CARBON FREE POWER PROJECT

August 12, 2022 Docket No. 99902052

U.S. Nuclear Regulatory Commission
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SUBJECT: NuScale Power, LLC Submittal of Carbon Free Power Project (CFPP) Combined License Application (COLA), "Volcano Hazards Analysis Methodology" White Paper, WP-122306, Revision 0, on behalf of CFPP, LLC

REFERENCES:
1. NuScale Power Letter to Nuclear Regulatory Commission, "Licensing Lead for Carbon Free Power Project, LLC", dated October 12, 2021 (ML21299A363)
2. LO-108994, NuScale Power, LLC Submittal of Presentation Materials, "Carbon Free Power Project (CFPP) Combined License Pre-application Engagement," PM-108461, Revision 0 (ML21312A556)

During a public meeting on November 18, 2021, CFPP presented to the NRC technical staff an overview of the CFPP volcanic hazards analysis methodology and its implementation of Regulatory Guide 4.26, "Volcanic Hazards Assessment for Proposed Nuclear Power Reactor Sites."

The purpose of this letter is to submit the enclosed CFPP Volcanic Hazards Analysis Approach Methodology white paper for the staff's review on behalf of CFPP. The paper describes the approach being used by the CFPP to identify, screen, and model potential volcanic hazards.

NRC staff has scheduled a public meeting on August 30, 2022 to provide feedback to the CFPP on the enclosed white paper. Additionally, CFPP plans to present the preliminary screening results to the NRC staff during the August 30th meeting.

If you have any questions, please contact Kyra Perkins at 980-349-4117 or at kperkins@nuscalepower.com.

Sincerely,

John Volkoff

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NuScale Power, LLC
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Enclosure 1: "Volcano Hazards Analysis Methodology" White Paper, WP-122306, Revision 0, nonproprietary

Enclosure 1:

"Volcano Hazards Analysis Methodology" White Paper,\ WP-122306, Revision 0, nonproprietary

Volcanic Hazards Analysis Approach Methodology

Executive Summary

The selected Carbon Free Power Project (CFPP) site at the Idaho National Laboratory (INL) location resides on the Eastern Snake River Plain (ESRP) which is a location of historical volcanic activity. The Combined License (COL) application for a NuScale Power Plant at the CFPP site is to be submitted with considerations for the new Regulatory Guide (RG) 4.26 which describes approaches for assessing volcanic hazards at a site. The early selection process for the CFPP site included an identification of a topographically elevated location due to considerations of the prior volcanic history in the areas in the vicinity of the site location. This paper is to describe the approach being used by the CFPP to identify, screen, and model the hazards in support of this selection.

The complex volcanic history of the site requires a comprehensive description of known historical hazards associated with volcanic activities. The emergence of volcanic vents in the ESRP resulted in ground deformation and the expulsion of lava and tephra onto the site. These volcanic phenomena are screened using criteria in accordance with the guidance of RG 4.26 for their relevance to the hazard assessment at the CFPP site.

The hazards that screen in will be modeled using techniques developed for the complexity of this location. The models will then be used to create a risk profile of hazards and their likeliness of impact to the CFPP site. These risks will then be assessed in an upcoming analysis for their impact on the systems, structures, and components, and used as a basis for mitigation measures to be taken for these hazards on the CFPP site.

1.0 Introduction

The purpose of the volcanic hazard analysis (VHA) for the CFPP is to identify and characterize the potential for future volcanic events occurring within the ESRP that may pose a hazard to the safety of the CFPP's planned NuScale Power Plant consisting of six NuScale Power Modules (NPMs). The VHA must provide sufficient information to understand and quantify the specific volcanic hazards that may impact the CFPP site. Therefore, the site-specific VHA will analyze the likelihood of these hazards and assess their physical characteristics, leading to a demonstration that the design and operation of the planned NuScale Power Plant at the CFPP site provide reasonable assurance of adequate radiological protection in accordance with the regulatory requirements of the U.S. Nuclear Regulatory Commission (NRC).

The CFPP site is located at the northern edge of the ESRP immediately south of the Arco Hills on the INL site. The site is centered at Latitude 43.63724 and Longitude -113.05510. The VHA is being performed per the guidance provided in RG 4.26, Revision 0, *Volcanic Hazards Assessment for Proposed Nuclear Power Reactor Sites* (NRC 2021). In the remainder of this white paper this will be referred to as RG 4.26.

Volcanic Hazards Analysis Approach Methodology

RG 4.26, represents the most definitive regulatory guidance for assessing volcanic hazards. RG 4.26 provides nuclear power reactor applicants with methods and approaches the NRC staff considers acceptable for the assessment of volcanic hazards in license applications. RG 4.26 also facilitates the NRC staff's review of VHAs performed by applicants to support the siting of new nuclear power reactors.

While the focus of RG 4.26 establishes regulatory guidance for conducting a VHA, RG 4.26 also provides an overview of important technical and regulatory considerations that underpin that guidance. This includes an overview of the types of volcanic hazards that should be evaluated with the understanding that there is a wide range of physical conditions that may impact the performance of safety-related structures, systems, and components.

