

JGR Solid Earth

RESEARCH ARTICLE

10.1029/2025JB033347

Key Points:

- Lithostratigraphic mapping of the Escanaba Trough reveals tectonic controls on volcanism and associated hydrothermal activity
- Magnetic inversion modeling identified intra-sediment hydrothermal alteration and/or sill and dyke emplacement
- Constrained inversion modeling can be used to distinguish between magnetic susceptibility variations in basement versus sediment layers

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Galley, C., Jamieson, J., Gartman, A., Yeo, I., Tominaga, M., Tivey, M., et al. (2026). Tectonic controls on volcanism and associated hydrothermal activity in a sediment-dominated mid-ocean ridge; Escanaba Trough. *Journal of Geophysical Research: Solid Earth*, 131, e2025JB033347. <https://doi.org/10.1029/2025JB033347>

Received 8 NOV 2025

Accepted 6 JUL 2026

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Tectonic Controls on Volcanism and Associated Hydrothermal Activity in a Sediment-Dominated Mid-Ocean Ridge; Escanaba Trough

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Abstract Mid-ocean ridges, the Earth's most extensive volcanic system, exhibit unique characteristics in sediment-dominant environments. Thick sediment cover insulates the crust and channels fluid along pathways that can lead to the formation of distinct crustal alteration patterns, exceptionally large mineral deposits, and specialized chemosynthetic ecosystems. This study presents an interdisciplinary investigation into the tectonics of the Escanaba Trough, a heavily sedimented axial valley at the southern Gorda Ridge in the Northeast Pacific Ocean. A primary challenge in such environments is overcoming the masking effect of thick sediments on basement structures that control magmatic and hydrothermal activity. We address this by employing three-dimensional (3D) magnetic modeling of high-resolution near-seafloor magnetic data collected by an autonomous underwater vehicle (AUV). The 2022 surveys with AUV Sentry provided data for 3D magnetic susceptibility models, refining our understanding of the geometry of sub-sediment laccoliths/saucer-shaped sills and hydrothermal alteration. In conjunction with a new 1:100,000 scale lithostratigraphic map, we outline the tectonic controls on the emplacement of Escanaba Trough's three main volcanic centers, characterize the geometry of its spreading segments, and provide volumetric data on the distribution of sub-sediment volcanism in the southern Gorda Ridge.

Plain Language Summary Mid-ocean ridges are extensive submarine volcanic systems that encircle the globe. In rare cases these ridges are located near continents whose erosion blankets them in thick layers of sediment, masking much of their structure and creating unique types of volcanos and deep-sea vents. This study presents a new geologic map of the Escanaba Trough, a sediment-dominant mid-ocean ridge segment off the coast of Oregon and California, USA, created from remote-sensing data sets. The map allowed for the quantification of the volume of volcanic material erupted below the sediment and helped explain the positioning of the region's three discrete volcanic centers. A closer inspection of Escanaba's deep-sea venting and volcanic processes was accomplished through the three-dimensional modeling of magnetic data collected during an expedition to the Escanaba Trough in 2022. These six magnetic models, created by modeling magnetic data collected near the seafloor by an autonomous underwater vehicle, refined our understanding on the emplacement and geometry of intrusions, deep-sea vents, and volcanoes in heavily sedimented portions of the seafloor where marine exploration continues to be challenging.

1. Introduction

Extending for over 70,000 km, mid-ocean ridges represent the Earth's most extensive volcanic system, where new oceanic crust is generated through seafloor spreading (Bird, 2003; Heezen et al., 1959; MacDonald et al., 1991). This fundamental tectono-volcanic process provides the thermal energy that drives submarine hydrothermal circulation, leading to significant heat and chemical exchange between the lithosphere and the ocean (Wolery & Sleep, 1976). However, in sediment-dominant ridge environments the presence of a thick sediment cover (i.e., 100s of meters) results in different forms of volcanic and hydrothermal activity than classically observed on lightly-sedimented mid-ocean ridges. Thick sediment layers can act as a low-permeability barrier (Normark et al., 1994), altering heat flow (Davis & Becker, 1983; Fisher & Becker, 1991), and significantly influencing the chemical evolution of hydrothermal fluids (Campbell et al., 1994; Von Damm et al., 2005). This distinct

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geological setting features unique crustal alteration patterns, such as sharp gradients in the extent of hydrothermal recrystallization within the individual flows and sills (Teagle & Alt, 2004), promotes the formation of exceptionally large and chemically distinct mineral deposits (Goodfellow & Franklin, 1993; Koski et al., 1988; Zierenberg et al., 1993), and supports specialized chemosynthetic ecosystems (Grassle & Petrecca, 1994). Understanding the volcanism and tectonics of hydrothermal circulation at sedimented ridges is crucial for comprehending the interplay between the blanketing sediments and the hydrothermal systems, seafloor spreading, and volcanic activity that contribute to Earth's global heat budget, ocean chemistry, mineralization, and the distribution of deep-sea life.

In this study, we conducted an interdisciplinary investigation into the tectonics of the Escanaba Trough, a heavily sedimented axial valley at the southern end of the Gorda Ridge, off the western coast of the United States of America. Sedimented ridges are globally significant as they have potential to host some of the planet's largest seafloor massive sulfide (SMS) deposits (e.g., the 9 Mt Bent Hill deposit, Middle Valley; Zierenberg et al., 1998), can trap methane and hydrocarbons (e.g., Guaymas Basin; Bazylnski et al., 1988), and can modify the way in which magmas are erupted and cooled (Clague et al., 2022), resulting in different crustal structure. A primary challenge in studying the tectonics and associated volcanics of sediment-dominant mid-ocean ridges is overcoming the presence of the thick sediment cover. The sediment cover masks much of the axial valley basement relief, making it difficult to determine the geometry of basement structures that control magmatic and hydrothermal activity. Imaging inter- or sub-sediment volcanic features therefore requires detailed geophysical remote sensing in tandem with geologic mapping to identify and define regional volcanic and structural controls, and deep-sea drilling (>500 mbsf) to verify results with physical samples.

Three-dimensional (3D) magnetic modeling provides a remote-sensing means to model the form and presence of volcanic and hydrothermal features within and below the cover of a sediment-covered mid-ocean ridge. An autonomous underwater vehicle (AUV), operating at ~60 m above the seafloor, can collect high-resolution magnetic and bathymetric data over target areas that can be analyzed to produce 3D models of basement alteration (Galley et al., 2021; Sztikar & Lim, 2025) and, as this study presents, sill emplacement within the sediments.

Previous magnetic and geologic mapping studies of the Escanaba Trough largely occurred in the 1980s and 1990s (Grassle & Petrecca, 1994; James et al., 1998; Karlin & Morton, 1983; Morton et al., 1994). Since then there have been significant advances in both technology and methodological approaches in the field of magnetic modeling (Galley et al., 2020; Sztikar et al., 2014; Tivey & Johnson, 2002) and seafloor lithological mapping (Baxter et al., 2025; Stewart et al., 2022). In 2022, the Escanaba Trough was surveyed during the TN403 expedition aboard the R/V Thomas G. Thompson with the AUV Sentry of the National Deep Submergence Facility (NDSF). The AUV was equipped with a 3-axis miniature fluxgate magnetometer to conduct high-resolution near-bottom magnetic surveys. These surveys were designed to produce 3D magnetic susceptibility models across Escanaba's main volcanic centers, refining our understanding of the geometry of the sub-sediment distribution of laccoliths and hydrothermal alteration. In tandem with a new 1:100,000 scale lithostratigraphic map of the study region, we outline the tectonic controls on the placement of Escanaba Trough's three main volcanic centers, the geometry of its spreading segments, and provide volumetric data on the distribution of sub-sediment volcanism in the southern Gorda Ridge. Together, these results can provide better constraints on resource potential and crustal construction at these important spreading centers.

1.1. Geologic Setting

1.1.1. Escanaba Trough

The Escanaba Trough forms the axial valley of the southern-most segment of the Gorda Ridge, a divergent plate boundary 250 km off the west coast of California and Oregon, U.S.A. (Figure 1). The Escanaba spreading segment is heavily sedimented with thicknesses ranging from tens of meters in the north to over a kilometer in the south (Gardner et al., 1993; Karlin & Morton, 1983). Most of the sediments are terrigenous and were deposited during the Pleistocene when sea-level was lower than at present (Vallier et al., 1973), at a rate estimated between 270 and 310 cm/kyr (Davis & Becker, 1983). However, currently, its close proximity to continental North America also provides higher modern sedimentation rates (13 cm/kyr; Normark et al., 1994) than a typical mid-ocean ridge (1.3 cm/kyr; Ewing & Ewing, 1967). Full spreading rates decrease southward along the Gorda Ridge from 56 mm/yr to 25 mm/yr (Figure 1), which has resulted in extensive deformation through rotation of the southern end of the Juan de Fuca plate, earning it the name Gorda Deformation Zone (Wilson, 1993). The

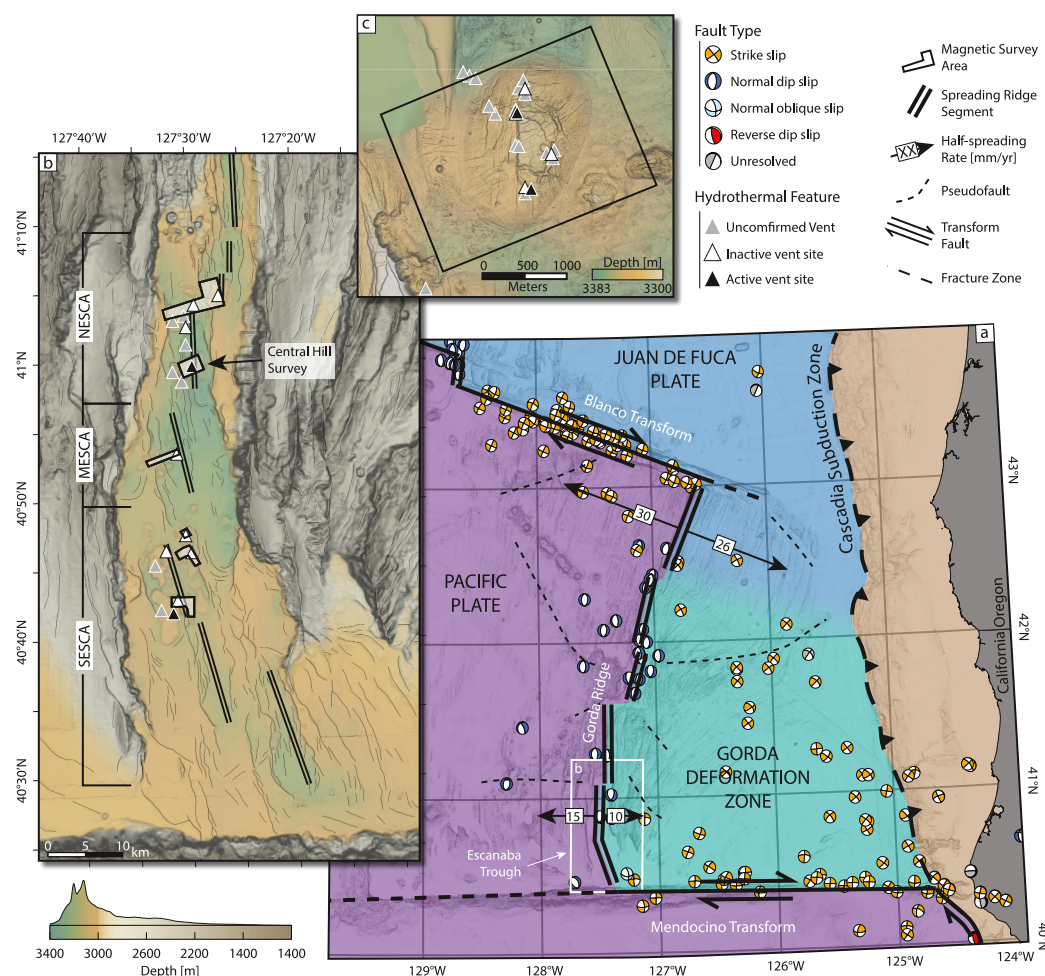


Figure 1. Map of the Escanaba Trough. (a) A regional map of the tectonic setting surrounding the Gorda Ridge spreading center (modified from Wilson, 1989), with central moment tensor data indicating faulting dynamics (Dziewonski et al., 1981; Ekström et al., 2012); (b) a map of the Escanaba Trough, with this study's six magnetic surveys outlined, including mapped lineaments as black lines; and (c) an inset of Central Hill as an example of an uplifted sediment mound that hosts the majority of the spreading segment's current hydrothermal activity. Bathymetric data sets used are from Clague et al. (2022) and the GMRT v4 compilation (Ryan et al., 2009).

southern end of the Escanaba spreading segment terminates at the right-lateral E-W-trending Mendocino strike-slip fault, the aseismic trace of which extends 4,000 km west of the Gorda Ridge (Fisk, Robert, et al., 1993). The Mendocino fracture zone separates the <6 Ma crust of the Gorda Deformation Zone from the older 27 Ma Pacific crust to its south (Fisk, Duncan, et al., 1993).

