Physiology, Geology and Geochemistry of the Southern Explorer Ridge
Seafloor Hydrothermal Site Using an Integrated GIS Database and 3D
Modeling

by

Yannick C. Beaudoin

A thesis submitted in conformity with the requirements for the degree of Master of Science
Graduate Department of Geology
University of Toronto
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Yannick Beaudoin

in partial fulfillment of the requirements for the degree of Master’s of Science, March 2001, Graduate Department of Geology, University of Toronto

ABSTRACT

Southern Explorer Ridge (SER) is an anomalously-rate shallow, intermediate spreading ridge located 200 kilometers off the west coast of Vancouver Island, Canada. It ranges in depth between 2600 and 1760 meters. For the first time, geological, geochemical and geophysical data collected from 15 cruises to SER have been assembled in a GIS format.

The distribution of published K/Ti ratios and Mg# values of basalt glass were plotted using GIS techniques. The variability of these geochemical parameters correlates with proximity to the axial dome and certain new as well as previously published structural and morphological features.

Three-dimensional modeling of Seabeam bathymetry and SeaMARC sonar data has provided enhanced visualization of SER. Physiological features make SER comparable to an elongate seamount. Specific morphological characteristics indicate that summit trough formation and evolution at SER result from non-steady state processes.
ACKNOWLEDGEMENTS

The author would first and foremost like to thank Dr. S. D. Scott for his support and encouragement. In addition, Dr. Scott provided me with incredible opportunities to work with various international research teams both on-land and at sea. The latter opened my eyes even wider to the wonderful and inspiring world of marine science.

Thank you to Dr. Larry Mayer for introducing me to the technology behind full-motion graphics modeling.

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A great thanks is due Dr. T. Pichler for setting me on the path of marine geology. He chose me as his assistant for research done in Papua New Guinea back in my undergraduate years. I haven’t looked back since.

Hats off to all the current and former students of the Scotiabank Marine Geology Laboratory. We had fun, we worked hard and we helped each other. Thanks.

A special thanks to TF, KB and VN, amazing friends that helped me move forward through it all.

Merci à mes parents pour leur support éternel. Sans vous je ne serai pas où je suis aujourd’hui.
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INTRODUCTION

The melding of computer technology and marine geoscience has taken large strides over the past 20 years. Computers have gone from being simple data collection tools to full-blown analytical and interpretive systems. Marine geoscience at the southern Explorer Ridge (SER) reached a climax from the mid 1980s to the mid 1990s when a series of research cruises studied, mapped, photographed and sampled the area (CASM III, 1984; SCHISM, 1984; CASM V, 1985; GSC/LDGO, 1985; CASM VI, 1986; CUROSS I, 1987; CUROSS II, 1988, CanRIDGE I, 1991; CanRIDGE II, 1992; CanRIDGE III 1994; CanRIDGE IV 1995). This study used the latest in data visualization technology to integrate by means of a geographical information system (GIS) the geochemistry, photography, sonar imagery and structural data obtained from the various cruises. The result is an almost complete database dedicated to the SER. All that is missing are some additional geological observations made on the SCHISM biological cruises. This database has enabled a much broader-based analysis and modeling than was previously possible leading to interpretations pertaining to the Ser’s physiography, structure, volcanic facies and axial trough formation and evolution.

This project was accomplished using a Pentium III 500 MHz PC with 256MB of RAM with the latest in mapping software. Though the figures and maps included in the text version are adequate for interpretation and analysis, best resolution and versatility can only be achieved by examining the models on a computer. CD-ROMs included with this thesis provide access to all files used over the course of the project.
CHAPTER 1: DEVELOPING THE SER GIS

Introduction

Recent advances in the development of GIS have had a significant impact on the way seafloor geology is now being presented. Unlike land-based fieldwork, early seafloor research often had to resort to manual plotting of observations on simple bathymetric maps and with inadequate navigation. Modern sea technology can now produce unparalleled images of the seafloor using various methods of acoustic and other geophysical techniques which make it possible for geologists to produce detailed 2D and 3D projections of any site. In addition to the visual modeling, interactive databases can be created and linked to form a digital environment of seafloor study areas. GIS work, as applied to marine geology, can bring together geochemistry, geophysics, bathymetry, sonar imagery, structure and any number of elements into one concise, co-registered setting. From pure science to industrial economic applications, such complete, versatile and expandable models are increasingly important research tools.

This paper focuses on the creation of a GIS for the southern Explorer Ridge system (SER), which lies 200 kilometers off the west coast of Vancouver Island, British Columbia. With nearly 20 years of accumulated data, this site was an excellent candidate for the application of computer modeling techniques and the development of an interactive digital database.

The first stage of the project involved the development of the 2 dimensional environment. The step-by-step outline used to describe the creation of the SER GIS covers all aspects behind the integration of various data sets and types. This includes methods of geographical correction for location sensitive data, the re-processing of certain types of data to fit the software requirements and the review of archived video and photographs used to describe the geology and physiology of the site.
The final stage of GIS application involved the static and kinematic 3-dimensional modeling of the study area. Although the available datasets are old, the visual models produced from them are still an important component of the final product. This chapter describes the procedures involved in creating these models with the software that was utilized. Software limitations did pose some problems, but overall, the main goals of the project were achieved.

**Base map**

The almost two decades of data that have been assembled on the SER were collected over the course of 15 separate cruises (Table 1). The first challenge was to choose an appropriate platform onto which to assemble and present these data. The most efficient, and cost effective software package for this project was determined to be MapInfo™ 5.0 Professional (MI; MapInfo is a trademark of MapInfo Corporation) and its associated modules. Its ability to process the files, the simplicity of its format and its compatibility with other major desktop mapping systems (e.g. AutoCAD and ARC/INFO) were key factors in the final choice.

The original Seabeam bathymetric data to be processed were made available by Dr. Andra Bobbit of NOAA’s Pacific Marine Environmental Laboratory as a UTM geo-referenced grid (WGS 84 geoid) with 150 meter data spacing. The dataset covered an extensive area including the SER, the Sovanco Transform Zone, and the northern tip of the Juan de Fuca Ridge system (Figure 1). The data were saved as an ASCII XYZ point file (see CDROM 1 \base maps\originals\expr100m.e00) and includes over 700,000 records. The set is based on the bathymetric traverses of the joint PGC/NOAA 1984 Discoverer cruise (Table 1). Using a PFE (Programmer’s File Editor), the file containing the records was split into more manageable units of no more than 30,000 records. Since much of the area covered by the dataset was beyond that needed for this project, a region bounded by specified UTM coordinates was delimited around
Figure 1: Regional bathymetric contour map of the northern Juan de Fuca Ridge, Sovanco Transform, and the southern Explorer Ridge.
<table>
<thead>
<tr>
<th>Year</th>
<th>Ship</th>
<th>Institution or Organization</th>
<th>Data Type</th>
<th>Navigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>R/V Kana Keoki</td>
<td>PGC/HIG</td>
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<td>Loran C</td>
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<td>Loran C/transport satellite</td>
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<td>Loran C</td>
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<tr>
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<td>CASM V</td>
<td>Photo, dredge, CTD</td>
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<tr>
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</tr>
<tr>
<td>1991</td>
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<td>CanRIDGE I</td>
<td>Photo, dredge, CTD</td>
<td>GPS/Loran C</td>
</tr>
<tr>
<td>1992</td>
<td>CFAV Endeavour</td>
<td>CanRIDGE II</td>
<td>Photo, dredge, CTD</td>
<td>GPS</td>
</tr>
<tr>
<td>1994</td>
<td>John P. Tully</td>
<td>CanRIDGE III</td>
<td>ROPOS-ROV dives</td>
<td>GPS (differential)</td>
</tr>
<tr>
<td>1995</td>
<td>John P. Tully</td>
<td>CanRIDGE IV</td>
<td>ROPOS-ROV dives</td>
<td>GPS (differential)</td>
</tr>
</tbody>
</table>

Abbreviations: PGC (Pacific Geoscience Centre); HIG (Hawaiian Institute of Geophysics); NOAA (National Oceanographic and Atmospheric Administration); LDGO (Lamont Doherty Geophysical Observatory); GSC (Geological Survey of Canada); CASM (Canadian American Seamount Project); CUROSS (Canadian University Research on Submarine Sulfides); CanRIDGE (Canadian Ridge Project); ROPOS (Remotely Operated Platform for Ocean Sciences).
the SER. With the MI desktop mapping package, a query template was created to search the records for all points found within this SER zone. These points were then dumped into a new MI table (see CDROM 1 file Base Maps\Local Maps_UTM\Point data\LOCALSER\finalpoints).

Compared to a contour line-based dataset, a point-based set provides much better resolution. In the case of the SER dataset, each point is assigned a geographical coordinate and a depth. With 150 meters spacing between each point, the coverage is more than adequate for this project.

The localized dataset is now ready to be gridded within MI using the Vertical Mapper™ 2.5 module (VM; Vertical Mapper is a trademark of Northwood Geoscience). Various interpolation methods can be applied which result in slightly to very different renderings of the data. The two best methods were determined to be Triangulation with smoothing and Natural Neighbour.