Figure 1 (Figure 1 from RG 4.26) displays the NRC flowchart for an acceptable VHA using an alternative engineering analysis approach. The VHA work scope addresses Steps 1 and 2 and includes sufficient VHA modeling to inform the assessment of screened in volcanic hazards for Step 3 in preparation of performing the alternative engineering analysis.

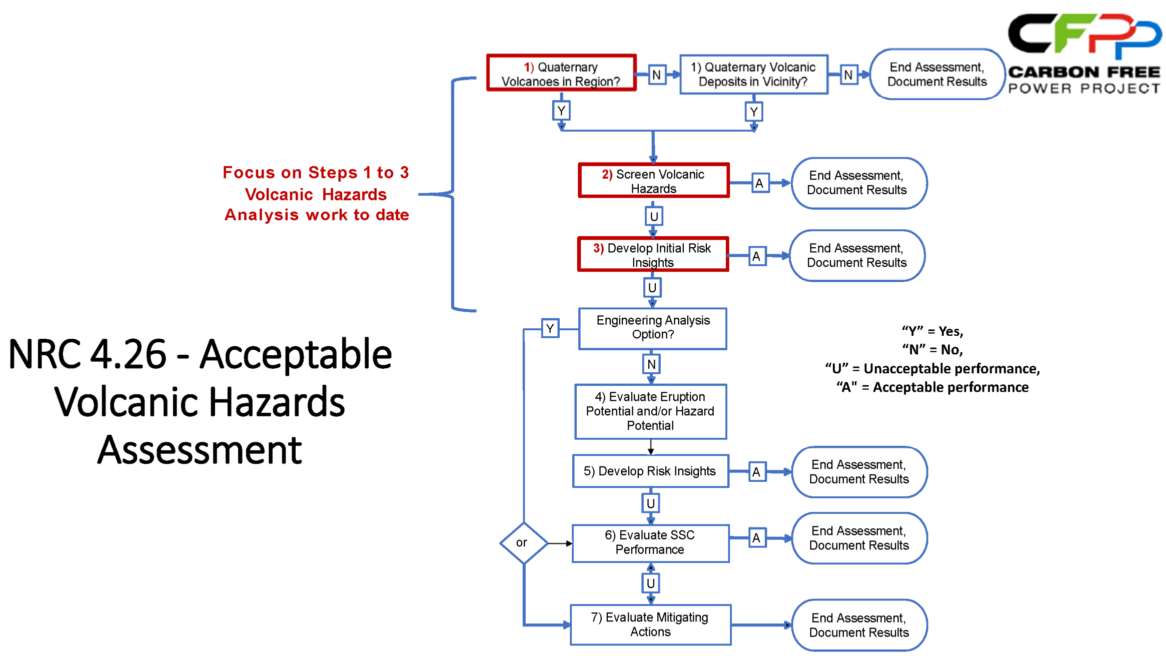

Figure 1: Nuclear Regulatory Commission flowchart for an acceptable volcanic hazards assessment using an alternative engineering analysis approach (Figure 1, NRC Regulatory Guide 4.26)

Volcanic Hazards Analysis Approach Methodology

The current approach for screening of volcanic hazards is to identify those volcanic phenomena having evidence of occurring within the Quaternary Period (i.e., over the last ~2.6 million years) at or near the CFPP site and to determine the maximum distance that these volcanic phenomena can have an effect, with respect to the distance between the source and the CFPP site. The approach to screening recognizes that the available data for each volcanic phenomena may be uncertain, and thus CFPP will only screen out volcanic phenomena when there is high confidence that this can be technically justified.

The development of a tectono-magmatic model plays an important role for assessing volcanic hazards. This model will define the tectonic and magmatic processes that control past volcanism which provides an understanding of which volcanic phenomena may occur in the future. Thus, the tectono-magmatic model guides the assessment for determining the likelihood of future volcanic phenomena. The development of a tectono-magmatic model is described in more detail in Section 3 of this white paper.

After Step 2, screening analysis of volcanic hazards, Step 3 will evaluate relevant data that informs the assessment of volcanic phenomena hazards that were screened in. For lava flow this includes assessing the spatial density of volcanic events and relevant distributions for the physical dimensions of these hazards, such as the thickness and volume of lava flows. Once the data are evaluated and integrated into the relevant hazard inputs, a series of volcanic simulations consistent with the eruption model will quantify the hazard at the CFPP site.

The VHA quantifies the uncertainties in data, models and methods, which are expected to involve large uncertainties in several model inputs. For example, the distribution of lava-flow thickness may be centered around a narrow range (~1m to 10 m), but may include rare lava flows that are significantly thicker (>20m). Therefore, a mean annual occurrence frequency will be integrated with the postulated physical characteristics of the volcanic phenomena that may impact the site (i.e., the thickness and volume of lava) for a comprehensive model.