Within the Escanaba Trough, seafloor spreading and its associated volcanism consists of three main segments: North Escanaba (NESCA), Mid-Escanaba (MESCA), and South Escanaba (SESCA) (Figure 1b). The SESCO segment can be further broken into a northern component that hosts active seafloor spreading, marked by the presence of the uplifted sedimented mounds, and a southern segment consisting of seemingly volcanically inactive rifts (Davis & Becker, 1983; Moore, 1970).

A characteristic feature of the Escanaba Trough, as well as other heavily sedimented spreading segments (e.g., Guaymas Basin, Fisher & Becker, 1991; Middle Valley, Zierenberg et al., 1998), is the numerous sediment mounds that occur along its neovolcanic zone. These mounds are most likely created through the emplacement of melts largely along the sediment-basement interface, in the form of sills and laccoliths (Morton et al., 1994). These mounds have morphologies that vary between ellipsoidal to flow-like, reflecting the style of sub-sediment volcanism that led to their formation (Clague et al., 2022).

Ring faults that encircle many of the mounds appear to have been created as the sediment blocks above the intrusive bodies were uplifted, and have been observed to act as a permeable pathway for hydrothermal fluids through the otherwise low-permeability mud layers covering the axial valley (Normark et al., 1994). As such, hydrothermal activity in the Escanaba Trough is largely focused around the uplifted sediment mounds (Zierenberg et al., 1993). It is believed that the sills and/or laccoliths that formed these mounds also act as heat sources, driving shallow hydrothermal circulation within the sediment layer along the ring faults (Zierenberg et al., 1993).

The geometry of the sills and laccoliths below the Escanaba Trough's uplifted mounds are still largely unknown, as the high-resolution seismic surveying needed to image the tops and edges of the sills has not yet been done. Seismic profiles presented in Morton et al. (1994) could image the tops of sills/laccoliths, but not their edges as to determine if they are purely strata-concordant or possess transgressive components (Galland et al., 2018). As a result, the consensus from volcanological studies of the Escanaba Trough is that low uplifted mounds (<20 m relief; Clague et al., 2022) are created from the injection of strata-concordant sills, and larger mounds form due to the emplacement of deep laccoliths (Clague et al., 2022; Morton et al., 1994).

While not yet identified in the Escanaba Trough, saucer-shaped sills have been observed in other sedimented, volcanically active regions of the seafloor (e.g., Guaymas Basin, Gallegos-Castillo et al., 2026; Kluesner, 2011; Canary Basin, Medialdea et al., 2017; Faroes-Shetland Basin, Thomson & Schofield, 2008), and are almost always associated with doming of the overburden layer (Galland et al., 2018). This sill geometry forms in response to an asymmetric stress field around the perimeter of the uplifted overburden, causing the edges of the sills to propagate upwards toward the seafloor (Galland et al., 2018). The minimum diameter at which a sill's edges begin to ascend depend mainly on its depth below the seafloor and tectonic stresses, with deeper sediment-basement interfaces (i.e., greater lithostatic pressure) promoting horizontal sill propagation and extensional tectonic stresses encouraging vertical propagation (Malthe-Sørenssen et al., 2004; Polteau et al., 2008; Walker & Gill, 2020).

1.1.2. Seafloor Geologic Mapping

Regional geologic mapping provides important insights into regional geological evolution, from crustal growth and tectonics to the volcanic processes. Geologic mapping of the seafloor specifically, while equally as important and impactful as mapping on land, is sparse in the scientific literature (Stewart et al., 2022). This is in large part due to most of our oceans being unexplored in detail (i.e., studied primarily through ship-based survey methods (Mayer et al., 2018)), and therefore we typically rely on satellite-based bathymetric and geophysical data sets that limit us to a global-scale resolution for mapping initiatives (e.g., the 1:35,000,000 world geologic map, Bouysse et al., 2000; and the 1:17,000,000 Circum-Pacific map, Scheibner et al., 2013). Additionally, such global maps often represent the geology of the seafloor by age, rather than distinguishing between rock types or geologic structures. However, methodologies have recently been developed, and continue to be improved upon, to create lithostratigraphic maps of the seafloor at the <1:1,000,000 scale using a suite of primarily remote-sensing based and ground truthing data sets (Baxter et al., 2025; Brandl et al., 2024; Stewart et al., 2022).

Previous maps created within the Escanaba Trough have largely focused on geomorphological features, that is, mapping uplifted mounds, surface lava flows, and landslides at the volcanic center scale (Clague et al., 2022; Morton et al., 1994; Zierenberg et al., 1993) and generalized regional maps of the volcanic edifices and axial valley sediments (Morton et al., 1994). This study's map differs from those by being a lithostratigraphic geologic map of the Escanaba Trough, which distinguishes basement rock and volcanic units.

1.2. Marine Magnetism

1.2.1. Magnetic Surveying

Marine magnetic surveys measure Earth's magnetic field variations above the seafloor. These measurements are typically studied in the form of a scalar total magnetic intensity, TMI_{crustal} , anomaly, which is derived by taking the magnitude of an observed magnetic field, B_{observed} , with any measurement platform noise, B_{platform} , subtracted (i.e., the induced and permanent magnetic signals produced from, in our study's case, metal and the motorized AUV that housed the magnetometer), and then subtracting the magnitude of the Earth's main magnetic field, B_{IGRF} , (i.e., the International Geomagnetic Reference Field; Alken et al., 2021) and the magnitude of any external, diurnal magnetic fields, B_{diurnal} ,

$$\text{TMI}_{\text{crustal}} = \|\mathbf{B}_{\text{observed}} - \mathbf{B}_{\text{platform}}\| - \|\mathbf{B}_{\text{IGRF}}\| - \|\mathbf{B}_{\text{diurnal}}\|. \quad (1)$$

This study's observed magnetic field data sets were measured as three-component vectors, which made it possible to isolate and remove the AUV's platform noise through a full-vector calibration (Tivey et al., 2014). This calibration involved spinning the AUV in the water column, distant from both the ship and seafloor, at least one 360° rotation. The AUV attitude and vector magnetic field data sets measured during the rotations were used to calculate the induced and permanent magnetization of the AUV using a least-squares solution (Tivey et al., 2014).

The variations in total magnetic intensity are sensitive to changes in crustal magnetization, which is composed of induced and remanent components. Remanent magnetization is generally created at the time of the crust's formation and will therefore hold the orientation of the Earth's field at that time (Blakely, 1996). Induced magnetization arises from the non-remanent rock magnetic properties of the crust and is always parallel to the present Earth's field direction (Blakely, 1996). At the regional scale (i.e., >20 km), total magnetic intensity variations are largely attributed to changes in the crustal remanent magnetization. Therefore, magnetic maps at that scale mainly highlight past polarity reversals of the Earth's magnetic field, providing information on seafloor spreading rate, history, and geometry (Pichon, 1968). Magnetic data collected over an oceanic spreading center's neovolcanic zone, which is typically crust that has only been exposed to the most recent positive polarity of Earth's field (i.e., Brunhes chron <0.78 Ma; Doell & Dalrymple, 1966), will contain anomalies that can be solely attributed to changes in magnitude of its magnetization. This is because it is assumed that all vector components of the crust's magnetization are in line with the Earth's field's direction. Earth's magnetic field also changes in intensity over time and this variation is also recorded by the remanent magnetization of the crust. This magnetic paleointensity variation can be modeled and accounted for in subsequent analyses (Bowles et al., 2006; Gee et al., 2000; Schouten et al., 1999).

Given that, within neovolcanic zones, all vector components of the crust's magnetization are in line with the Earth's field we can make the assumption that changes in magnetization can be simplified to changes caused by variations in a scalar effective magnetic susceptibility, χ_{eff} . This effective magnetic susceptibility is a combination of the magnetic susceptibility and remanent magnetization,

$$\begin{aligned} \mathbf{B} &= \mu_o (\mathbf{M}_{\text{ind}} + \mathbf{M}_{\text{rem}}) \\ &= \chi \mathbf{B}_o + \mu_o \mathbf{M}_{\text{rem}} \\ &= \left(\chi + \mu_o \frac{\mathbf{M}_{\text{rem}} \cdot \hat{\mathbf{B}}_o}{\|\mathbf{B}_o\|} \right) \mathbf{B}_o \\ &= \chi_{\text{eff}} \mathbf{B}_o. \end{aligned} \quad (2)$$

In Equation 2, $\mathbf{B}$ is the measured magnetic field, μ_o is the permeability of free space ($\mu_o = 4\pi \times 10^{-7} \text{ Tm}^2/\text{A}$), $\mathbf{M}_{\text{ind}}$ is the induced magnetization, $\mathbf{M}_{\text{rem}}$ the remanent magnetization, χ is magnetic susceptibility, and $\mathbf{B}_o$ is the Earth's magnetic field, typically derived from the International Geomagnetic Reference Field (Alken et al., 2021).

1.2.2. Magnetic Properties of Sediment-Hosted Hydrothermal Systems

The study of the vent field-scale magnetic architecture of modern hydrothermal systems has been largely dominated by unsedimented systems, that is, intermediate-, mafic-, and ultramafic-hosted sites (Caratori Tontini et al., 2012; Galley et al., 2021; Lim et al., 2019; Sztikar et al., 2014; Sztikar & Murton, 2018; Tivey & Johnson, 2002). Sediment-hosted hydrothermal systems are much more rare, currently making up 3% of known or inferred vent fields (Beaulieu & Szafranski, 2020). The primary cause of this rarity is because only a small percentage of mid-ocean ridges occur proximal to continental crust.

A sediment-hosted hydrothermal system can be generalized as a two-layer system, with a sediment layer overlying basaltic crust. From a magnetic property perspective, effective magnetic susceptibility in the basement layer can be hydrothermally or thermally altered from a base value of $\sim 10^{-1}$ SI to less than 10^{-3} SI (Ade-Hall et al., 1971; Galley et al., 2021; Wang et al., 2020). This decrease in effective magnetic susceptibility is largely due to the hydrothermal dissolution of titanomagnetite (Wang et al., 2020). However, the acquisition of a

chemical remanent magnetization on the order of 10^{-4} SI has been observed in hydrothermally altered basalt as a result of the precipitation of ferrimagnetic iron sulfide and oxide minerals (Wang et al., 2020).

