which some type of rock type and grade have been recorded. For  $N$  rock types, the algorithm proceeds by searching for a boundary between rock types  $k$  and  $k'$ ,  $k=1,\dots,N-1$ ,  $k'=k+1,\dots,N$ . When a boundary between these rock types is found, the grade level within rock type  $k$  is plotted against distance from the boundary on one side of the plot and the grade level within rock type  $k'$  is plotted against distance on the other side of the plot. The scatters of points on either side of the plot are used to calculate the regression and determine the intercepts of the P5 and P95 lines. This information is then used to classify the boundary types.

The methodology can also be applied in two dimensions. In this case, a categorical rock type model is required as input. Each data is visited in turn determining the distance to the nearest other facies. This distance as well as the local grade level are sufficient to build the grade level versus distance contact plot.

### Example

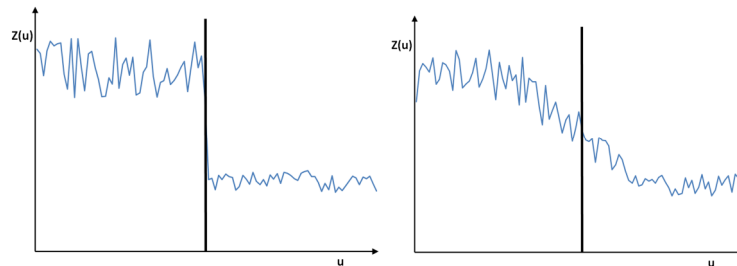
This tool is applied to some lead-zinc data. There are 367 holes drilled in a 2 km x 2 km area. The grade of zinc is dependent on the rock type. The four main rock types have codes 14, 18, 21 and 28. Rock types 14 and 21 are associated with high zinc grades while rock types 18 and 28 are associated with low zinc grades. The natures of the boundaries between these four rock types are shown in **Figure 5**. The first thing to note is that rock type 21 is never adjacent to rock types 14 and 18, it is only adjacent to rock type 28. Therefore, of the six possible boundary's, only four are present. The only hard boundary occurs between rock types 14 and 28 where the mean grade in rock type 28 is less than the *P5* grade in rock type 14. The local variance also changes significantly across this boundary. The transitions from rock type 14 to 18, 18 to 28, and 21 to 28 are also characterized by a significant change in local variance. The change in local mean for these three boundaries does not justify the 'hard' classification. None of the boundaries exhibit any significant trend in the grade nearby.

### Conclusions

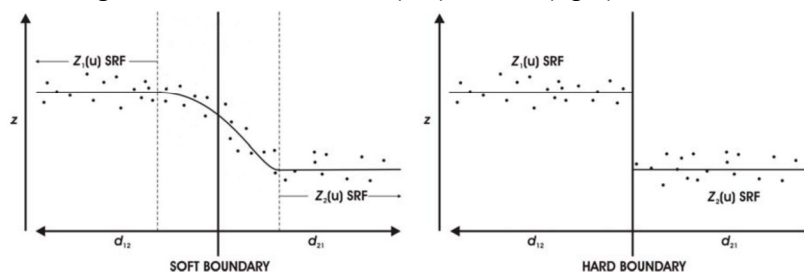
The decision of stationarity is an important one in geostatistics. Part of making this decision involves investigating the presence and nature of geologic boundaries. The properties of some geologic variable can change significantly from one domain to another. The nature of the transition has important modeling implications. The tool presented allows the nature of geologic transitions to be evaluated quickly and easily. The correct modeling techniques can then be employed to ensure that the model is as consistent with the geology as possible.