Triangulation with smoothing is essentially a process of grid generation that is most often applied to data such as elevation readings. According to Northwood (1999), the surface created by triangulation passes through all of the original points while generating some degree of "overshoot" above local high values and "undershoot" below local low values. Original data points are connected in their reference space by a series of triangular faces. This creates a system referred to as the Triangular Irregular Network (TIN) (Northwood, 1999). Northwood (1999) further expands as follows: "Points are connected based on a nearest neighbour relationship (the Delaunay criterion) which states that a circumcircle drawn around any triangle will not enclose the vertices of any other triangle. The surface is then smoothed and fitted to the TIN using a bivariate fifth-order polynominal expression in the X and Y direction for each triangle face. This method guarantees continuity and smoothness of the surface within each triangle."

The Natural Neighbour method is a more complex application and can be somewhat more time consuming depending on system resources. This method is a geometric estimation
technique that uses delimited regions generated around each data point. It is ideal when dealing with highly linear distributions of data as in the case of the SER bathymetry. Northwood (1999) explains that it makes use of an area-weighting method to determine a new value for each grid node. At every node in the new grid, a new natural neighbourhood region is generated that effectively overlies various portions of the original ones surrounding each point. The new grid value is calculated as the average of the surrounding point values proportionately weighted according to the intersection area of each point. This calculation is primarily affected by the minimum separation allowed between data points before aggregation of the points is initiated. It is also affected by the cell size chosen for the final appearance of the grid. Both these options are specified by the user depending on the resolution and visualization criteria.

The result in both cases is a detailed seafloor map (Figure 2) focusing on the immediate area surrounding the SER (see CDROM 1 directory: Base Maps\Local Maps_UTM\GRID\LOCASER\pointgridNN2.tab and LOCASER\pointgridTRI.tab). Other interpolation techniques can also be applied, but the results may not be appropriate for analysis.

**Two-dimensional layered approach**

Most desktop mapping packages use a layered approach in the construction of geographical or geological maps which promotes versatility in data manipulation and which permits juxtaposition of various data sets. Using a base map as the underlying foundation, individual layers of geo-referenced data are plotted to produce a very complete portrait of the SER. For the sake of clarity, the procedure used to develop the visual database will be outlined as a function of the creation of each individual layer. The initial goal of the project involved the integration of data in a 2 dimensional setting
Figure 2: Two-dimensional shaded relief map of the SER. The associated color scheme is shown in the legend box.
Towfish stations

Direct seafloor observations at SER were accomplished using a deep towed system in which a video and still camera package are dragged about 3 m above the ocean bottom behind the research vessel. This method is analogous to walking a traverse on land along a pre-determined path. The observations made by the towfish are recorded as stations at specific time intervals. For any given station, the depth of the towfish and the length of cable that extends from the ship are also recorded. The key problem with the deep towed method, in the absence of a transponder navigation net, is the difficulty in determining with good accuracy the geographical location of the towfish for any given station.

The first stage in determining the towfish's coordinates involves calculating the horizontal distance between it and the ship. The Catenary method (Darling, 1966) is used for this type of problem. It is similar to the Pythagorean equation but is specifically applicable to curves rather than straight lines. As the towfish is dragged behind the ship, the cable retains a curved appearance (Figure 3). Since the length of cable and towfish depth are known, it is relatively simple to determine the horizontal distance from the ship. Using the Excel spreadsheet program, the Catenary equation was applied to the 45 deep towed tracks that were plotted for this project.

Once a good estimate of the ship to towfish distance was known, coordinates could be assigned to the latter by making simple corrections to the positional data for the ship. It is important to note that, unless otherwise stated in the cruise log, the towfish was always assumed to be directly behind the ship. Survey tracks were straight lines to avoid large offsets between the ship and the towfish during turns. Both the wire angle, and the azimuth were also noted at regular intervals.

Subsequently, correction factors were applied to the new towfish coordinates in accordance with those made to the original ship positions. These factors are outlined in Petrie
Figure 3: When a towfish is pulled along behind a ship, the shape of the cable acquires a curved shape that can be approximated by the Catenary geometrical equation. Assuming that at any given time the towfish is directly behind the ship, and that the length of cable being dragged is known, a more precise geographical position can be calculated by applying the formula.
(1995) and serve to convert older Loran C and SatNAV data to the modern Global Positioning System of coordinates used during the most recent cruises. As explained by Petrie (1995), the positional correction factors were determined for each cruise by echo sounding traverses made over a prominent and unmistakable volcanic cone at the shallowest depth of the SER named the "Pimple". The resulting sets of towfish locations from individual cruises are therefore identically geo-referenced with respect to one another and can be plotted together within any desired projection system.

Video and still camera observations: Volcanic facies layer

The first mapping component of this project was the construction of an integrated volcanic facies layer that included deep tow and submersible observations from all cruises to SER. Over 9000 frames of 35 mm still photography, and 315 hours of both black and white and colour video coverage of SER have been archived since the early 1980's. The entire video and photographic archive, which had been previously described in cruise reports and summarized by Petrie (1995), was reviewed again in order to produce consistent results from the perspective of a single observer. A colour code was used to identify specific volcanic facies (i.e., pillowed flows, lobate flows, sheet flows) at each recorded station. With all deep-towed tracks plotted together on one layer (Figure 4), the coverage over the central ridge of the SER was complete. Figure 5 represents the final 2 dimensional volcanic facies map for the SER.

SeaMARC I and SeaMARC II layers

A key goal of this study involved the integration of SeaMARC I (deep tow, high resolution) and II (shallow tow, lower resolution) side scan sonar data within the visual database.
Figure 4: Ship tow tracks for cruises to SER. The combination of all tracks results in extensive coverage of the area. Individual cruises are color-coded as indicated in the legend.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cruise</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>GSC/LDGO</td>
</tr>
<tr>
<td>1988</td>
<td>CUROSS II</td>
</tr>
<tr>
<td>1987</td>
<td>CUROSS I</td>
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<td>CASM VI</td>
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<td>1985</td>
<td>CASM V</td>
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<tr>
<td>1984</td>
<td>CASM III</td>
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<td>1995</td>
<td>CanRIDGE IV</td>
</tr>
<tr>
<td>1994</td>
<td>CanRIDGE III</td>
</tr>
<tr>
<td>1992</td>
<td>CanRIDGE II</td>
</tr>
<tr>
<td>1991</td>
<td>CanRIDGE I</td>
</tr>
</tbody>
</table>
Figure 5: The geographically corrected deep-tow and submersible lithological data was integrated into one volcanic facies map. The map is superimposed on the bathymetry dataset (courtesy of NOAA's Pacific Marine Environmental Laboratory). Though the scale of the map is relatively small, the map is the first such compilation at SER that includes the observations from all cruises to this area.
The first obstacle encountered was the unavailability of the original unprocessed data. Therefore, imagery processed by Petrie (1995) (Figures 6a, 6b, 6c and 6d) had to be used and adapted to the specifications of the software. This imagery had previously been geo-referenced and corrected using a latitude-longitude coordinate system and the WGS 84 geoid. Processed as acoustic raster images of the seafloor, these files were imported into the MapInfo workspace using a versatile, core import utility. In order to modify their projection parameters to fit the base bathymetric data, coordinates of known seafloor features like the “Pimple” and the Magic Mountain hydrothermal site, as well as those of selected points within an embedded grid, were identified and registered in MapInfo. The end result is a geographically compatible overlay of the SeaMARC imagery on top of the bathymetric data (Figures 7a and 7b).

**Structural geology**

Structural representation and interpretation of SER were accomplished through the manipulation of the SeaMARC data and interpretation of the new bathymetric model, all done within the MapInfo workspace (Figure 8). Preliminary work by Petrie (1995) was somewhat expanded upon as a consequence of the increased resolution capacity of more recent software. However, since no new sonar data have been collected, the main focus of work done in this section involved the integration of previous work with the bathymetry within the digital setting.

As in the previous side scan sonar study, fault dips were determined (where possible) by the strength of the returned acoustic reflection, given the known direction of insonification (Petrie, 1995). A strong acoustic reflector (or a strong return reflection in the direction of insonification) produced dark signatures in the images, whereas a weak reflector (or a weak return reflection) produced grey signatures on the images. Shadows, such as those produced by volcanic edifices, resulted in bright white signatures.
Figure 6a: SeaMARC I side scan sonar image produced by Petrie (1995). The image is of a track taken along the north-central ridge crest.
**Figure 6b:** Regional SeaMARC I side scan sonar mosaic produced by Petrie (1995). High backscatter intensities are indicated by dark shades and low backscatter returns are light shades.
Figure 6c: High resolution, 2 km swath width, SeaMARC I side scan sonar image produced by Petrie (1995). The image is a close-up of the main area of hydrothermal activity.
Figure 6d: Regional SeaMARC II side scan sonar mosaic produced by Petrie (1995).
Figure 7a: SeaMARC I mosaic (Petrie, 1995) of the entire SER overlain on the bathymetry model (2 dimensional version with shaded relief).
Figure 7b: SeaMARC II mosaic (Petrie, 1995) of the SER overlain on the bathymetry model (2 dimensional model with shaded relief).
Figure 8: Integrated model of SER structure (modified from Petrie (1995), SeaMARC I mosaic (Petrie, 1995), and 2 dimensional bathymetry (with shaded relief).
Structural observations made with the new bathymetric model were based on the identification of lineations, topographic changes and other major features. Observations were outlined on a separate layer either to stand alone or be compared to, and integrated with, observations made with the side scan sonar imagery.

The structural data were incorporated as a separate layer derived from drawing and highlighting features observed in the sonar images (Figure 9). As a free layer, it can be overlain on top of any mapped data for comparative purposes.