Magnetic susceptibility values within the sediment layer are generally much lower than those of a basaltic basement, that is, on the order of 10^{-7} – 10^{-4} SI (Karlin & Zierenberg, 1994). In proximity to vent sites, sediment core samples have recorded magnetic anomalies coinciding with the presence of sulfide minerals. However, the anomalies are small and generally associated with the deposition of hydrothermal plume-fallout (Karlin & Zierenberg, 1994). In contrast to hemipelagic sediment ($\sim 4.0 \times 10^{-4}$ SI), coarser grained turbidites have a higher magnetic susceptibility ($\sim 7.5 \times 10^{-4}$ SI), with sulfide-rich sediment having the highest values ($\sim 1.0 \times 10^{-3}$ SI), as observed from core sampling within the Escanaba Trough. However, these variations are all very small and have been observed to occur across thin lenses in the sediment (< 1 m; Karlin & Zierenberg, 1994), and therefore, with a typical resolution of 50 m, would be difficult to identify in a magnetic model created at the vent field-scale. The approximate 50 m edge length of a model's tetrahedral cells implies each cell's magnetic susceptibility value represents the average value throughout an approximate $15,000 \text{ m}^3$ volume.

1.2.3. Previous Magnetic Modeling Work

The magnetic properties of the Escanaba Trough basement have been previously studied through the analysis and modeling of regional magnetic data collected by surface ship-mounted magnetometer (Karlin & Morton, 1983). The magnetic maps show a general southward decrease in total magnetic field intensity along the axial valley, which was further studied through inverse and forward modeling (Karlin & Morton, 1983). A regional Parker and Huestis-style 3D inversion (assuming a 500 m thick magnetized layer; Parker & Huestis, 1974; Karlin & Morton, 1983) and a north-south oriented 2D forward model (Karlin & Morton, 1983) were created from the regional magnetic data. The modeling shows a persistent decrease in crustal magnetization southward along the trough, correlating with the increase in sediment thickness. Therefore it was concluded that the decrease in magnetization observed within the Escanaba Trough was likely due to the slower cooling of the less frequently observed basaltic intrusions below the thicker sediment cover in the south (J. Morton et al., 1994), with possibly increased thermal demagnetization due to the increased thickness of the insulating semipermeable sediments (Karlin & Morton, 1983; Levi & Riddihough, 1986).

2. Methods and Data

2.1. Geologic Mapping

A 1:100,000 scale geologic map of the Escanaba Trough was created following the workflow established by Stewart et al. (2022). The mapping primarily relied on bathymetric data, which included the 1 m resolution AUV multibeam data collected during the TN403 cruise and from the compilation by Clague et al. (2022) (cruises RCSN204 and RCSN393), the 50 m-resolution ship-based multibeam data from TN403, and the 61 m resolution Global Multi-Resolution Topography (GMRT) compilation (Ryan et al., 2009). Additional data sets included the multibeam backscatter data collected by the AUV Sentry during TN403, which aided in distinguishing between sediment and surface basalt flows, the EMAG2 version 2 satellite-derived magnetic field model (Maus et al., 2009), which provided information of the kinematic history of the crust, and the Surface Water and Ocean Topography (SWOT) satellite-derived gravity data (Yu et al., 2024). Temperature and oxidation-reduction potential (ORP) data were collected during the TN403 AUV dives using the National Oceanographic and Atmospheric Administration-Pacific Marine Environmental Laboratory's Miniature Autonomous Plume Recorder (MAPR), which was used to infer the presence of active hydrothermal venting within the survey areas.

Ground-truthing was performed using remotely-operated vehicle- based video recordings and sample data collected during TN403 with ROV Jason, along with information from Clague et al. (2022). Seismic profiles from (Davis & Becker, 1983; Moore, 1970; Morton et al., 1994) provided sub-seafloor information that helped map the crustal spreading ridges and rifts within the Escanaba Trough.

Our lithostratigraphic legend was adopted from Baxter et al. (2025), who made a similar geologic map of Canada's Pacific Exclusive Economic Zone that included the northern segments of the Juan de Fuca ridge. Following this legend, the crust of the Escanaba Trough was classified by the formation types described in Figure 2. The formation map aims to classify bedrock geology in a lithostratigraphic framework. Different types of sediments were not differentiated in our mapping. The oceanic crust was subdivided into upper (axial), mid

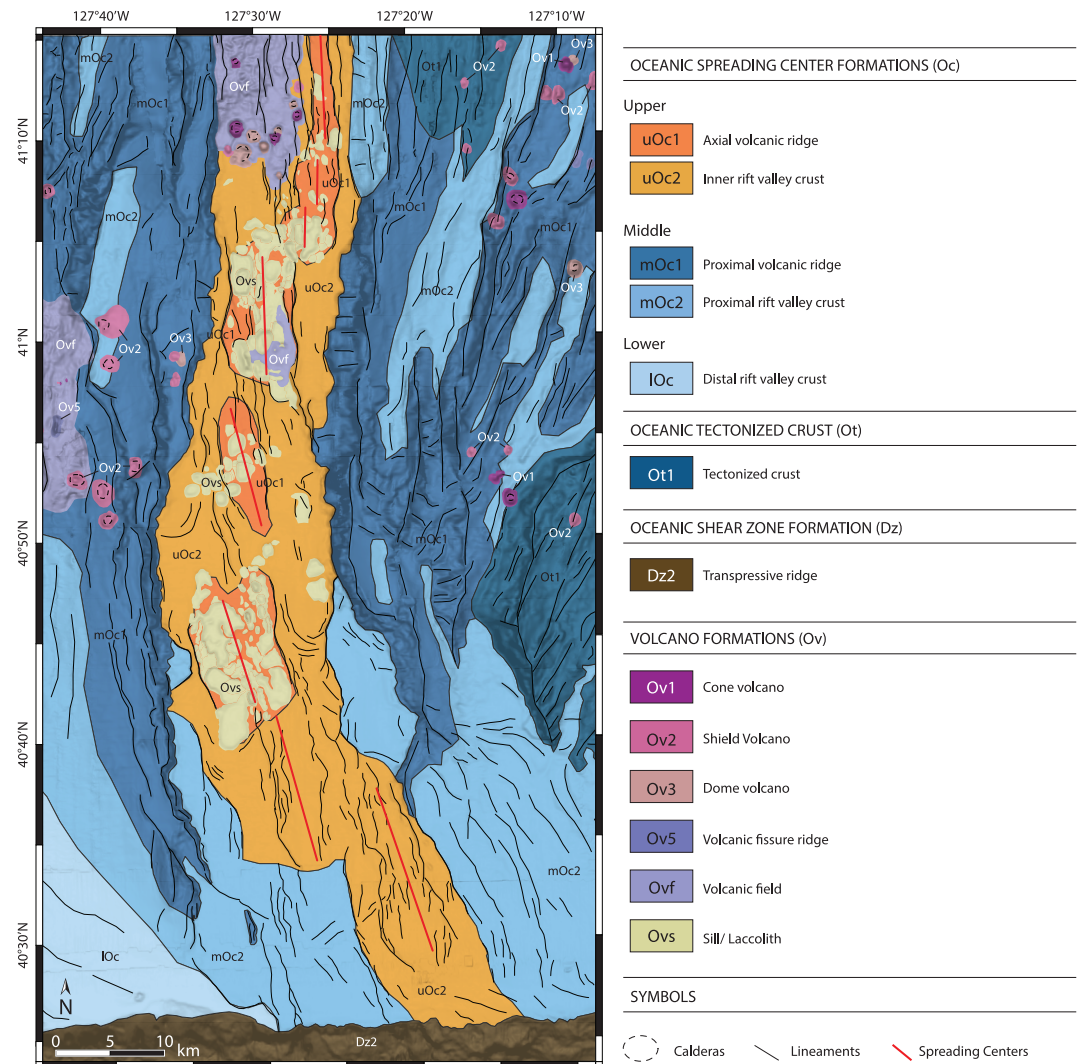


Figure 2. A reduced 1:100,000-scale geologic map of the Escanaba Trough at the formation level.

(proximal), and lower (distal) formations based on the inferred stratigraphic position and their location relative to a spreading center. The axial oceanic crust (formation uOc) is located within the neovolcanic zone and usually forms the floor of an inner rift valley. The proximal rift valley crust (formation mOc) is located outside of the neovolcanic zone, described as faulted rift valley crust located outside of the inner rift valley. Distal rift valley crust (formation lOc) is located outside of the rift valley and beyond the ridge flank of the spreading center, which is typically heavily obscured by sediment.

In addition to the oceanic spreading center associated formations, the legend also includes oceanic tectonized crust (formation Ot) and oceanic shear zones (formation Dz). Oceanic tectonized crust is classified as an uplifted crustal block with complex faulting patterns overprinting the spreading-induced fabric. Of the oceanic shear zone formations described in Baxter et al. (2025), only the transpressive ridge crust (Dz2) occurs within this study's map, which is described as an elongated thrust block of oceanic crust with intense secondary fault fabric and is commonly associated with transform faulting.

The volcanoes within the study region (formation Ov) were mapped according to their morphology, either as a cone volcano (Ov1), shield volcano (Ov2), dome volcano (Ov3), fissure volcanos (Ov5), or volcanic field (Ovf). Volcanic fields are defined as a broad area of lava flows and volcanoclastic material surrounding a number of closely spaced volcanoes, generally such that the outlines of the individual volcanoes within the fields are difficult to identify. The axial volcano classification (Ov4) was not used in this study as the thick sediment cover within the

neovolcanic zone masked their morphologies, although the mapped sills/laccoliths (Ovs) were likely manifestations of this type of volcano. Clague et al. (2022) also classified different morphologies for the laccoliths, further organizing them into morphological sub-types.

2.2. Normalized Volume of Volcanic Material

To quantify the volume of volcanic material erupted along spreading segments, independent of segment length, a normalized volume was used (Bai et al., 2023; Galley et al., 2024; see Figure S1 in Supporting Information S1). The normalized volume was calculated by gridding the polygons of the mapped laccoliths with a 100 m spaced collection of points (fine enough resolution to minimize the loss of any features of the mound geometries). The volume for each of these points was calculated assuming they represented a 100×100 m area of the seafloor, with the height of the rectangular prism equal to the difference between the seafloor depth at that point and the depth to the deepest point along the perimeter of the uplifted mound containing the point. An additional assumption was that the volume of the uplifted mounds represented the volume of their laccoliths, however due to compaction this is likely a minimum volume estimate. The volumes of the rectangular prisms were then summed in the east-west direction (direction of spreading) to derive a volume per 100 m in the north-south direction. A sliding window sum of width 1 km was used to convert the volume per 100 m data to a normalized volume with units km^3/km . This normalized volume could then be used to quantify volcanic activity along spreading segments within the Escanaba Trough.

2.3. Inversion Modeling

Six magnetic susceptibility models were created in this study using minimum-structure inversion modeling. This modeling method solves for a 3D distribution of magnetic susceptibility that produces a magnetic signal closely matching the measured data set. These six models were created from six separate magnetic surveys spanning different sections of the Escanaba Trough.

The inversion models were solved by iteratively minimizing a term called the objective function,

$$\phi = \lambda\phi_d + \phi_m + \phi_s. \quad (3)$$

The objective function is composed of a data misfit term, ϕ_d , a model smoothness term, ϕ_m , and a model smallness term, ϕ_s . λ is a trade-off parameter (Parker, 1977). More details into the structure of the objective function are provided in Supporting Information S1.

The data misfit term is primarily composed of the difference between the observed data (i.e., the measured magnetic data in this study) and the predicted data (i.e., the forward signal calculated from the inversion model). Therefore, minimizing this term leads to the creation of an inversion model that, if one calculated the magnetic field anomaly produced by it, would closely match the observed data.