### References

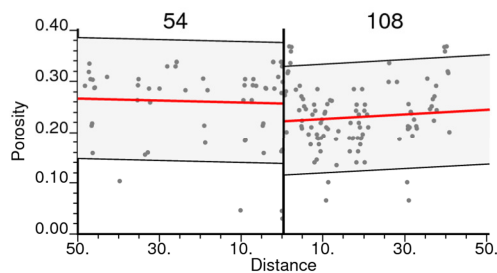
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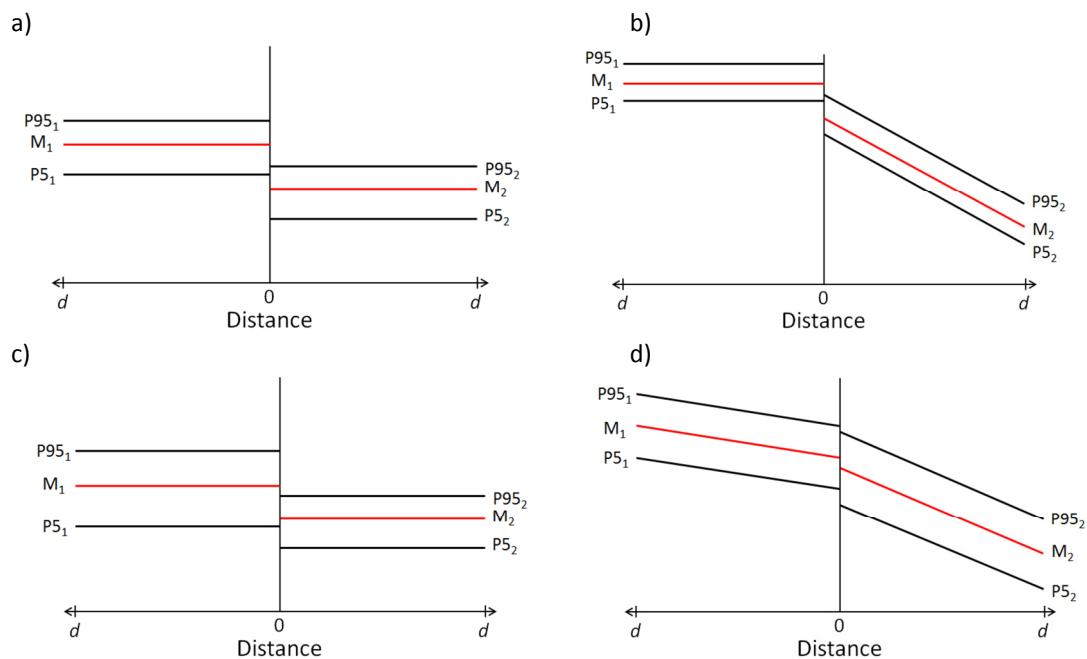
**Figure 1:** Illustration of hard (left) and soft (right) boundaries.



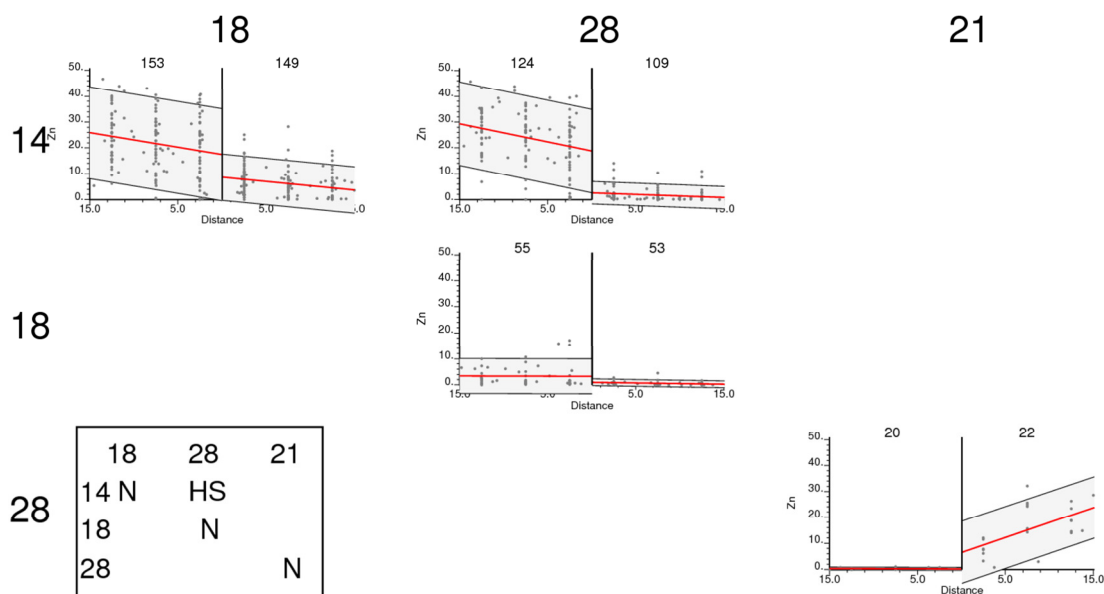
**Figure 2:** General form of contact plot for soft and hard boundaries (modified from McLennan, 2008).



**Figure 3:** Example of contact plot produced by this work.



**Figure 4:** Boundary types: a) hard stationary, b) hard non-stationary, c) none, d) soft.



**Figure 5:** Contact plots of the contacts between rock types 14, 18, 21, and 28.