**Geochemical database**

The geochemical database for SER is an assemblage of all previously published and unpublished data from Barrett et al. (1988), Scott et al. (1990), M. Constantin (unpublished), Hannington (1989), and Michael et al. (1989). It includes all whole rock, REE, sulfide and basalt glass analyses done on samples from SER. With MapInfo’s ability to directly import tables from many spreadsheet programs, assimilating all the geochemical results into the SER GIS was relatively simple. The first stage involved the proper geo-referencing of all sample locations.

Location data for the various samples collected in the vicinity of SER also had to be positionally corrected for each specific cruise that did not use the GPS system as a navigational aid. The same factors as for the deep towed tracks were used for this adjustment (Petrie, 1995). Once corrected, sample locations were pooled into one MapInfo table, assigned a symbol and plotted in the geographical grid of the SER (Figures 10a and 10b).

Since the MapInfo package is interactive and queryable, any information including geochemical data, physical description, sample identification, etc., can be viewed by simply selecting the symbol representing the specific sample. Any new results can easily be added from within MapInfo, or by importing a new spreadsheet file.
Structural Geology of SER

Outline of volcanic edifice
Lineations
Crater
Major fault dipping SE
Major fault dipping NW
Boundary of ridge crest
Sediment channels
Figure 10a: Location of all volcanic rock samples recovered at SER (from Scott et al., 1990; Constantin, unpublished; Michael et al, 1989).

Figure 10b: Location of all sulfide samples recovered at SER (from Hannington, 1989).
Distribution of economic metals

SER contains some of the most important (in size) seafloor sulfide deposits discovered to date (Scott et al., 1990). Developing and applying a GIS system to assess the economic potential of SER was one of the main motivations behind this project. Although the number of recovered sulfide samples was too limited to permit any kind of reliable estimate or conclusion as to grade of deposits, the process of integrating and displaying available economic data within the SER GIS is an initial step that can be complemented with further sulfide sampling.

The same process used to assimilate the geochemical sample data was used for the sulfide samples including proper geo-referencing, plotting and display. Within MapInfo, the user has several display options from which to choose that depend on variables such as sample number and distribution. With the limited number of samples for this project, a graduated thematic map theme was used (Figures 11a, 11b, 11c and 11d). This theme assigns a graduated symbol to the dataset. The higher the value for a specific sample, the bigger the assigned symbol. Thus the displayed map will show the concentration and distribution of a particular element by means of the size and location of the assigned symbol.

Ideally, with adequate samples and a good distribution within a certain area, a grid theme could be used to present economic metal concentrations using continuous color variations across a map. It would then be easier to discern, target and further examine areas of interest.

Summary

At this stage a comprehensive and interactive digital database of the SER is now available. By using a staged “construction” methodology, individual geological components are melded together into a broad-based 2 dimensional GIS. Separate datasets can be interchanged,
Figure 11a: Cu (wt%) content in sulfides near the Magic Mountain hydrothermal area. A graduated legend was used to better represent the values for individual samples (data from Hannington, 1989).
Figure 11b: Gold (ppb) content in sulfides near the Magic Mountain hydrothermal area. A graduated legend was used to better represent the values for individual samples (data from Hannington, 1989).
Figure 11c: Silver (ppm) content in sulfides near the Magic Mountain hydrothermal area. A graduated legend was used to better represent the values for individual samples (data from Hannington, 1989).
Figure 11d: Zinc (wt %) content in sulfides near the Magic Mountain hydrothermal area. A graduated legend was used to better represent the values for individual samples (data from Hannington, 1989).
compared and updated to provide an overall picture of the seafloor site comparable to results achieved for land-based exploration surveys. In the case of SER, important information that could be added to the GIS includes the distribution of sedimentary cover and biological organisms throughout the ridge area.

With the technical foundations now established, the stage is set for the manipulation of the GIS in a 3 dimensional environment. The application of various computer techniques can make data presentation and management that much easier, and impressive.

**Three-dimensional data modelling**

Many new seafloor mapping systems can produce real or near real-time results while in the field (or on the ship). This project involved the modeling of archived data and therefore did not necessitate a true real-time capable platform. The 3 dimensional portion of the project was divided into two sections that are nevertheless linked.

The first involves the creation of high-resolution 3D static models of various datasets. The resulting models provide a visualization quality that allows for easier and more precise interpretation of the data.

The second section transforms the still models into fly-through full motion mosaics. Maintaining image resolution within these environments is an important issue. Two different software and hardware systems were used and the results, including limitations and advantages, were compared.
**3D models**

The creation of a 3 dimensional environment from an established GIS is relatively simple to do. For the SER project, the initial stage of still-imagery modelling was accomplished using Northwood Geoscience’s VM software package. The first step in the creation of the SER 3D world involved the next step in processing of the seafloor bathymetric data. All geographical corrections and interpolation techniques applied to the data in the initial building stages of the 2D GIS are fully transferable to VM. VM’s *grid manager* function applies the next set of options needed to render data in three dimensions.

*Rendering images with Vertical Mapper*

With a proper point grid developed earlier, the bathymetric data are immediately ready to be imported into VM’s grid manager. Since the SER data depict bathymetry, a color scheme was assigned for specified depths. Before rendering the file in full 3D, relief shading can be done within the MI workspace by toggling options of the VM grid manager (Figure 2). Whether or not relief shading is added has no effect on the resulting 3D model rendered by VM. The model is displayed in a modifiable environment that allows changes to distance from points of view, camera zoom value, inclination, azimuth, lighting, background characteristics and map boundaries. The final result is an impressive high-resolution 3D image that, for this project, acted as a base layer for various data sets.

A problem occurred when the first 3D bathymetric model was produced using the latitude/longitude coordinate system. Specific seafloor locations with well-known geographical coordinates were markedly offset within VM’s lat/long grid. This distortion is not a bug with either the MI or VM programs. It is better understood as a constraint of using the
latitude/longitude projection system when working in a digital 3D environment. Grids within MI are dealt with as raster images composed of square cells. In order to have square cells, the grids must have the same distance in degrees in both directions. Since the latitude/longitude projection is a spherical one (i.e. the distance between two longitudes decreases from the equator to the poles), MI must distort the raster image, which displaces the location of reference points. If the data to be presented are not geographically sensitive, then the models produced can still serve their purpose. In this case, proper geo-referencing was vital and therefore a simple modification was made. In the end, all data to be modeled in 3D was kept in its original UTM projection system. Since the UTM grid makes use of a consistent unit of measure in both directions (i.e. the distance between two northings or two eastings is always the same), it was the most precise system to use.

**Layers in 3D**

An impressive capability of the VM software is its multi-layered approach to 3D modeling. The grid manager allows the user to drape files of geo-referenced data over an underlying grid. This was at the heart of the creation of the SER 3D digital projection. It is also an important tool for the development of a GIS for any seafloor location.

For the SER environment, the transfer of layers from 2D to 3D is done first by displaying a layer of data (e.g., structures) over the bathymetry layer within MI. This allows VM to create a drape of the overlying data. Once the bathymetric grid is opened in VM, the drape can be loaded and is displayed as an integrated component of the base map (Figures 12a and 12b).

Beyond simply adding drapes to grids, the VM environment allows for the display of multiple individual grids with their associated drape files. For example, analyses of basalt glass
Figure 12a: Three-dimensional bathymetric model of the SER and surrounding sites.
Figure 12b: Three-dimensional bathymetric model of SER with overlain structural data. The overlay is an example of how different information can be draped onto a base grid.
from of the SER were presented as grids created from thematic distribution maps based on the element or ratio values of each sample.

Interpolation techniques were applied to the geochemical tables in order to produce a proper representation of the data. For both the Mg# values and K/Ti ratios, an advanced natural neighbor interpolation was used. With the low sample density for SER, it is important that the value of every sample is plotted. Therefore, the first step of interpolation, which involved data aggregation, was set such that no aggregation would take place. Second, to have a good resolution for the final grid, a cell size (defined in map units; 20 in this instance) was chosen. The following step was perhaps the most important. Interpolation between points separated by large distances is undesirable for this study. It is therefore necessary to limit the area of interpolation based on the geographical distribution of the samples. The Delaunay triangulation setting is responsible for this parameter and for the purposes of this study, a low value of 500 was chosen. Finally, VM offers the user three methods of natural neighbor analysis: 1) constant, 2) linear and 3) slope. The linear solution was the most appropriate because of the distribution of the samples (Northwood 1999a).

The resulting grids could not be draped over a bathymetric grid since they were not related to relief and seafloor topography. The geochemical grids were instead displayed above the bathymetric grid, yet separate from it (Figure 13). Thus the geographical association between each grid was preserved and the proper display of each data set ensured.
Figure 13: Three-dimensional model demonstrating how separate grids containing different data, that are geo-referenced with respect to each other, can be displayed as one image. As an example, in this figure a grid showing K/Ti ratio values, and one showing Mg# values are overlain separately over the base bathymetric model of the SER. The black dots on each grid represent sample locations.
More options with Vertical Mapper

Three other important tools featured in VM's grid manager are the profile tool, the grid trimming tool and the grid re-project tool. These were used in developing and perfecting the SER 3D environment. The accompanying Northwood Geoscience software manuals give a good description of each tool's parameters and capabilities.