Simply minimizing the data misfit term creates a non-unique inverse problem, as many distributions of magnetic susceptibility within a volume can be created to reproduce the observed data (Parker, 1994). The model smoothness term was included to correct for this. An Occam's Razor approach was used, which adopts the framework that the simplest distribution of magnetic susceptibility needed to reproduce the observed data constitutes the best model (Constable et al., 1987). The model smoothness term minimizes the difference in magnetic susceptibility between neighboring cells in the model, promoting a smoothed distribution. This approach assumes the smoothest subsurface model is the simplest, an assumption that has been demonstrated to be an effective measure in inverting geophysical data sets (Oldenburg & Pratt, 2007). We used a total variation norm within the model smoothness term, which balanced the necessary smoothing of anomalies needed to calculate a unique solution with a more ideal sharpening of their boundaries as to better resolve their geometries (Galley et al., 2020).

The final term included in our objective function, the model smallness term, allowed us to incorporate a priori constraints on the model. The primary constraint we considered was the presence of a thick sediment layer over all the modeled regions. Unaltered sediment has very low magnetic susceptibilities ($\sim 10^{-3}$ SI; Karlin & Zierenberg, 1994), especially compared to unaltered basaltic basement ($\sim 10^{-1}$ SI; Wang et al., 2020). This would, in theory, create a strongly layered magnetic susceptibility model in the Escanaba Trough. However, an unconstrained inversion model would not be able to resolve the interface between the sediment and basement but rather

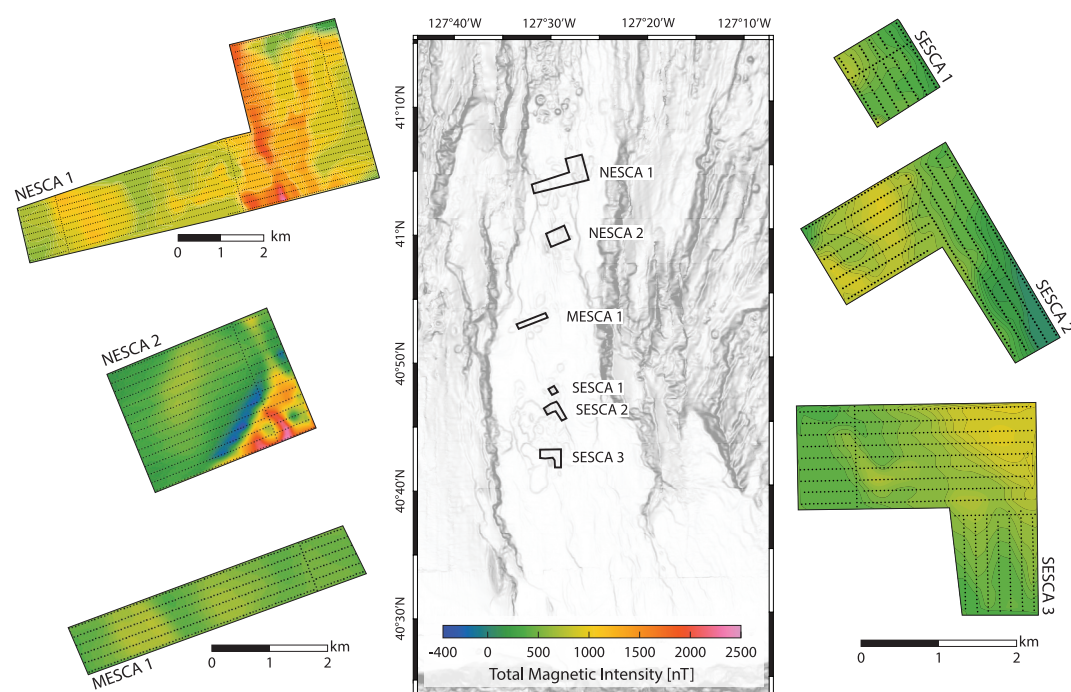


Figure 3. The six total magnetic intensity surveys collected for this study. The black points in each survey denote the measurement locations used in the inversion modeling. The NESCA 2 and MESCA 1 surveys share a scale bar, and surveys SESCA 1–3 share a scale bar. In the middle is a shaded-relief bathymetric map of the Escanaba Trough (Ryan et al., 2009).

would vertically smooth the magnetic susceptibility values across the volume (Figures S2c and S2f in Supporting Information S1). Our smallness term includes the difference between the inversion model and a pre-constructed reference model designed with a 0 SI sediment layer over a 0.1 SI basement layer (Figures S2e and S2h in Supporting Information S1). Therefore, minimizing the smallness term will promote the final inversion model to more closely resemble the reference model. A weighting term controls how closely the inverse model resembles the reference model, with a weighting of 10^{-5} being chosen through iterative testing (see Supporting Information S1 for more information). The thickness of the sediment layer in each of the reference models constructed as part of this study was derived from the sediment thickness model by Gardner et al. (1993).

2.4. Modeled Magnetic Data

All magnetic inversion models from this study were created by modeling the AUV-derived total magnetic intensity data collected during the TN403 cruise (Figure 3). The surveys were designed with 150 m line spacing at a 6 Hz frequency. The data were initially processed by performing a full-vector calibration to isolate and remove the TMI signal created by AUV Sentry's induced and permanent magnetizations (Figure S3 in Supporting Information S1). Some residual heading and drift-based artifacts were removed through leveling the data to each survey's tie line and performing linear heading corrections (Figure S5 in Supporting Information S1; see Supporting Information S1 for more information).

The model meshes (i.e., the cell-based, discretized model of the crust) were all made using the 50 m resolution ship-multibeam data collected during TN403. Unstructured meshes were used in all the study's inversion modeling, allowing the top of the models to easily match the variable bathymetric surface and the inclusion of the sediment-basement interface within the model volume (Figure S6 in Supporting Information S1). The surface of the meshes were constructed using the program Triangle (Shewchuk, 1996), and the volumes below the meshes' surfaces were discretized by tetrahedral cells with the program TetGen (Si, 2015). While the dimensions of the cells are variable throughout the models, it was ensured that within the inferred sediment layer and the core basement volumes the maximum edge length of the tetrahedral cells were less than 50 m, the minimum distance between magnetic data points.

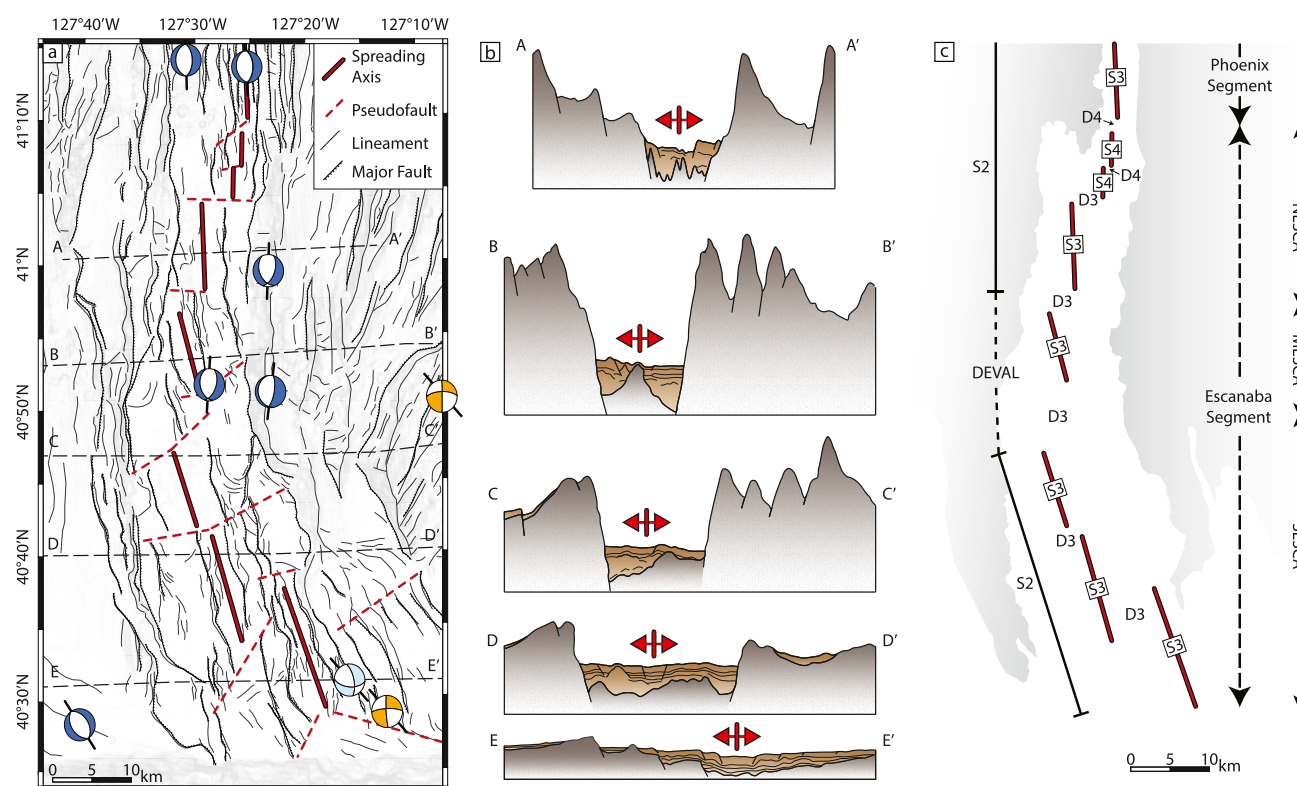


Figure 4. Locations of mapped spreading center axes and their discontinuities within the Escanaba Trough. (a) A map of the spreading center axes, major faults, lineaments, and pseudofaults overlaying a slope-shaded map of the seafloor. The central moment tensors follow the same legend as in Figure 1, with the thick black lines denoting their S_{Hmax} orientation. Black dashed lines show locations of shown in (b). (b) Example interpreted seismic sections. The sediment accumulation depicted in the cross-sections is interpreted from previously published seismic surveys (AA': Morton et al., 1994; BB', CC', DD', and EE': Moore, 1970). The vertical exaggeration of the profiles is approximately 10:1. (c) A classification of Escanaba's spreading centers (S#) and their discontinuities (D#), as defined by (MacDonald, 1998; MacDonald et al., 1991). DEVAL—deviation in axial linearity.

3. Results

This study presents two main results, a lithostratigraphic map of the Escanaba Trough (Figure 3) and a collection of six 3D magnetic inversion models across the Escanaba Segment's volcanic centers revealing their near-surface (~ 1 km bsf) magnetic susceptibility variations (Figures 6–8).

3.1. Geologic Map

3.1.1. Structural Features

Regional bathymetric maps (i.e., the TN403 50 m multibeam and 61 m GMRT maps; Ryan et al., 2009) were used to map the lineaments, a subset of which was classified as major faults. Major faults were identified based off their across-strike bathymetric profiles, which was used to determine if the vertical displacement of the fault blocks was visible. The “major” designation was assigned if they were only visible in regional bathymetric data sets (greater than 50 m resolution). Using the surface structures inferred from the mapped major faults, along with the subsurface structures revealed by legacy seismic sections (Figure 4b; Morton et al., 1994; Moore, 1970), the positions and orientations of the sub-sediment spreading centers were mapped. Discontinuities in the major faults, likely produced by the segmented seafloor spreading, were mapped as well (Figure 4a). The mapped spreading segments and their discontinuities were classified using the scheme developed by MacDonald et al. (1991) (Figure 4c).

The orientation of the mapped spreading center axes varies across the Escanaba Trough. Within NESCA and the Phoenix Segments (north of 40°57'N) the spreading centers are oriented north-south. However, the MESCA volcanic zone appears to mark a transition in orientation where the spreading centers begin undergoing a

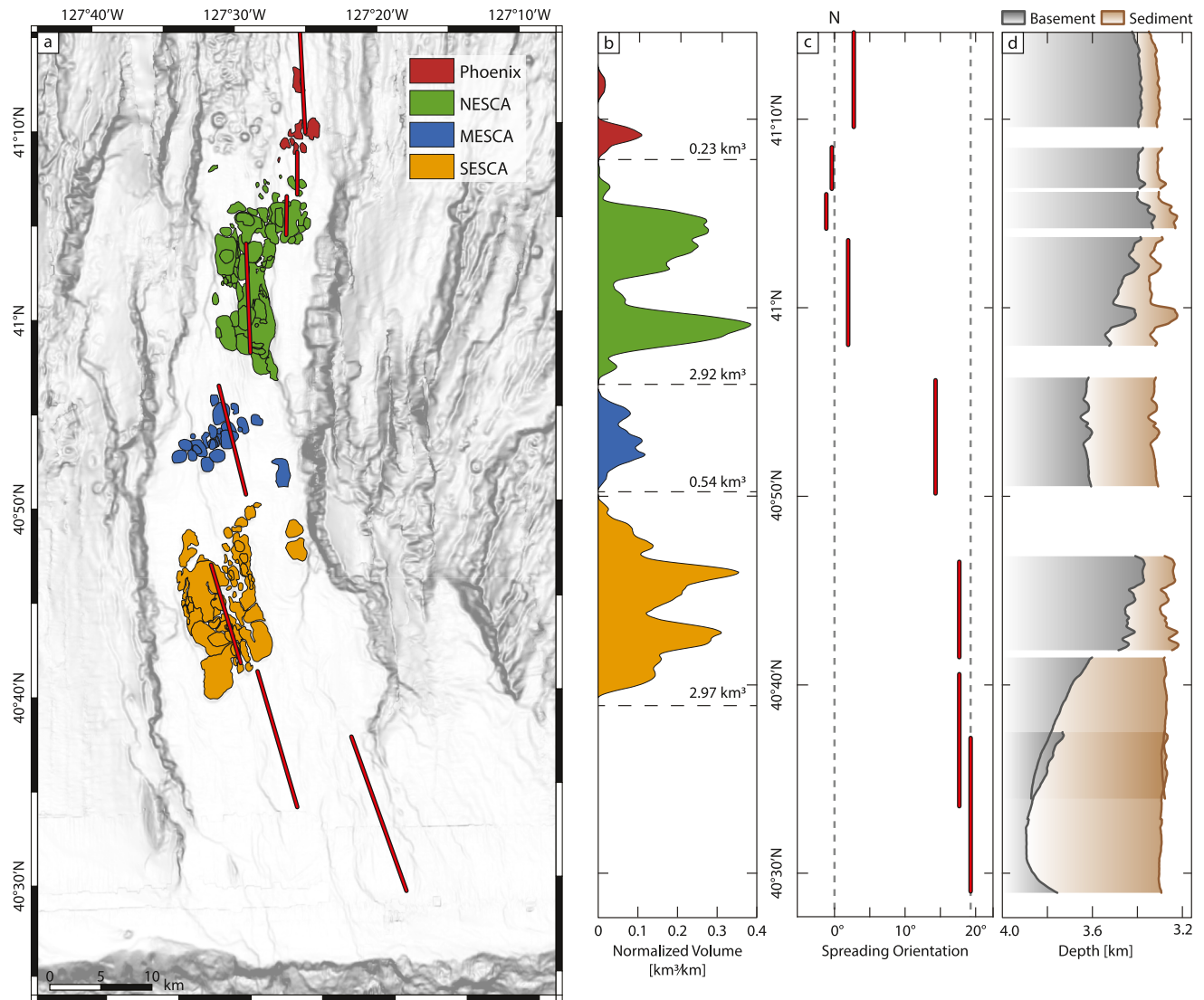


Figure 5. Map of the laccoliths and surface flows along side the orientation of seafloor spreading and depth to the basement-sediment interface. (a) Map of the laccoliths/sills, colored by their volcanic centers. The red lines denote the spreading axes. (b) A plot of normalized volume for the mounds (see Methods Section 2.2), following the same color legend as in (a). The dotted lines separate the volcanic centers, with the total volume of laccolith and surface flow for each center written. (c) The orientation of the spreading axes within the Escanaba Trough. (d) The depth to the seafloor and the depth to the basement-sediment interface along each of the spreading segments (Gardner et al., 1993).

counterclockwise rotation of 19.2° . The spreading center axis within SESCA maintains a 19.2° orientation (Figure 5c).

3.1.2. Laccoliths/Sills

A total of 252 laccoliths/sills were mapped from the compiled bathymetric data sets (see Section 2.1), covering an area of 206 km^2 . The associated mounds are focused within Escanaba's three volcanic centers, NESCA, MESCA, and SESCA. The mapped portion of the Phoenix segment hosts the least amount of sub-sediment volcanism with an area of 7.5 km^2 , NESCA's laccoliths cover 84.7 km^2 , MESCA's cover 25.1 km^2 , and SESCA's cover 89.3 km^2 . The volume of each of the laccoliths/sills was calculated with respect to the greatest depth along each of their perimeters, providing an estimate to the volume of magma erupted along the sediment-basement interface. The mounds in the mapped portion of the Phoenix segment amounted to 0.23 km^3 of laccolith, the mounds in the NESCA segment 2.92 km^3 , MESCA 0.54 km^3 , and SESCA 2.97 km^3 . Variations in volume within each of the

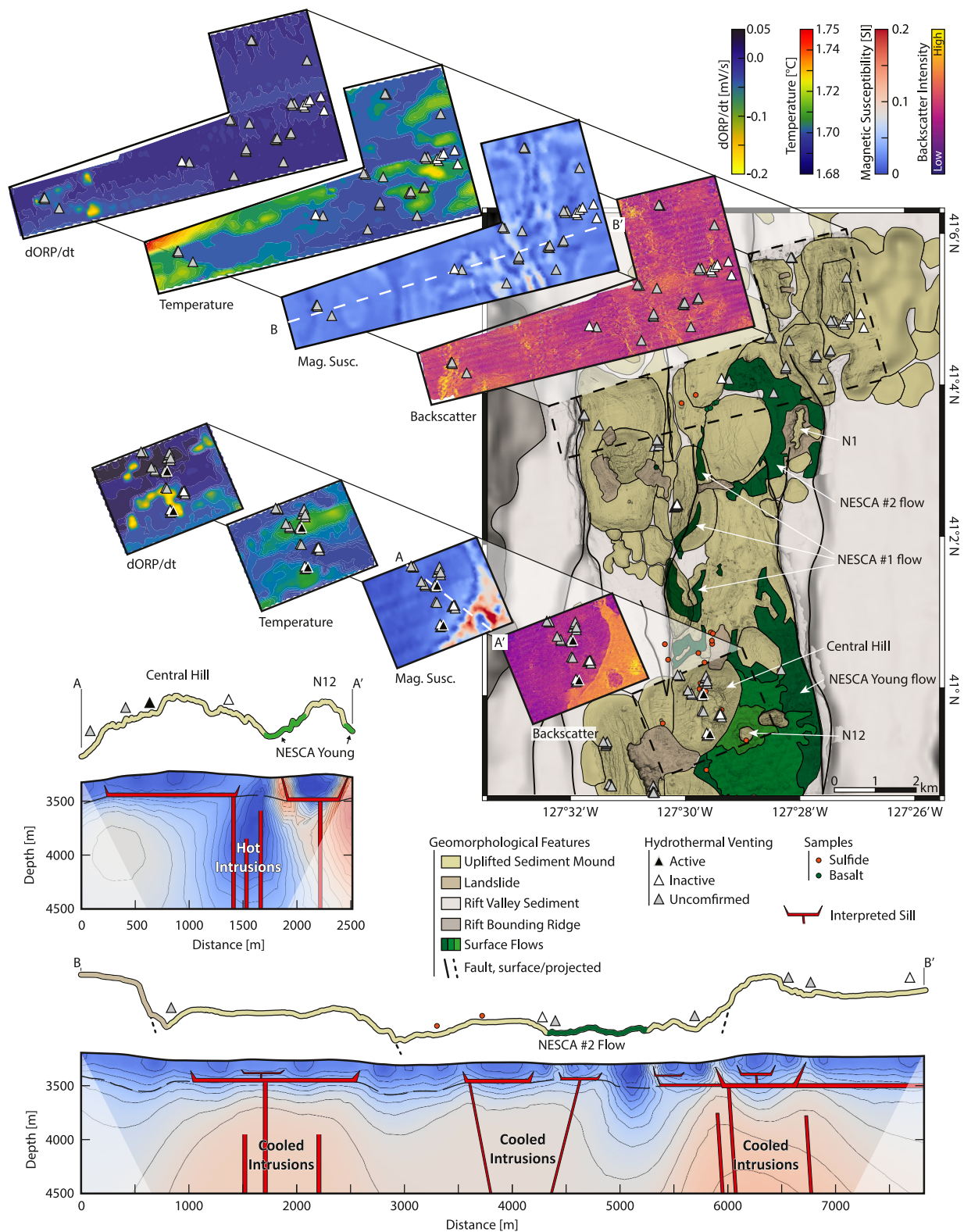


Figure 6.

volcanic centers can be visualized by plotting a normalized volume, which portrays the volume of laccolith per kilometer north-south along the Escanaba Trough (see Methods Section 2.2). There was a mean normalized volume of 0.02 km³/km throughout the portion of the mapped Phoenix segment, a mean of 0.13 km³/km along the NESCA segment, a mean of 0.05 km³/km along MESCA, and a mean of 0.14 km³/km along SESCA.

3.2. Magnetic Models

To better our understanding of the geometry of Escanaba's intra-sediment sills and basement alteration, six magnetic susceptibility models were created using the AUV-derived magnetic data. Two models were created within the NESCA volcanic center, one model within MESCA, and three models within the SESCA segment. Interpretations were added to each of the model cross-sections shown in Figures 6–8, showing potential sill geometry and depth in each of the volcanic centers. The length and thickness of the interpreted sills were determined from the length and height of their associated uplifted sediment mounds, and their depth and the geometry of their edges (i.e., identified as a laccolith or saucer-shaped sill) were determined from their coincident magnetic susceptibility anomalies. The geometry of the interpreted intrusions is highly uncertain, however their presence and approximate temperature (i.e., hot being >580°C, cooled <580°C) were determined from the coincident magnetic susceptibility anomalies.

3.2.1. NESCA Models

The two models in the NESCA volcanic zone contain the most variation in seafloor magnetic susceptibility of all the magnetic models. The highest magnetic susceptibility values are associated with volcanic flows (i.e., the NESCA Young, NESCA #1, and NESCA #2 flows), consistent with the higher magnetic mineral abundance in basalt relative to the surrounding sediment (Figure 6). The southern NESCA magnetic model is centered over the Central Hill uplifted sediment mound, where multiple sites of hydrothermal venting have been observed (Clague et al., 2022). The NESCA Young flow can be distinguished on the eastern side of the Central Hill model by its high magnetic susceptibility and high backscatter intensity. The uplifted sediment block of Hill N12 can be distinguished as a magnetic susceptibility low (Figure 6 map and cross-section AA'). Hill N12 is thought to be the source of the NESCA Young flow (Clague et al., 2022), which erupted from the ring fissures around its perimeter, and is reflected in the magnetic model by the high magnetic susceptibility around the base of the mound where the flow is likely thickest and most recent. At the seafloor, Central Hill is shown to be slightly more magnetically susceptible than the mound to its west and the landslide to its south (Figure 6). These faint anomalies are most pronounced on the northeastern and southwestern flanks of the uplifted mound, where most hydrothermal venting was observed (Figure 6). A cross-section through the Central Hill model reveals a low to zero magnetic susceptibility anomaly below the mound (Figure 6 AA'), which, with the aid of the synthetic modeling presented in Supporting Information S1 (Figure S2), is identified as potentially being the thermally demagnetized mafic intrusion whose heat is likely driving the hydrothermal venting on the mound, or a hydrothermally demagnetized fluid upflow zone in the mafic basement (Galley et al., 2020).