Profile tool

The profile tool is designed to display a cross-section of a grid along a line or polyline defined in an MI window. It generates a query of grid values that are then displayed as an X, Y line plot in a VM Graph window (Figure 14a and 14b). Whether the data are elevation (or depth), or geochemistry, or of another type, the graph produced provides a key format to display any relevant data. The Graph window is unique to VM and contains a number of settings that control display and handling of the plot and legend. Within the Graph Window, plots for all spatially coincident grids open at the time of profiling are shown separately.

Grid trimming tool

The 3D grid trimmer tool is a simple function that allows for a given grid file to be trimmed along an outer margin by using a predefined polygon created in an MI window. There were many instances during the SER project where data were concentrated in small areas that did not require a regional sized map to be displayed. Creating smaller maps also allowed for better resolution of certain grid files, since much less data were being processed and displayed.
Figure 14a: Cross-section profile of the SER. The section is located in Figure 14b.
Figure 14b: Location of cross-section (Figure 14a) profile line.
**Grid re-project tool**

With the problems encountered using the latitude/longitude coordinate system, VM's grid re-project tool became an important asset. This tool transforms a grid from its existing coordinate system to another MI supported system. The command makes use of quadratic surfaces to transform X, Y locations in the original grid to the new projection system using four cell blocks (Northwood 1999a). It uses a variation of the bilinear interpolator to re-calculate new cell values at each transformed grid cell. The method has been developed to be accurate to within five percent of the new grid cell size at any location across the new grid extent. For instance, a new cell size of 100 meters will incur a ±5 meters offset. Once again, for certain models, high accuracy is not crucial. Therefore this procedure enables the user to avoid having to re-process the original data tables.

**Full motion modelling**

*Full motion, fly-through kinetic modelling using Fledermaus™*

The two initial fly-through models produced for the SER project were done with the assistance of Dr. Larry Mayer at the University of New Brunswick's Ocean Mapping Group. In conjunction with Interactive Visualization Systems, a software design company in Fredericton, New Brunswick, the Group developed a high-end, full-motion modeling program known as Fledermaus™ initially set up on a UNIX Silicon Graphics system. Both SER models were based on the original bathymetric data archived at NOAA’s Pacific Marine Environmental Laboratory. At this stage, no external geo-referencing was necessary since Fledermaus simply creates its own geographical grid based on the projection system already applied to the data. After choosing an
appropriate color scheme to emphasize depth change, it was a simple matter to import and process the bathymetric table. Once the processing was complete, an impressive high resolution fly-through model of SER seafloor topography was produced.

A notable feature of the Fledermaus package lies in its hardware components. To navigate the environment created, the user utilizes a freehand joystick, which can be moved in mid-air in any direction desired. An ultrasonic link tells the program where the joystick is in space and performs the appropriate translations within the 3D realm. This allows for an unprecedented freedom of movement and manipulation, which can result in the creation of smooth, realistic animations.

The final stage in producing the kinetic 3D SER model with Fledermaus involved the recording of an animation based on a preset flight path. The computer processes the flight path once it is chosen and saved by the user. At each point along the way, environmental parameters including camera angle, speed and elevation (from seafloor) are recorded. The end result is a digital movie that can be viewed on any high performance computer platform, or can be transferred to a television-based format (see CDROM 3 SER2.exe and CDROM 4 SER1.mov).

*Full motion, fly-through modelling using Virtual Frontier*

The Virtual Frontier™ package (VF; Virtual Frontier is a trademark of Northwood Geoscience Ltd.) works in conjunction with MapInfo, but unlike VM, it is an entirely self-contained program. It runs off a Microsoft Windows based PC system. In addition to using MapInfo tables (converted to a grid file by VM), its import utility can auto-detect and convert the following formats: ASCII GRID, CRC-500, DTED, GSC GRID, GeoSoft®, MONA, UK Ordinance Survey Grid, and USGS DEM (Northwood, 1999b).
The SER bathymetric grid was imported and converted within VF (see CDROM 3 VFSER1.exe and VFSER2.exe). The conversion of the file into a textured three-dimensional terrain is simple and relatively quick. Once the terrain is generated, it can be flown over and manipulated. Parameters such as lighting, visibility, background, resolution, velocity and altitude can easily be altered from an options window.

An important feature of VF is its versatility in letting the user edit the 3D environment. For instance, in the case of the SER bathymetry file, markers could be added to indicate the locations of key features (see CDROM 4 VFSER3.exe). Also, drape files generated by VM could be imported and overlaid on base grids. This procedure enabled the production of full motion animations of the facies geology of the SER as draped over the seafloor topography (see CDROM 4 VFSER4.exe). The same technique was applied to the SER sonar data (see CDROM 5 VFSER5.exe and CDROM 5 VFSER6.exe).

All models can be flown through by using the mouse, keyboard or external joystick. Depending on the hardware support for the system, the resampling rate and the number of generated polygons can be adjusted. Reducing the values of these options will improve VF's rendering speed (Northwood, 1999). In addition to free flying, a flight path can be generated and saved by creating nodes via the 2D version of the model shown in an adjoining window. Each node can be edited, allowing for adjustments to elevation, speed, and camera angle. Once the path is complete, VF records a digital movie using a frame-by-frame approach. The end results, as previously seen, are produced in a Movies for Windows (.avi) file format.
CHAPTER 2: GEOLOGY OF THE SOUTHERN EXPLORER RIDGE:
INTERPRETATIONS AND RESULTS

Introduction

The Explorer Ridge system is a 110 kilometer long, northeast-trending area of seafloor spreading that lies approximately 200 kilometers off the west coast of Vancouver Island (Figure 1). The region is characterized by a network of spreading centers and basins that lie north of the Juan de Fuca Ridge and north of the Sovanco Transform. The full spreading rate of the system is about 6 cm per year (Riddihough, 1977; 1984). From a tectonic perspective, Explorer Ridge separates the Pacific Plate from the Explorer Plate, which is in the process of being subducted under western North America via the Cascadia Subduction Zone. Examination by Wilson (1965) and Riddihough (1977) considered the tectonic complexity of the area, including the interaction between the many lithospheric plates. The descriptions of the three main segments that make up the Explorer ridge system, identified as the Southern Explorer Ridge (SER), Explorer Deep and the Northern Explorer Ridge, were put forth by Riddihough (1977, 1984). This fragmentation has produced several distinct segments distinguished by morphology, geochemistry and tectonic setting. Riddihough (1984) and Botros and Johnson, (1988) have interpreted the ridge system as having originated from the Northern Juan de Fuca Ridge. They argue that current features of Explorer Ridge have resulted from the fragmentation of the Northern Juan de Fuca through a series of rift propagating events that took place at around 4 Ma.


**Southern Explorer Ridge**

The focus of this study is specific to the southernmost part of the Explorer Ridge segment referred to as the Southern Explorer Ridge (SER). High-resolution Seabeam swath mapping (Energy Mines and Resources, 1984) was used as the main source of information to provide insight into the tectonic setting and physiology of SER (Botros and Johnson, 1988; Michael et al., 1989; Scott et al., 1990). These early bathymetric data also provided details of the physiography in the immediate vicinity of SER including a short ridge and axial valley system lying just to the east of SER, referred to as the Seminole Segment. Samples of fresh basalts found on the segment’s floor seem to indicate that it is actively spreading (Scott et al., 1990).

A clearer picture of the SER has emerged by applying computer modeling techniques to the data, and using it as a foundation for a GIS. Marine research in the early 80’s depended significantly on the availability of reliable bathymetric data and sonar imagery of the target area. Between 1983 and 1984, an extensive acoustic mapping campaign using Seabeam, SeaMARC II and SeaMARC I sonar took place in the Northeast Pacific and included the SER (Davis et al., 1984; Davis et al., 1985; Davis et al., 1987; Malahoff et al., 1984). Complete processing and geo-referencing of the acoustic data were completed in 1995 (Petrie, 1995). Models produced in Chapter 1 allow for a much more quantitative and integrated interpretation of the SER’s physiography.

Over the years, acoustic imagery was accumulated and combined with results from cruises that made use of various geographical locating techniques in conjunction with deep towed camera/video equipment (CASM III, 1984; CASM V, 1985; GSC/LDGO, 1985; CASM VI, 1986; CUROSS I, 1987; CUROSS II, 1988, CanRIDGE I, 1991; CanRIDGE II, 1992). This provided an opportunity for the study and description of the physiography and tectonics of SER.
Previously, researchers relied on seismic data (Hyndman et al., 1978), seismic sounding surveys (Malecek and Clowes, 1978), marine magnetics (Atwater, 1970; Peter and Lattimore, 1969; Riddihough, 1977) and some gravity data (Stacey, 1973). Using the more recent data, Kappel et al. (1986) suggested that effusive volcanism rather than tectonic processes was the key factor responsible for the construction of the ridge. It has also been proposed that SER is lengthening northward (Scott et al., 1990), a suggestion supported by magnetic data (Botros and Johnson, 1988).

In addition to ridge building, the formation and evolution of the axial trough have been addressed. A model developed by Kappel and Ryan (1986) for ridge segments along the southern Juan de Fuca has been applied to the SER. The authors interpreted the formation and evolution of the crestal ridge as the result of non-steady state processes. A comparison between steady state and non-steady state evolution as applied to the SER is discussed in a later section.