The cross-sections through the northern-most NESCA magnetic model reveal features below the uplifted mounds with higher magnetic susceptibility than that of background (Figure 6 BB', distances 1,000–2,500 m and 5,500–7,000 m), possibly representing young intrusions that have cooled below the basement's Curie temperature and have not undergone high-temperature hydrothermal alteration (Wang et al., 2020). With time, the magnetic susceptibility within the seafloor decreases as the rock is exposed to further alteration (Klitgord et al., 1975; Petersen et al., 1979). As such, younger melt intrusions could stand out from their surroundings in terms of magnetic susceptibility, even when their compositions are similar to the surrounding rock.

Figure 6. The MAPR data and subseafloor magnetic models for the NESCA volcanic center. The map highlights seafloor morphological features within the volcanic center, with the addition of mapped hydrothermal vent sites and sample collection locations (Clague et al., 2022). Different generations of lava flows are shown in varying colors of green (Clague et al., 2022). Associated with the map are collections of insets showing, from right to left, the backscatter data collected in the spring of 2022, the seafloor surface of the magnetic susceptibility models (Mag. Susc.), water temperature along Sentry's 60 m altitude flight surface, and the time derivative of oxidation-reduction potential along the same survey track. AA' and BB' are cross-sections through the 3D magnetic susceptibility models, contoured at 0.01 SI intervals and showing the estimated depth of the sediment-basement/sill interface as a dashed black line (0.04 SI iso-layer). Above the magnetic susceptibility cross-sections are bathymetric profiles of the seafloor, colored according to the map's legend, with a 5:1 vertical exaggeration. Named mounds are labeled, and the edges of the cross-sections are shaded to represent an increase in model uncertainty.

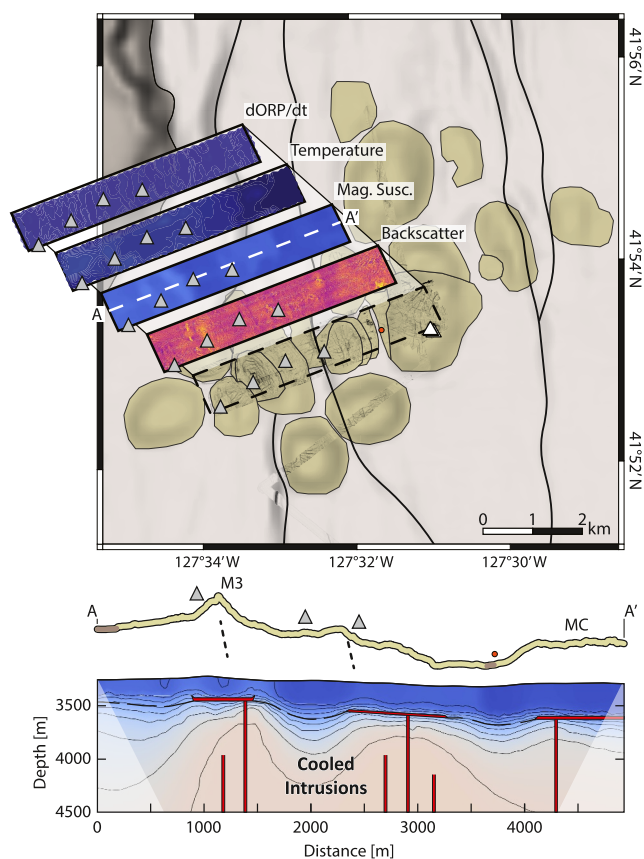


Figure 7. The MAPR data and magnetic inversion model from the MESCA volcanic center. The geomorphological map of MESCA follows the same legend as in Figure 6. The map insets are, from right to left, seafloor backscatter, seafloor magnetic susceptibility (Mag. Susc.), water temperature at a 60 m altitude above the seafloor, and the time derivative of ORP at 60 m altitude above the seafloor. Below is a cross-section through the 3D magnetic susceptibility model, contoured at 0.01 SI intervals, with a 5:1 vertically exaggerated bathymetric profile above it. Named mounds are labeled.

passing mound S3 and a chain of unnamed mounds. Faint magnetic susceptibility anomalies in the sediment layer are visible around mound S3, on its western flank where inactive hydrothermal chimneys have been found, but are largely absent in the rest of the model. Anomalies in each of the three SESCO backscatter surveys appear to be primarily caused by slope. There are no anomalous features visible in the temperature or time derivative ORP maps (Figure 8), indicating a lack of detectible hydrothermal venting within the survey area. The two northmost SESCO model areas, at 40°46'N and 40°48'N, were surveyed as part of the same dive (Sentry Dive 642), unfortunately during this dive the MAPR only collected data at the start of the survey, leaving data gaps in the temperature and time derivative ORP maps over the 40°46'N survey area, and no MAPR data over the 40°48'N survey area.

4. Discussion

The results of this study were used to evaluate the structure of the Escanaba Trough on the regional and hydrothermal vent field scales. Here, we discuss how the geologic map was used to clarify the tectonic controls on the formation of Escanaba's volcanic centers, and how the magnetic models across those volcanic centers have updated our understanding on the geometry of the sub-sediment laccoliths and associated sills. The magnetic models also have the potential to reveal hydrothermal alteration around the uplifted mounds, and show how the degree of alteration of the basaltic basement rock changes across the different volcanic centers.

Anomalies are visible in both sets of temperature and time derivative ORP maps (Figure 6), indicating that there was active hydrothermal venting within the NESCA survey areas at the time of data collection (May–June 2022).

3.2.2. MESCA Model

The one AUV magnetic survey collected in the MESCA volcanic zone covered a 1 × 5 km area spanning the western portion of the axial volcanic ridge (Figure 7). Modeling of the data shows minor variations in magnetic susceptibility in the sediment layer and two ~0.1 SI anomalies at 1,400 m and 3,000 m within the basement layer (Figure 7 AA'). The low magnetic susceptibility values in the sediment layer indicate that the survey likely did not overlap any surface flows, similar to what was observed in NESCA (Figure 6). The two anomalies in the basement, which align with major faults, could be cooled intrusive bodies, similar to what was also observed in the northern NESCA magnetic model (Figure 6 BB'). Anomalies in the backscatter data appear to be mainly associated with bathymetric slope and as such do not indicate the presence of any surface flows. There are no anomalous features visible in the temperature or time derivative ORP maps (Figure 7), indicating a lack of active hydrothermal venting within the survey area.

3.2.3. SESCO Models

Three AUV magnetic surveys were collected over the SESCO volcanic zone during the TN403 cruise (Figure 3). The northern survey covers a single mound, North Hill, which, when modeled, revealed little to no variation in magnetic susceptibility in the sediment layer (Figure 8 cross-section AA', minor anomalies at distances 300 and 700 m). The southern corner of the model covers a portion of the SESCO lava flow (Clague et al., 2022), reflected by the high magnetic susceptibility anomaly. The central SESCO model includes the mounds 3170 Hill, East Hill, and an unnamed mound that hosts inactive chimneys (Figure 8). Magnetic susceptibility anomalies are visible around 3170 Hill, and extend to the unnamed mound to its east. The orientation of the magnetic susceptibility anomalies, which are approximately parallel to the direction of seafloor spreading, are the same in the sediment layers of the northern and middle SESCO magnetic models. The southernmost SESCO magnetic model wraps around the mound S4, and encompasses

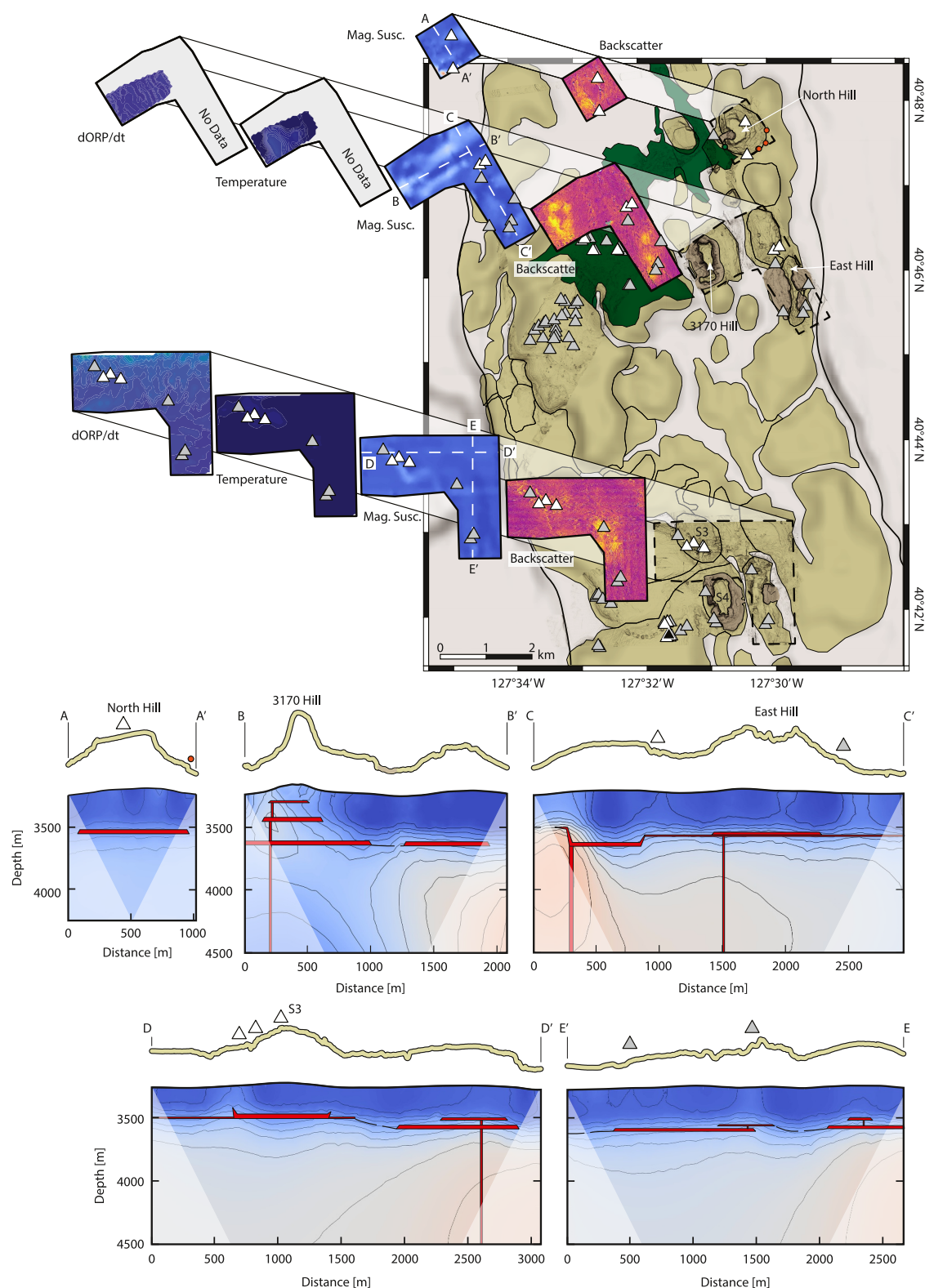


Figure 8. A map of the SCSA volcanic center, showing its three modeled survey locations. The maps, models and data sets shown here follow the legend depicted in Figure 6. From right to left the map insets are seafloor backscatter, seafloor magnetic susceptibility, water temperature at a 60 m altitude above the seafloor, and the time derivative of ORP at a 60 m altitude above the seafloor. Below are cross-sections through the three 3D magnetic susceptibility models, contoured at 0.01 SI intervals, with 5:1 vertically exaggerated bathymetric line profiles above them. Named mounds are labeled.