The discovery of sulfide deposits by deep-sea photography and the Pisces IV submersible in 1984 (Scott et al., 1985; Tunnicliffe et al., 1984, 1986) encouraged further marine research at SER. So far, over 60 sulfide deposits have been located along the ridge’s axial graben (Scott et al., 1985, 1986, 1990, 1995; Tunnicliffe et al., 1986). Manned submersible observations using the Pisces IV led to the discovery of Magic Mountain, at 300m in diameter the most prominent hydrothermal vent field identified so far at SER (Tunnicliffe et al., 1986). Another vent field referred to as AGOR 171 was located by means of mapping its hydrothermal plume in the water column above the ridge (McConachy and Scott, 1987). Scott et al. (1990) reported on the composition and mineralogy of some of the recovered samples; more analyses were carried out by M. Constantin (unpublished). Both sets of data indicate high base metals, but gold values are among the lowest in the northeast Pacific (Hannington et al., 1986).

Basalt samples were first dredged from the region in 1969 (Grill et al., 1981). Extensive petrological and geochemical work was performed on samples recovered from SER by Michael
et al. (1989) and Constantin and Scott (1994). Studies of incompatible elements in these MORBs
(Michael et al., 1985; Shea et al., 1985; Shea, 1987) have shown a compositional diversity
proximal to the shallowest, dome part of the SER which suggests that the underlying magma
chamber is not long-lived, nor is it well-mixed. Further petrogenetic study of the basalts is in
progress (Constantin et al., in prep.).

Observations

Physiography and geochemistry

Published (Barrett et al., 1988, Hannington, 1989, Michael et al., 1989) and unpublished
(M. Constantin, pers. comm.) analytical data for SER basalts were integrated with new
SeaMARC/bathymetric models described in Chapter 1. Physiography and ridge morphology
described by Michael et al. (1989), Scott et al. (1990) and Petrie (1995) are expanded upon based
on three-dimensional models produced in Chapter 1. The latter models are also used to observe
more clearly the changes in ridge trend, or “devals” (Michael et al. 1989), seen along the SER.

Basalt glass geochemistry is used to determine and distinguish the discrete sections of the
SER and any correlation there may be with the ridge’s physiology. This type of correlation was
suggested by Michael et al. (1989) as further evidence of the subsegmentation of the SER.

Geochemical parameters presented in the present study include the incompatible elements K and
Ti as analyzed in basalt glasses. The K/Ti ratio is an indication of the state of mantle source
enrichment of erupted mid-ocean ridge basalts (depleted, transitional, and enriched) and serves to
distinguish mantle sources that give rise to these basalt types (Hekinian et al., 1989). Major
basaltic chemical classes are recognized by the following K/Ti ratio values: <0.14; depleted
basalts, 0.14-0.25; transitional basalts, and >0.25; enriched basalts.
Mg# values (100 x Mg²⁺/(Mg²⁺ + Fe²⁺)) indicate how evolved the ridge basalts are. Hekinian et al. (1989) define the least evolved basalts as having Mg# values of 66-70, the more evolved as having Mg# values of 58-66, and the most evolved as having values of 55-61.

Petrie (1995) defined in broad terms three morphologically discrete segments of the SER: north, south, and central. Added to this is the axial dome section that refers to the area encompassing the shallowest portion of the SER. This established separation is used to develop a more comprehensive interpretation of the SER as a whole.

**Southern section**

Proceeding from the southern tip of the SER, the GIS imagery shows a gradually narrowing trough with a smooth floor (Figures 15a and 15b). Smoothing of the floor was most likely caused by basalt flows emanating from the flanks or crest (Scott et al., 1990). Any pre-existing axial ridge in this area has almost disappeared and is only distinguished by a scattered series of small remnant volcanic cones (Petrie, 1995). There is no apparent axial graben and the walls of the trough are somewhat less defined (Figure 16).

Further up the ridge, a transition point is reached where the ridge morphology begins to vary. An axial crest begins to rise from the slightly narrowing trough floor (Figure 16) and a structural feature affects the relief of the western wall. The latter evolves from being relatively smooth and of low relief to being about 50 meters above the eastern wall (Figure 16). Strong SeaMARC I reflector characteristics associated with the western wall are interpreted to be the signature of a major normal fault with a ridge parallel strike (Petrie, 1995). In this section of the SER, any normal faulting along the eastern wall is not clearly defined on the side scan sonar.
Figure 15a: Three-dimensional model of the bathymetry of the SER's southern section. The view has a vertical exaggeration factor of 1.50 and an inclination of 30° towards the south. Inset shows the sectioning of the SER.
Figure 15b: Three-dimensional model of the SeaMARC I sonar mosaic (from Petrie, 1995) overlain on the SER's southern section bathymetry. The view has a vertical exaggeration factor of 1.50 and an inclination of 30° towards the south. Inset shows the sectioning of the SER.
Figure 16: Three-dimensional cross-section profile of the SER's southern section. The view has a vertical exaggeration factor of 2.00 with an inclination of 30° towards the southwest. Inset shows the location of each profile line.
images. The morphology suggests that this part of the ridge is magma starved, as proposed by Michael et al. (1989). Nevertheless, both side scan and bathymetric data indicate the presence of well-defined volcanic structures.

**Geochemistry of the southern section**

The observation and interpretation of geochemical patterns in the southern part of the SER must take into account that it has not undergone recent, large scale volcanism as have the volcanically younger sections to the north (Michael et al., 1989; Scott et al., 1990). Also, sampling in this section was limited. Taken together, these compromise interpretation of the analytical results from these samples.

Geochemical analyses of basalt glass suggest that the southern section of the SER is characterized by varying compositions (Figures 17a and 17b). Two samples from the northernmost part of the section show some of the highest Mg# values analyzed at SER suggesting the local eruption of more primitive basalts. Samples range from more evolved to more primitive towards the south. However, with only 5 samples recovered in an area that is nearly 25 kilometers long, any spatial analysis is not robust.

The K/Ti incompatible element ratio values are quite constant throughout the southern section (Figure 17b). This part of the SER is characterized by moderately enriched transitional basalts. The two samples near the southern tip of the ridge are slightly more enriched and show undepleted basalt characteristics according to Hekinian et al.'s (1989) classification scheme. As was the case with the Mg# values, any transition or continuum between sample sites cannot be determined.
Figure 17a: Three-dimensional geochemical model of the SER's southern section. The overlying grid contains the Mg# values for this part of the ridge. Sample locations are shown on both displayed grids (black dots). Geochemical data is from Michael et al. (1989), and Constatin (unpublished). The view has no vertical exaggeration factor and an inclination of 35° to the west.
Figure 17b: Three-dimensional geochemical model of the SER's southern section. The overlying grid contains the K/Ti ratio values for this part of the ridge. Sample locations are shown on both displayed grids. Geochemical data is from Michael et al. (1989), and Constantin (unpublished). The view has no vertical exaggeration and an inclination of 35° to the west.
**Central section**

The central section of the SER is the most structurally complex. The transition between the southern and central section is marked by a major fault crosscutting the ridge along a NNW-SSE trend (Figure 18). Figure 19 is a three-dimensional profile of this central section fault which also marks an important transition in both relief and structural characteristics. Major ridge features appear to be continuous across the fault (Figure 18). The fault lineament indicates that it is continuous for some distance beyond the graben walls, and disappears at the edge of the SER’s flanks. Normal faulting along the eastern wall (Figure 20) becomes increasingly well-defined north of the central section fault. It essentially marks the beginning of SER’s well-developed axial graben. It also marks a change in cross section profile. The dominant elevation between the graben walls passes over to the eastern flank and remains as such northward along the rest of the defined graben (Figure 21). The southernmost of two major volcanic mounds on the eastern wall specifically marks this relief change and is clearly visible on SeaMARC I imagery (Figure 22). The central section fault is further emphasized by a high standing structure centered on the axial ridge (Figure 18). On the western side, bathymetric data suggest the presence of a collapsed feature overlying the central section fault. Movement on the fault is difficult to determine and is reviewed under “Discussion”.

Approximately 2.9 kilometers south of the axial dome, the western wall shows a 320 meter offset following a NE-SW trending lineament that seems to indicate a sinistral movement (Figure 23). Two similar, less distinct bends or kinks are found at 4.45 kilometers and 6.40 kilometers south of the axial dome along the western wall and show sinistral and dextral movement respectively. Possible faults responsible for these features cannot be resolved with the current bathymetric models.
a vertical exaggeration of factor of 1.50 and an inclination of 35° to the south.

central section fault (CSF) and a volcanic mound on the axial ridge. The view has
Figure 18: Bathymetry of the SYN's central section depicting the locations of the
Axial Ridge
Central Synclinal Section
CSF
point 1: depth = -2243 m
point 2: depth = -2109 m
point 3: depth = -2238 m
point 4: depth = -2086 m
point 5: depth = -1940 m
point 6: depth = -1762 m
point 7: depth = -2010 m
point 8: depth = -1853 m

Figure 19: Three-dimensional profile of the central section fault (CSF). Depth values for individual sites are identified. Inset shows the trace of the fault. The view has a vertical exaggeration factor of 1.50 and an inclination of 8° towards the southeast.
Figure 20: Three-dimensional SeaMARC I mosaic (modified from Petrie 1995) depicting the normal faulting along the eastern wall of the SER's central section. The view has a vertical exaggeration factor of 3.00 and an inclination of 30° to the southwest.
Figure 21: Three-dimensional profile of the central section bathymetry. The central axis, and western and eastern walls are identified.Inset shows the location of each profile line. The view has a vertical exaggeration factor of 2.00 and an inclination of 30° towards the southwest.
Figure 22: Three-dimensional SeaMARC I mosaic (modified from Petrie 1995) of the SER's central section. The central section fault (CSF) and two major volcanic mounds are identified. The view has a vertical exaggeration factor of 2.00 and an inclination of 30° to the south.
Figure 23: The western wall within the central section is offset in certain locations. The three identifiable offsets are indicated.
The most noticeable morphological feature of this section is clearly the ridge offset defined by Michael et al. (1989). An overlapping spreading center is distinctly visible in this area (Figure 24). The overlapping spreading center in the central section is defined as two separate axial spreading ridges. The western axial spreading ridge is currently SER's predominant spreading ridge and is much better defined than the eastern one. It preserves a general ridge-parallel trend of 027° (Scott et al. 1990) until it becomes indistinguishable in the vicinity of the axial dome. Strong acoustic shadows (bright white on SeaMARC I images), interpreted to be volcanic edifices by Petrie (1995), occur all along the western axial spreading ridge. The sonar data are complemented by marked variations in bathymetry along that part of the axial spreading ridge.