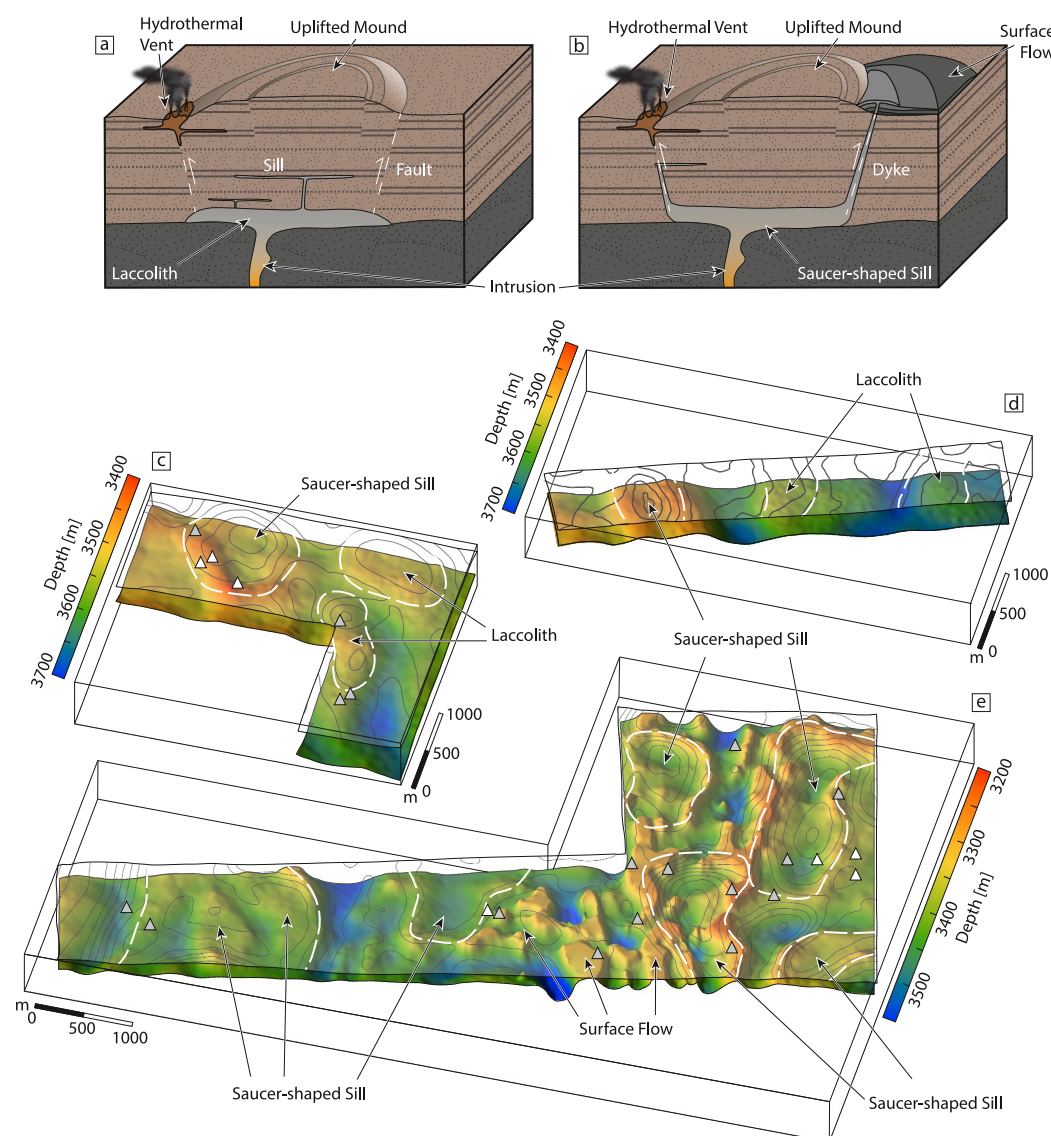


Figure 9. Conceptual models of laccolith and sill emplacement below and within the uplifted sediment mounds in the Escanaba Trough. (a) The classic depiction of an Escanaba uplifted mound (Morton et al., 1994), with a central laccolith providing the majority of the inflation that forms the mounds and minor basaltic sills intruded into the sedimentary layers. (b) A model of a saucer-shaped sill, with a concordant inner sill surrounded by transgressive inclined sheets (Galland et al., 2018), possibly resulting in dyke-fed surface flows. Both conceptual models can host hydrothermal vents. A comparison of the modeled sediment-sill/basement interface (0.04 SI isolayer) from the 3D inversion model of the, (c), SESA 3, (d) MESCA, and (e), NESCA 1 data sets, colored by depth below sealevel. Highlighted uplifted mounds are encircled by a dashed white line, and the translucent bathymetric surface includes 10 m black depth contours. White triangles represent inactive hydrothermal chimneys, and gray triangles are suspected hydrothermal chimneys.

4.1. Tectonic Controls on Escanaba Trough's Volcanic Centers

The Gorda ridge is made up of 5 segments, which, from north to south, are: North Gorda, Jackson, Central, Phoenix, and Escanaba (Rona et al., 1992). Escanaba is structurally unique from these other spreading segments in how more segmented its spreading centers are. Each of the four segments north of Escanaba are composed of single continuous S1 or S2 segments (MacDonald, 1998), ranging from 25–65 km long (Figure 1). By contrast, the Escanaba Trough contains seven S3 segments separated by lateral offsets, and ranging in length from 4–15 km (Figure 4). The segmentation of Escanaba into multiple spreading centers is likely caused by the rotational stress from the Cascadia subduction zone and its proximity to the Mendocino Transform Fault, as reflected by the

rotation of the individual spreading centers (Figures 4 and 5c) and the transition from normal dip slip faulting, to normal oblique slip, then to the strike slip faulting of the Mendocino Transform Fault (see CMTs in Figures 1 and 4a).

The segmentation at Escanaba is reflected in the distribution of volcanic centers. There are clear boundaries between NESCA, MESCA, and SESCA, marked by gaps in the uplifted sediment mounds that represent volcanic activity along the ridge axis (Figures 5a and 5b). The lower degree of volcanism in the zone between NESCA and SESCA (Figure 5b) aligns with the observed 19° rotation in spreading center orientation (Figure 5c), as well with a ~200 m deepening of the basement layer (Figure 4d). This would indicate that there is less crustal inflation occurring where spreading in the Escanaba Trough undergoes a change in orientation, which would likely lead to less near-seafloor volcanism. This is typical of a slow-spreading ridge non-transform offset (Sempere et al., 1993) or a deviations in axial linearity (DEVAL), defined by sharp changes in spreading axis orientation with very little offset (Anderson et al., 2017).

The depth to basement, relative to the seafloor, is deepest at the southern Escanaba Trough, where seafloor spreading is dominated by rifting with a lack of laccoliths (Figure 4 DD' and EE'; Figure 5d). As previously observed in (Karlin & Morton, 1983), the lack of volcanism likely due to a depression of the mantle isotherms caused by cooling effects from the nearby old, cold Pacific plate on the other side of the Mendocino Fracture Zone.

The mapped laccoliths from the Phoenix segment are only a portion of the volcanic features that extend along the rest of the segment, past the northern limits of the mapped region. As such, the calculated volume of volcanic features along the approximately 20% length of the Phoenix segment that was mapped were not used to infer anything about that segment as a whole.

4.2. Geometry of the Sub-Sediment Sills and Laccoliths

Previous studies of the formation of uplifted sediment mounds within the heavily-sedimented neovolcanic zone of the Escanaba Trough have proposed that they are largely caused by the pooling of magma at the sediment-basement interface, forming laccoliths (Clague et al., 2022; Denlinger & Holmes, 1994; Morton et al., 1990). This addition of volume uplifts the overlying sediment like a piston, creating ring faults about its perimeter. As previously proposed, these ring faults likely act as permeable pathways for hydrothermal fluids, leading to the occurrence of hydrothermal vents at the perimeters of some of the mounds in the Escanaba Trough (Clague et al., 2022; Morton et al., 1994). In some cases, magma has ascended along these ring faults to reach the seafloor to form surface flows (e.g., the NESCA Young flow originating from hill N12's ring faults, and the NESCA #2 flow originating from hill N1's faults; Figure 6; Clague et al., 2022). In this section we explore the possible mechanisms behind the higher than background modeled magnetic susceptibility anomalies that occur in the sedimentary layer within and surrounding the uplifted mounds (Figures 6–8), and how they relate to magmatic and/or hydrothermal processes. The occurrence of high magnetic susceptibility anomalies around the perimeters of the some of the uplifted mounds (primarily found in NESCA) might suggest that the laccoliths in those areas are not flat-lying along the sediment basement interface but are instead “saucer-shaped” sills (Galland et al., 2018). Hills N1 and N12, and the associated surface flows surrounding them, demonstrate that ring faults around the uplifted mounds can act as pathways for not just hydrothermal fluids but also magma (Clague et al., 2022). Therefore, it is reasonable to assume that there are likely other mounds in the Escanaba Trough that host ring mafic dykes that did not reach the seafloor (i.e., saucer-shaped sills; Figure 9b). While the presence and relative size of the upturned edges of saucer-shaped sills can be inferred from the presented 3D magnetic models, their exact geometry is beyond the modeling resolution of this study. AUV-derived magnetic data is typically collected at an average altitude of 60 m, and, as in this study, with a line spacing of approximately 100–150 m. As such, the magnetic susceptibility models could be generated at a resolution of no better than 50 m resolution. Along with the necessary model smoothing that occurs in minimum-structure inversion modeling to generate a unique solution, any high susceptibility dyke feature would likely have a width on the order of meters (Denlinger & Holmes, 1994) and a maximum length equal to the sediment's thickness (e.g., ~100–200 m through NESCA; Gardner et al., 1993), and would be averaged with the surrounding sediment within the approximately 50 × 50 × 50 m cells of the model. Examples of such features in the modeled sediment layer include the high magnetic susceptibility anomalies surrounding hill N12 in cross-section AA' in Figure 6, likely representing the mafic

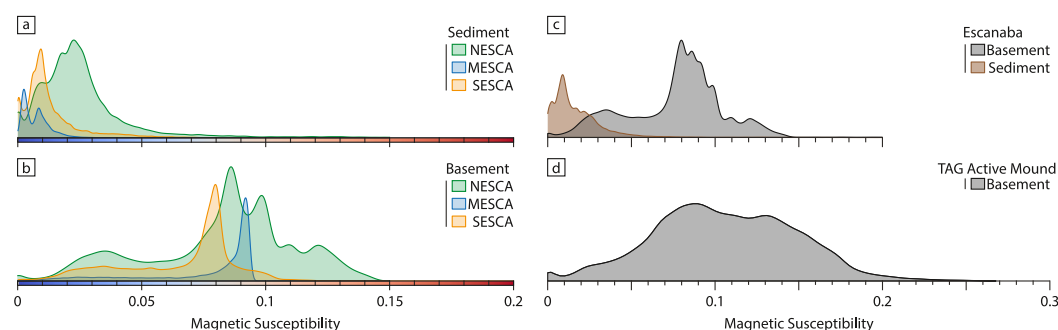


Figure 10. Probability distributions for modeled magnetic susceptibility found in (a), sediment, and (b), basement layers of the NESCA, MESCA, and SESCA volcanic centers, as derived from this study's inversion models. (c), the probability distributions for the six Escanaba inversion models from this study, representing sedimented basalt-hosted hydrothermal systems, compared to (d), the inversion of the TAG active mound from (Galley et al., 2021), representing an unsedimented basalt-hosted hydrothermal system.

dykes that fed the NESCA Young flow (Clague et al., 2022), and the many anomalies bordering the uplifted mounds in Figure 6 cross-section BB' and Figure 9d.