The eastern axial spreading ridge is apparent on the new bathymetric model (Figure 24). It is less high standing and lies at the bottom of East Valley. It appears to be discontinuous just past the halfway point of its total length. The strike varies from 036° at the southern end to 039° at its most northern extremity (Figure 25). There is no evidence (from deep towed observations) to indicate any recent magmatic activity emanating from this ridge.

**Geochemistry of the central section**

Figure 26 is a three-dimensional model showing Mg# values for the SER's central section. Although samples in the southern part of the central section are few in number, they are well distributed. In addition, this section appears to have undergone some relatively recent volcanic activity (Petrie 1995) especially in the vicinity of the central section fault. Therefore, more reliable observations and interpretations can be made than was possible for the southern section.
Figure 24: Three-dimensional bathymetry model of the SER's central section emphasizing the western and eastern axial spreading ridges that make up the overlapping spreading center (OSC). Inset is a two-dimensional view of the OSC.
Figure 25: Bathymetric model of SER showing a variation in strike of the eastern ASR.
Figure 26: Three-dimensional model showing the Mg# values for the SER's central section. The location of samples is represented by black dots that are reproduced on each displayed grid. The view has no vertical exaggeration and an inclination of 30° to the west.
Compositions of basalt glass appear to be affected by both the central section fault and the overlapping spreading center. The central section fault marks a geochemical transition from some of the most evolved basalts to the south, to more primitive ones to the north. In fact, the entire central section is made up of some of the least fractionated magmas at SER. It is also notable that there does not appear to be a high \( \text{Mg}\# \) variability, though any elaboration is inhibited by the paucity of samples.

The entire length of the western axial spreading ridge is characterized by samples with slightly higher \( \text{Mg}\# \)'s than the off axis samples. The next transition occurs at the northern boundary of the section where sampling was quite extensive. Here, the change in \( \text{Mg}\# \) values is apparent. It begins at the western wall offset south of the axial dome. At this point, the generally constant low values of the central section are replaced by higher, and highly variable \( \text{Mg}\# \) values. More observations associated with this offset are included with the observations of the axial dome.

Figure 27 is a three-dimensional model showing \( K/\text{Ti} \) ratio values for the SER's central section. The central section fault also marks a south to north change in basalt enrichment relative to the southern section. Samples from the north side of the fault consist of transitional to undepleted basalts. The offset caused by the overlapping spreading center appears to be an east to west transition boundary. The east to west trend associated with the overlapping spreading center involves an abrupt change from undepleted to transitional lavas. Samples recovered on or near the eastern axial spreading ridge are more enriched (undepleted basalts) than those recovered from the western axial spreading ridge (transitional basalts).

As with \( \text{Mg}\# \)'s, an increase in local variability near the central section fault is also likely though, once again, low sampling density leaves little room for interpretation. The general south
Figure 27: Three-dimensional model showing the K/Ti ratio values for the SER’s central section. The location of samples is represented by black dots that are reproduced on each displayed grid. The view has no vertical exaggeration factor and an inclination of 30° to the west.
to north trend involves an enrichment of the basalts from transitional to undepleted whereas Mg# values remain relatively constant.

**Northern section and the axial dome**

The new bathymetric modeling allows an unparalleled view of the SER's axial dome. The key difference with respect to the other sections of the SER is the dominance of volcanic features. Extension in this area is clearly associated with significant magmatism (Kappel and Ryan, 1986; Scott et al., 1990). The biggest casualty of this transition is the axial graben. It's definition begins to be lost immediately at the boundary with the central section. The elevation of the western wall eventually becomes virtually indistinguishable from the background relief of the dome. On the other hand, both the axial spreading ridge and the eastern wall can clearly be traced over the dome (Figure 28).

The width of the eastern valley becomes progressively narrower towards the north. Just south of the axial dome, it is about 280 meters wide. Slightly to the north, the valley is no more than 90 meters wide. About 2.4 kilometers northeast of the center of the dome, the eastern wall loses its definition. Only the central axial ridge remains relatively intact though less defined.

The trace of the axial spreading ridge in Figure 28 clearly indicates a gradual change in trend. The strike changes from 019° south of the dome to 033° on the northern side. On a smaller scale, these changes are associated with a series of faults trending 136° located just to the north of the bathymetric minimum. The lack of horizontal offset associated with these faults would indicate that they are likely planes of normal movement. At this resolution, only the major structures can be observed. It is probable that smaller-scale, parallel faults are also present in the
Figure 28: Three-dimensional bathymetry model of the northern section and axial dome including major structures and features. The view has a vertical exaggeration factor of 2.00 and an inclination of 60° towards the southeast.
Figure 29: Three-dimensional cross-section profile of the northern section and axial dome. The eastern wall and axial spreading ridge are well defined. The view has NO vertical exaggeration and an inclination of 25° to the south. Inset shows the profile lines for each cross-section.
area. Large and extensive volcanic structures are present all over the axial dome, but especially in the vicinity of these large faults.

The profile of the axial graben undergoes another important change that supports the idea of increased influence of magmatism on ridge expansion. Figure 29 shows the inflation of the axial spreading ridge to a level that exceeds the height of both graben walls. Over a distance of 500 meters, the elevation of the axial spreading ridge changes from being deeper than the eastern wall, to almost 50 meters higher. The axial spreading ridge culminates at a shallow depth of 1760 meters at a point known as ‘the Pimple’ or bathymetric minimum (Scott et al., 1990; Petrie 1996). The site is dominated by a large volcanic edifice clearly visible on side scan imagery (Petrie, 1995).

To the northeast, beyond the SER’s shallowest point, the ridge quickly becomes narrower and more disorganized. Volcanic features still dominate and no clear tectonic pattern is visible at the GIS’s resolution. On the other hand, PISCES IV submersible observations show the presence of horst and graben and box canyon topography on the northern flank of the axial dome (CASM IV, 1986; Scott et al., 1990). The main axial ridge can still be traced out to nearly 17 kilometers past the center of the axial dome. A final deval brings its trend to 008°.

**Geochemistry of the northern section and axial dome**

Analyses of basalt glasses from the axial dome (Michael et al., 1989; M. Constantin, unpublished) yield highly variable Mg# values (Figure 30) indicating variable degrees of magma evolution. Numerous studies have interpreted this diversity in basalt composition to preclude the existence of a long-lived, well-mixed magma chamber beneath the SER (Michael et al., 1985;
Figure 30: Three-dimensional model showing the Mg# values for the SER's axial dome and northern section. The location of samples is represented by black dots that are reproduced on each displayed grid. The view has no vertical exaggeration and an inclination of 30° to the west.

★ indicates the location of Magic Mountain
Figure 31: Three-dimensional model showing the K/Ti ratio values for the SER's axial dome and northern section. The location of samples is represented by black dots that are reproduced on each displayed grid. The view has no vertical exaggeration and an inclination of 30° to the west.

* indicates the location of Magic Mountain
1989; Shea et al., 1985; Shea, 1987; Scott et al., 1990). In general, K/Ti values (Figure 31) are more constant on the axial dome with only local exceptions.

Taking into consideration the local variability in K/Ti values, the majority of samples in the vicinity of the central dome are undepleted basalts. However, certain samples, specifically in the vicinity of the Magic Mountain site, are highly enriched, undepleted basalts. Samples further north beyond the dome are also of undepleted basalt.

The transition seen in the Mg# values appears to be associated with a major structure transecting the SER on the northern edge of the dome (Figure 28). The latter is the second in a series of three parallel NW-SE trending faults. They mark the change from highly variable to more constantly low to moderate values. Associations and correlations for any pattern seen further north, are unclear due to the low sample density. However, an area approximately 11 kilometers northeast of Magic Mountain is characterized by more highly variable Mg# values. The combination of consistently highly enriched, variably evolved basalts covering the axial dome is further evidence suggesting that lava flows in this area are isolated and temporally discrete, but emanate from a single underlying magmatic source. Magma from the source made it’s way to the near surface filling individual chambers, which allowed for the different degrees of basalt evolution as seen in the recovered samples.

**Volcanic facies**

Figures 32a, 32b, and 32c show a series of volcanic facies maps featuring different display parameters. These maps were constructed from data collected during all relevant cruises to the SER (CASM III, 1984; CASM V, 1985; GSC/LDGO, 1985; CASM VI, 1986; CUROSS I,
Figure 32b

- Pillowed flows; interpreted contact
- Lobate flows; interpreted contact
- Sheet flows; interpreted contact
- Marker point
Figure 32a: Two-dimensional volcanic facies model for the SER. Only the unit outlines are shown in order to emphasize the relationship with the underlying bathymetry (data from CASM III, 1984; CASM V, 1985; GSC/LDGO, 1985; CASM VI, 1986; CUROSS I, 1987; CUROSS II, 1988, CanRIDGE I, 1991; CanRIDGE II, 1992).

1987; CUROSS II, 1988, CanRIDGE I, 1991; CanRIDGE II, 1992). Video and still photography obtained using the ROPOS remotely operated vehicle (CanRIDGE III 1994; CanRIDGE IV 1995) could not be included in this model. Scale size for the available bathymetric data was too large to accommodate the area covered by ROPOS. However, this video and photography was used to compare the physical characteristics of the flow types. The map units, made up of separate flows, were delimited based on the dominant flow type characterizing a given area. The volcanic facies that were identified are sheet, lobate and pillow.

Sheet flows show a somewhat subdued south to north change in distribution. The southernmost sheet flow unit extends from the floor of the axial valley (to the south of the axial spreading ridge's starting point), to the east side of the rising axial spreading ridge. Finally, it overlaps the eastern graben wall on to the flank of the ridge. A much smaller sheet unit lies just to the north. It seems to be restricted to the crest and flank of the eastern wall. The third unit is located just to the southeast of the axial dome approximately 1.7 km from the eastern wall in an area of notable relief associated with constructional volcanism. This unit is in near contact with the next sheet flow that extends from south of the dome to north of the bathymetric minimum (Figures 32a, 32b, and 32c). The latter flow overlaps the crest of the axial spreading ridge and the crest and flank of the eastern wall. The areas of the bathymetric minimum and the Magic Mountain hydrothermal field both lie within its boundaries. Two more sheet units lie slightly removed from the ridge: one to the northwest of the dome and the other on the eastern edge of the map. Coverage in these areas was not extensive, so observations are not conclusive.

There are three main units of lobate flows at SER. The first two lie off the ridge axis at the edge of the eastern flank. The third main unit stretches from the southern section of the SER to just north of the axial dome. The flows are mainly concentrated along the floor of the axial valley. Certain sections of the axial spreading ridge (including the area of the offset) are dominated by this unit. About 5 km south of the dome, the unit spills over both the western and
eastern graben walls. At its contact with the central sheet flow unit, the lobate unit branches off with one arm extending to the western side of the axial dome, and the other to the east and on to the north.

Pillowed flows, as previously mentioned, occur throughout the SER. Nevertheless, there are three areas where the flows are extensively pillowed. The main unit extends from the southern to the northern edges of the map covering the entire eastern flank of the SER. Only in the southern section does this unit span the width of the SER, including both walls and the axial spreading ridge. The northern part of the unit overlaps and encompasses the Seminole Segment. It is more likely that other flow types also characterize this area, but limited coverage prevents a more detailed observation. A central unit of pillowed flows extends from the map’s northern edge to the axial dome. It encompasses the northern part of the axial spreading ridge as well as the eastern side of the dome itself. To the west, the last pillowed unit covers the western edge of the dome and map, and extends south including part of the western wall.

Discussion

*Correlation between ridge crosscutting structures and geochemistry*

Limited by locally concentrated sampling, geochemical patterns can be seen only in the vicinity of the axial dome, and the boundary between the central and southern sections. Both these sites feature major tectonic structures that affect the spatial distribution of lavas that have varying degrees of evolution and enrichment.

Basalts near the central section fault and overlapping spreading center show geochemical characteristics that are similar to those found on the axial dome. Even with the limited number of samples it is apparent that separate eruption events in this area have yielded a spectrum of
compositionally variable basalts similar to the pattern seen at the axial dome. The CSF may be a structural weakness that allowed for easier, more direct access of lavas to the seafloor. Michael et al. (1989) make reference to a flow originating from the bathymetric minimum as a source for transitional basalts near the central part of the SER. This same process, exemplified by documented cases of extensive dikes at Hawaii and Iceland (Sigurdsson and Sparks, 1978), would serve to explain the diversity of basalt compositions seen in the vicinity of the central section fault.

Langmuir et al. (1986) observed that highly evolved basalts tend to erupt in association with small axial deviations and larger overlapping spreading centers. This seems to be the case at SER where highly evolved basalts were recovered within the area of the overlapping spreading center and central section fault. Interestingly, an even clearer pattern associated with the offset is observed in the K/Ti ratios in this area. A sample taken along the eastern axial spreading center is highly enriched while that taken from the western axial spreading center is depleted. It appears that different magmatic regimes characterized the volcanism along each ridge.

The structural geology of the axial dome is most likely more complex than is observed on the new SER bathymetry model. Even so, the resolution of 150 meters is adequate to identify certain major crosscutting faults. Three of these faults are found to the north of the axial dome.

These structures seem to be linked to the area of the highest compositional variability of the basalts. It is likely that multiple underlying short-lived, unmixed magma chambers, as explained by Michael et al. (1989) and Scott et al. (1990), have used these faults as conduits to bring lavas to the seafloor. In fact, their presence may be responsible for the prevention of the formation of a longer-lived, more continuous chamber. It is hypothesized that magma rising from the deeper source region under the dome is given relatively easy access to the seafloor via these faults, preventing a longer-term accumulation and residency in the subsurface.
These faults also crosscut the major along-axis normal faults that define the axial graben. This factor, in conjunction with smaller scale normal faults producing horst and graben topography (Scott et al. 1990), is also an important factor in the focusing of hydrothermal activity. The intersection of these faults could produce fluid pathways of high permeability that control the distribution of sulphide deposits, as proposed by Scott (1978) for the Hokuroku district in Japan. The Magic Mountain hydrothermal area, the largest sulphide deposit known at SER (Tunnicliffe et al., 1986; Scott et al., 1985, 1990), lies near the intersection of the eastern graben normal fault system and the first major crosscutting northern fault. Although it has never been visually confirmed, the AGOR 171 hydrothermal anomaly identified by McConachy and Scott (1987) apparently lies on or near a series of faults that transect sheet flows (Figure 6a). The axis-parallel western normal fault system may underlie this area thus creating a similar intersection point. Figure 6a also shows a bright “white patch” over the AGOR 171 site that can be explained by the venting of hot water that absorbs or refracts the sonar waves causing a low backscatter signature.

The bathymetric minimum (“Pimple”) of SER lies just south of the intersection between the second northern fault and the axial spreading ridge. Once again these types of sites tend to focus more extensive volcanic activity that result in the building of large and high standing volcanic structures. The more constant trace element values in this area suggest that erupted material came from the same deep source but that individual flows had varying residency times in discrete, shallow subsurface magma chambers. This allowed for each flow to fractionate differently.

Just north of the second transecting fault, the axial spreading ridge undergoes another deviation in axial linearity, or ‘deval’. The ensuing transition from primitive to evolved magmas is therefore an expected occurrence that further indicates the influence of such structures on the
composition of the ridge basalts. However, the noticeable sample paucity in that area renders any conclusions speculative.

**Volcanic facies**

Lava types found at SER are a consequence of such physical properties as flow temperature, viscosity and effusion rates. Assuming a constant lava chemistry, a variety of physically different lava forms are produced through eruptive events. This spectrum of lava morphology is caused by (or is at least partially dependant upon) changes in the physical conditions associated with submarine eruptions.

Bonatti and Harrison (1988) describe the physical factors that promote the formation of sheet and pillowed flows during seafloor eruptive events. In their model, sheet flows are characterized by 1) high temperature, 2) low crystal/liquid ratio, 3) low viscosity and 4) high discharge rate of the lava. In addition, Ballard et al. (1981) concluded that sheet flows are indicative of brief eruptive events and that they constitute the lower member of discrete sheet-pillow assemblages. The occurrence of the most important sheet flow unit at SER over the main dome area is consistent with the assumption that the volcanic regime in this area is the most recent example of higher intensity volcanism. Most of the hydrothermal activity observed thus far at SER is proximal to the sheet flow unit. Observations recorded by Ballard et al. (1981) at other seafloor spreading sites indicate that most hydrothermal activity can be found within the zone of most recent volcanism. Thus hydrothermal activity tends to follow the same cyclic pattern as the volcanism. The timing and spatial relation of volcanism has been explained by magma rising to the surface from ridge-axis chambers and being temporarily stored in an underlying dyke system where it interacts with fluids circulating through the highly fissured upper crust (Ballard et al. 1981).
Pillowed flows are indicative of higher viscosity, higher crystal/liquid ratio, lower temperature and lower discharge rate than for sheet flows. Pillowed lavas are also associated with more prolonged eruptive events than are sheet flows (Ballard et al. 1981). Eruption sequences along the rift zone of a spreading center initially occur as brief, more intense events (sheet flows) followed by sustained events (pillowed flows) coming from discrete locations along the rift (Ballard et al., 1981). At SER, the dominance of pillowed flows is more likely due to the fact that they represent the last stages of older sequences of volcanic activity. Sheet flows do tend to underlie the pillowed units that are proximal to the ridge as observed in photographic and video footage (CASM III, 1984; CASM V, 1985; GSC/LDGO, 1985; CASM VI, 1986; CUROSS I, 1987; CUROSS II, 1988, CanRIDGE I, 1991; CanRIDGE II, 1992; CanRIDGE III, 1994; CanRIDGE IV, 1995). Lobate flows are an intermediary type of flow with physical parameters in between those for pillowed and sheet flows. At SER, they are concentrated relatively near the ridge and also in proximity to the axial dome.