As the sills and basaltic basement host higher magnetic susceptibilities than sediment, an approximate depth to the top of the sills/sediment-basement interface can be derived from the 3D inversion models. This was accomplished by extracting a magnetic susceptibility isolayer from the models that best represented this interface. Through testing, 0.04 SI was found to best approximate this boundary, in comparing it to the regional Gardner et al. (1993) model and reflectors from the Morton et al. (1994) seismic profiles. 0.04 SI is also the mid-point between the 0.0 SI sediments and mean basement susceptibility of 0.08 SI (Figure 10). The modeled top of the sills/sediment-basement interface for the NESCA 1, MESCA, and SESCA 3 models are shown in Figure 9, with mean thicknesses of 131 ± 63 m, 293 ± 53 m, and 292 ± 47 m, respectively. Across the same model areas, the sediment thicknesses from the Gardner et al. (1993) model are 96 ± 2 m, 235 ± 52 m, and 332 ± 40 m, respectively. While generally useful to study the 3D geometry of the sills in the Escanaba Trough and determine if they are laccoliths or saucer-shaped sill (Figure 9), approximating this interface by a magnetic susceptibility isolayer fails when the modeled area contains rock heated beyond its Curie temperature ($\sim 580^\circ\text{C}$). The NESCA 2 model is an example where the 0.04 SI isolayer would incorrectly show a large depression in the basement topography (Figure 6 cross-section AA'), when this depression in the isolayer likely represents a hot intrusion.

4.3. Detecting Hydrothermal Alteration in Sedimented Environments

Fault-controlled magma injections are not the only process that can generate the magnetic anomalies observed beneath the margins of the mounds. Alternatively, hydrothermal alteration may be the cause for the magnetic susceptibility anomalies surrounding many, but not all, of the uplifted mounds, as also observed at the Middle Valley Bent Hill mounds (Tivey, 1994). Near-seafloor magnetic surveys performed over the Middle Valley Bent Hill mounds, which are hydrothermally active uplifted sediment mounds located 20 km east of the northern Juan de Fuca spreading center, revealed high, positive total magnetic field anomalies that drilling from Ocean Drilling Program Leg 169 confirmed to be due to hydrothermally precipitated magnetite within the thick sediment layer.

Pyrrhotite is the primary magnetic mineral within hydrothermal chimneys and sulfide-rich sediments at Escanaba Trough (Karlin & Zierenberg, 1994). The pyrrhotite mineral group ranges in composition from FeS (troilite) to Fe_7S_8 , (monoclinic pyrrhotite), and hexagonal pyrrhotite exhibiting compositions between Fe_9S_{10} , and $\text{Fe}_{11}\text{S}_{12}$ (Morimoto et al., 1975; Wang & Salveson, 2005). The sulfide formations at Escanaba have previously been reported to be primarily composed of hexagonal pyrrhotite, which is classically non-magnetic (James et al., 1998; Karlin & Zierenberg, 1994; Koski et al., 1994; Zierenberg et al., 1993). Hexagonal pyrrhotite is typically anti-ferromagnetic at ambient temperatures. However, if heated beyond its $200\text{--}220^\circ\text{C}$ γ -transition (but still below its $275\text{--}295^\circ\text{C}$ Curie temperature; Rochette et al., 1990), hexagonal pyrrhotite has been observed to become ferromagnetic (Rochette et al., 1990). This magnetic transition is metastable after cooling back below its γ -transition temperature (Bennett & Graham, 1981). Therefore, within the Escanaba Trough it is expected that hydrothermally precipitated pyrrhotite that remains at temperatures less than $200\text{--}220^\circ\text{C}$ since its formation (i.e., low-temperature

hydrothermal venting) will be antiferromagnetic, resulting in non-anomalous magnetic susceptibility values compared to the surrounding sediment. On the other hand, hexagonal pyrrhotite that has been reheated to temperatures between its γ -transition and Curie point (i.e., exposed to high-temperature hydrothermal venting at ~ 220 – 295°C) could be anomalously magnetically susceptible with respect to the surrounding sediment. Hydrothermal venting in the Escanaba Trough has been measured at temperatures between 108 and 217°C (Campbell et al., 1994; Von Damm et al., 2005), and magnetic susceptibility measurements conducted on sulfide bearing sediment cores (Adamczyk et al., 2025) exhibit magnetic susceptibility values an order of magnitude above the median hemipelagic sediment.

Results from the northern-most magnetic model from NESCA indicate that most of the mounds in the area are ringed by magnetic susceptibility anomalies, but visual surveys have not found the presence of sulfide deposits or venting to be as widespread. A lack of widespread time-derivative ORP and temperature anomalies corroborate this (Figure 6). As such, while possible, it appears more likely that these anomalies are caused by the intrusion of mafic dykes into the sediment around the mounds (Figure 9).

4.4. Sub-Sediment Basement Alteration

Three-dimensional magnetic inversion modeling provides information on how magnetic susceptibility varies both laterally and with depth, creating the opportunity to image the magnetic properties of the sediment and underlying basement along the length of the Escanaba Trough.

We surveyed approximately 37.8 km^2 of seafloor in this study, and, when considering a minimum 1 km depth sensitivity below the seafloor defined by the smallest survey length (SESCA1; Figure 3), this area amounts to imaging about 37.8 km^3 of sediment and basement rock. By isolating the basement from the sediment layer using the Gardner et al. (1993) sediment thickness model, Figure 10c shows the cumulative magnetic susceptibility distribution of all six models' basement layers, with a primary peak at 0.085 SI, and minor peaks at 0.035 and 0.125 SI. This distribution can be compared to a similarly created model of the Trans-Atlantic Geotraverse (TAG) active mound on the Mid-Atlantic Ridge, which, like Escanaba, is a basalt-hosted hydrothermal system, but with little to no sediment cover (Figure 10d; Galley et al., 2021). Both distributions show similar peaks in magnetic susceptibility, but with varying amplitudes. The approximate 0.085 SI peak at TAG was interpreted to represent background, unaltered basalt, with the lower values peaking at approximately 0.03 and 0 SI, representing varying degrees of hydrothermal alteration (Galley et al., 2021). These interpretations likely hold for the Escanaba models as well, with an increase in the amplitude of the 0.035 SI peak representing an increase in basement alteration due to the overlying sediment cover (Karlin & Morton, 1983; Levi & Riddihough, 1986).

Grouping the modeled Escanaba magnetic susceptibility distributions by their volcanic centers (i.e., NESCA, MESCA, and SESCO) reveals a southward trend of decreasing basement magnetic susceptibility similar to previously model results (Karlin & Morton, 1983) (Figure 10b). Whereas the NESCA models show significant portions with magnetic susceptibilities greater than 0.1 SI, the MESCA model primarily contains a single peak at 0.09 SI, and the combined SESCO models show a peak at 0.08 SI with little to no magnetic susceptibility greater than 0.1 SI. It has been considered that the variable geometry of the modeled magnetic surveys could affect the distributions shown in Figure 10. In theory, if a given survey was larger or shaped differently then the normalized form of its corresponding magnetic susceptibility model could change, but only because it may then include some unknown feature(s) with anomalously high or low magnetic susceptibility. Occam's Razor would suggest that without additional information suggesting otherwise, the study's six magnetic susceptibility models likely represent their respective volcanic centers.

The sediment layer in each of the Escanaba volcanic centers appears to contain three magnetic susceptibility peaks, at 0.0, 0.01, and 0.02 SI, of varying magnitude (Figure 10a). The MESCA model has the lowest magnetic susceptibility values, with a dominant peak just greater than 0.0 SI. NESCA has the greatest magnetic susceptibility values in its sediment layer, with the dominant peak of 0.02 SI, and SESCO is between MESCA and NESCA with a prominent peak at 0.01 SI. Assuming that the magnetic susceptibility anomalies represent the presence of intrusive igneous rock and/or hydrothermal alteration, the distributions of magnetic susceptibilities illustrated in Figure 10a suggest that NESCA hosts more sediment sills and dykes than the other two volcanic centers and/or higher temperature hydrothermal systems, which would lead to greater sulfide precipitation on or within the sediment layer. Both NESCA and SESCO contain similar volumes of laccoliths and surface flows (Figure 5b), indicating similar levels of volcanic activity. However, sediment thickness within the SESCO models

is much greater on average than at NESCA (230 vs. 130 m; Gardner et al., 1993). The difference in lithostatic pressure caused by varying sediment thickness could account for differences in sill/dyke emplacement styles (Kavanagh et al., 2006), causing more magma to be vertically emplaced within the sediment layer in NESCA (i.e., Figures 9b and 9e) than in SESCA (i.e., Figures 9a and 9c).

Following the hypothesis that high-temperature hydrothermal sulfide mineralization could cause the magnetic susceptibility anomalies (see Discussion Section 4.3), high-temperature venting has yet to be observed anywhere except on Central Hill, in NESCA (Von Damm et al., 2005). No active hydrothermal venting has been observed in MESCA, although inactive chimneys have been found (Figure 7), and only low-temperature/diffuse venting has been observed in SESCA, southwest of hill S4 (Figure 8). Therefore, the differences in the NESCA, MESCA, and SESCA magnetic susceptibility distributions in Figure 10a could also reflect varying styles of dominant hydrothermal venting between the volcanic centers. However, as previously mentioned, the sill/dyke emplacement versus hydrothermal sulfide accumulation models used to explain the presence of magnetic susceptibility anomalies in Escanaba sediments are not mutually exclusive, and some combination of both could be the cause of the observed anomaly patterns.

5. Conclusions

Sedimented mid-ocean ridges are rare geological settings where the presence of the thick sediments influences volcanism and associated hydrothermal venting by insulating the crust, altering fluid chemistry, and generating some of the largest known massive sulfide deposits on the modern seafloor. Due to their thick sediment cover, the study of these environments presents significant challenges, and a reliance on remote-sensing methods. A compilation of new and legacy bathymetric, seismic, gravity, and magnetic data at a regional scale culminated in the generation of a new lithostratigraphic map of the Escanaba Trough. With this geologic map the volume of sub-sediment volcanism was calculated, and the controls on the placement of the axial valley's three main volcanic centers were determined by deciphering the architecture of its spreading segments. Additionally, this study summarizes the results of six new near-seafloor magnetic survey data sets that were modeled to identify the presence and geometry of volcanic sill emplacement and associated hydrothermal activity within and below Escanaba's uplifted sediment mounds.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The magnetic data modeled in this study is available for download through the United States Geological Survey (Galley et al., 2026), and the bathymetry data collected during cruise TN403 is available through the Marine Geoscience Data System (Yeo et al., 2026). The inversion software used to create the models for this study is property of Memorial University of Newfoundland and Geotexera Inc. and is available upon request from the authors for academic purposes only. Figures included in this manuscript were produced with the programs Paraview (Ayachit, 2015), MATLAB (MathWorks, 2025), Adobe Illustrator (Adobe, 2024), and/or ArcGIS Pro (ESRI, 2025). Many of the colormaps used in this manuscript were from Kovesi (2015).

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Acknowledgments

We would like to thank the support and professionalism of the captain, crew, and the ROV and AUV technical teams from the R/V Thomas G. Thompson during the TN403 expedition. Funding for this project was provided by a Canada Research Chair Grant (950-230933) and NSERC Discovery Grant (RGPIN-2017-05548), held by Dr. John Jamieson. All inversion modeling was performed on Digital Research Alliance of Canada clusters, which are funded by the Government of Canada. Escanaba Trough: Exploring the Seafloor and Oceanic Footprints is an interagency effort involving the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey, and the Bureau of Ocean Energy Management. Funding is acknowledged from NOAA Ocean Exploration via its Ocean Exploration Fiscal Year 2019 Funding Opportunity and through the National Oceanographic Partnership Program (NOPP), the USGS Coastal and Marine Hazards and Resources Enhanced Funding Opportunities, the Bureau of Ocean Energy Management through Interagency Agreement M19PG00021 with the United States Geological Survey, and the USGS Coastal and Marine Hazards and Resources Program, and Mineral Resources Program. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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