Because of the rapid spatial variation of lava types at SER, a more detailed study of the relationship between sheet, lobate and pillowed flows at SER is needed to fully understand the local volcanology. It would provide a clearer picture of the sequencing of the various flow types within a given stratigraphic assemblage. The scale at which the available bathymetric data was produced is too small to appropriately analyze and interpret the smaller features that define a specific assemblage.

**Evolution of the crestal ridge at SER**

The resolution of the bathymetric models enable detailed investigation of the axial topography. Of particular interest is the physiography of the axial spreading ridge. Kappel and Ryan (1986) discuss two separate models for the evolution of crestal ridge topography at various
spreading centers along the Juan de Fuca Ridge: a steady state model and a non-steady state model.

The steady-state model explains how the zone of axial rifting at low-spreading rate midocean ridges coincides with steady state depression (Atwater and Mudie, 1968, 1973; Deffeyes, 1970; Macdonald, 1982). In simple terms, ocean crust at seafloor spreading centers is created in a narrow zone in the middle of the rift and moves progressively away from the axis as subsequent eruptive events split the solidified lavas of the previous events (Harrison, 1968; Cann, 1968). Young crust migrates out of the rift valley by stepping up a series of inward facing normal faults. Crestal terrain is tectonically reorganized as it moves further away from the rift axis, which leads to a decrease in vertical offset of the scarps, and a reversal of fault dips (Atwater and Mudie, 1968, 1973; Macdonald and Luyendyk, 1977; Macdonald and Atwater, 1978) and a rotation of fault blocks (Davis and Lister, 1977; Harrison and Stieltjes, 1977; Laughton and Searle, 1979). Sleep (1969) and Lachenbruch (1973) proposed that rift valleys on slow-spreading ridges were depressions caused by hydraulic head loss and viscous drag in a narrow conduit of upward flowing asthenospheric material. Tapponier and Francheteau (1978) instead proposed that the depression was created by the extension and necking of the lithosphere near the axis. A third theory suggested by Deffeyes (1970), Palmasson (1973) and Anderson and Noltimier (1973) explains the formation of the axial depression to be the result of the disproportion in the widths of the axial extension zone and axial volcanic zone.

The non-steady state model suggests that the formation and evolution of an axial trough follows a variable cycle. Kappel and Ryan (1986) define it as a cycle that includes periods in which there is 1) extrusive volcanic construction which widens the crestal ridge prior to the collapse of the summit depression, 2) collapse within the summit region of the crestal ridge to form an axial trough during a phase of volcanic inactivity, and 3) renewed magmatism in the axial trough as its floor widens by extension and brittle fracture of the upper crust. This episodic
model implies that the width of the young seafloor affected by volcanic extrusion or dominated by tectonic stretching varies through time.

Kappel and Ryan (1986) noted six main points of crestal ridge characteristics from side scan sonar observations which led to their characterization of the non-steady state model: 1) the plan view shape of crestal ridges is bow-like; 2) the flanks of the crestal ridge have a scroll-shaped form in cross section; 3) the flanks of the crestal ridge have few observable faults and fissures, and contain a texture of overlapping bulbous mounds; 4) where the axial depression has a constant width, it has a nearly constant depth, and its floor is flooded by volcanic flows that postdate the flows on the rim of the ridge; 5) where the axial depression is of variable width, the narrowest parts are the shallowest and the widest parts are the deepest, and in many instances the floor of the valley contains flows that are broken from, but were once contiguous with, those on the rim; and 6) where the axial depression is wide enough to contain a nascent crestal ridge, its floor is extensively faulted and fissured, and these faults and fissures are, in part, covered by flows. Kappel and Ryan (1986) used these points to explain crestal ridge evolution at their study areas to be the result of a non-steady state, relatively short-lived process. They consider the crestal ridge to be primarily a volcanic construction and the axial trough to be collapsed in the ridge’s summit. Scott et al.’s (1990) description of the SER being likened to an “elongate seamount” is consistent with this model.

The same type of model best applies to the SER to explain the formation and evolution of the axial trough. The bow-like shape is evident in side profile (Figure 33), and transects yield a similar profile to that described by Kappel and Ryan (1986). Petrie (1995) described only minor amounts of faulting on either flank of the ridge. In addition, in side scan images he observed that constructional volcanism was the predominant feature along and beyond the flanks. Concerning axial depression width, the central section remains generally constant as does the depth of the valley floor. The width varies along the southern section. In accordance with the model proposed
Figure 33: Three-dimensional side profile of the SER's bathymetry. This view has a vertical exaggeration factor of 3.00 and an inclination of 10° towards the east.
by Kappel and Ryan (1986), the widest section is the deepest whereas the narrowest is the shallowest. SeaMARC I images interpreted by Petrie (1995) indicate extensive along-axis faulting of the valley floor in the area where a central axial ridge crest is present. In the vicinity of the axial dome, the axial graben loses definition. Extensive faulting can still be observed on the eastern side of the dome, but likely more recent flows have covered structures on the western side (Davis et al., 1984). At this point, the central axial ridge is the shallowest component. The eastern wall still acts as a barrier to lava flows moving in that direction. On the other hand, the western wall is almost entirely absent allowing for volcanic flows to travel down slope to the western edges of the ridge.

A non-steady state model applied to the SER also explains the distribution of discrete volcanic centers along the ridge. This model involves a periodicity in the magmatic regime. During periods of heightened activity and magma supply, it is more likely that material originates from the most inflated portion of the ridge, travels laterally and erupts along its axis. The SER, especially in the region of the axial dome, is currently in one of these periods of high volcanic activity, equivalent to the T1/T2 stages of Kappel and Ryan (1986).

Bathymetry in the southern reaches of the SER is more in line with the later T3 and T4 stages of development. This section is relatively highly tectonized and shows no signs of any recent volcanic activity. This is an added indication that ridge evolution at SER is determined by periodicity in the magmatic regime. The southern section may be showing the remnant morphology of a previous time of magmatic expansion. Its distance from the current center of renewed activity may be an indication that new magma on a large scale may not make it back to this section unless the regime continues increasing in intensity.
CONCLUSION

GIS applied to seafloor geology and geochemistry is an increasingly important tool developing a comprehensive understanding of the interaction of various processes. The creation of the SER GIS involved the application of various data modeling techniques. By integrating the many different data sets, a comprehensive representation was produced.

The first important step is the development of an appropriate methodology. The platform used for the SER project, a Pentium III 500 Mhz desktop computer with 256 MB of RAM supporting MapInfo, Vertical Mapper and Virtual Frontier software, was ideal to promote a straightforward approach to database development and three dimensional modeling.

The next step involves the use of appropriate data analysis tools to correct any geographically sensitive data, interpolate effectively the data that needs to be presented and create a final format that is as simplistic, yet as precise and relevant as possible. For this step, it is important to know and understand key features of the data, including its geographical distribution.

Finally, versatility and presentation are qualities that must be addressed prior to the completion of a seafloor GIS. Compatibility with other systems and programs is an important feature of any software used that must be addressed when developing a GIS. Also, the manipulation and addition of data to the GIS must always remain an option since data is continuously collected by new scientific research.

Structural features at SER appear to have an important relationship with basalt chemistry. The areas surrounding the overlapping spreading center, central section fault and the three dome faults are characterized by lavas having various degrees of enrichment and fractionation. Both faults may represent the structural weaknesses necessary to provide access for lava flows from the underlying source (beneath the axial dome) to travel in the subsurface and erupt at different
points and times along the ridge. This spatial and temporal variability in eruptive events would create the geochemical patterns seen at SER. In addition, the variability in the composition of lavas associated with the OSC could be a consequence of the combination of the different volcanic regimes associated with the interacting spreading centers.

Orthogonal fault patterns considered to be especially conducive to the focusing of hydrothermal activity (Scott, 1979) are present at SER primarily in the area of the axial dome. The intersections of major cross-cutting faults (as seen in the bathymetric models) with axis parallel normal faults (as seen on side scan sonar images) provide the best examples of intense hydrothermal activity, including that seen at the Magic Mountain hydrothermal field.

The eruption of specific lava types at SER is linked to the physical conditions of the magma source at a given time. These conditions include: 1) viscosity, 2) crystal/liquid ratio, 3) temperature, and 4) discharge rate (Bonatti and Harrison, 1988). Sheet flows, indicative of younger, higher temperature, low viscosity volcanism are associated with the hydrothermal activity observed at SER. Lava types are also a consequence of the style of eruption where sheet flows represent brief events and pillowed flows more sustained volcanism (Ballard et al., 1981).

Axial trough formation and evolution at SER is best explained by Kappel and Ryan’s (1986) non-steady state model. Characteristics of the SER crestal ridge are similar to those outlined by Kappel and Ryan (1986) for medium-rate spreading centers like the Juan de Fuca Ridge. In profile, the SER is bow shaped (Figure 33). The side scan sonar mosaic (Figure 6b) shows that faulting is focused within the walls of the ridge and that the flanks are characterized by numerous overlapping volcanic constructions. The widest parts of the SER’s axial trough (Figure 2, southern section) are also its deepest. The depression’s depth decreases with the narrowing of the trough towards the north. Side scan sonar images (Figures 6a, 6b, 20 and 22) show intense faulting associated with the SER’s crestal ridge. In some areas, post-faulting lava flows have partially covered the structures.
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