Lava flow modeling allows the analyst to understand, for a given event location, how far the lava can travel given the effusion rate and existing topography, in the context of the frequency of those events. Enough simulations are performed to ensure that the hazard can be quantified. Once those hazards have been quantified the risk insights from the modeling will be evaluated in the engineering analysis option for impact to the structures, systems, and components (SSCs) of the NuScale Power Plant located on the CFPP site and possible mitigation strategies in Steps 6 and 7.

Volcanic Hazards Analysis Approach Methodology

As described in RG 4.26:

> *A "risk-informed" approach to regulatory decision-making represents a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety.*

Thus, the work scope for a VHA needs to be structured to provide sufficient information to support a "risk-informed" approach for assessing volcanic hazards. In this context, the VHA needs to focus on improved decision making by providing the hazard context leading to improved risk insights. For the CFPP, the VHA will include probabilistic hazard analyses sufficient to understand the potential hazards that may impact the CFPP site.

It is also important to recognize that RG 4.26 includes discussion of the Senior Seismic Hazards Analysis Committee (SSHAC) Guidelines as an acceptable method to account for a wide range of uncertainties in the analysis of natural hazards. The most recent SSHAC guidelines are found in NRC NUREG-2213, *Updated Implementation Guidelines for SSHAC Hazard Studies*, October 2018. The VHA being performed for CFPP recognizes that the INL is completing a site-wide Probabilistic Volcanic Hazard Analysis (PVHA) following SSHAC Level 3 guidance. CFPP is taking steps to integrate and coordinate the CFPP VHA with the INL SSHAC Level 3 PVHA.

The alternative engineering analysis approach requires that the initial risk insights use the maximum-magnitude volcanic hazard that is inferred from the work performed to screen volcanic hazards. RG 4.26 does not provide an explicit definition for the maximum-magnitude volcanic hazards. As such, maximum-magnitude volcanic hazards are those that are considered possible from the maximum bound of past events and consistent with current geologic conditions.

The CFPP VHA will include sufficient modeling to calculate the likelihood of a future lava eruption and the associated hazards, including inundation of the CFPP site. The results of this work will be used to define the maximum-magnitude lava flow for consideration on an annual exceedance frequency (AEF) basis.

Sufficient modeling and sensitivity analysis will be performed to understand the model inputs that control the hazards. Thus, maximum-magnitude is informed by technically defensible modeling to understand both the annual frequency and the associated input parameter that results in the hazard, and more importantly does not automatically equate to "worst-case" input.

Volcanic Hazards Analysis Approach Methodology

Consistent with a risk-informed approach, the VHA will provide input for assessing risk insights to support NuScale in addressing design and operational issues related to volcanic hazards. As stated in RG 4.26, the risk-informed approach enhances the deterministic approach by:

- Allowing explicit consideration of a broader set of potential challenges to safety.
- Providing a logical means for prioritizing these challenges based on risk significant operating experience, and/or engineering judgment.
- Facilitating consideration of a broader set of resources to defend against these challenges.
- Explicitly identifying and quantifying sources of uncertainty in the analysis (although such analyses do not necessarily reflect all important sources of uncertainty).
- Leading to better decision-making by providing a means to test the sensitivity of the results to key assumptions.

Volcanic Hazards Analysis Approach Methodology

2.0 Approach to Analyzing Volcanic Hazards for the CFPP

The VHA must provide sufficient information to understand and quantify potential future volcanic events that may pose a hazard to the safety of the planned NuScale Power Plant at the CFPP site. The approach to analyzing volcanic hazards recognizes that the assessment of certain volcanic hazards is complex and that significant uncertainties exist relative to understanding the physical processes that generate these hazards. Certain volcanic hazards are rare events. Therefore, the assessment of volcanic hazards must ensure that:

- Sufficient data are available to assess the hazards
- Steps are taken to objectively evaluate these data and the associated data uncertainties
- An evaluation of hazard models and methods is performed that can be used to quantify the associated hazards
- Integration of data, models, and methods is performed leading to defining hazard inputs (including uncertainties) and hazard analysis modeling
- Complete and transparent documentation is provided for the hazard analysis.

Multiple assessments of volcanic hazards have been completed over the past 40 years for facilities at the Idaho National Laboratory and within the ESRP. These investigations have concluded that certain volcanic phenomena present within the Quaternary geologic record of the ESRP have probabilities of future occurrence. The VHA team will evaluate these previous hazard investigations in its analyses of potential hazards that may impact the CFPP site.

The CFPP has assembled a VHA team that consists of experienced geologists, volcanologists, and hazard analysts. The VHA Team has prepared a Project Execution Plan (RIZZO, 2021) that is structured to provide sufficient information to support a “risk-informed” approach for assessing volcanic hazards. In this context, the VHA Project Execution Plan (PEP) presents an approach, regulatory guidance, key activities, quality assurance requirements, and a schedule for identifying and characterizing the potential volcanic hazards for the CFPP site.

The approach to assessing volcanic hazards includes field and laboratory investigations, identification and characterization of volcanic phenomena, and quantification of screened in volcanic phenomena to assess the associated hazards, culminating in a VHA report. The work scope leading to a risk informed assessment of volcanic hazards at the CFPP site are summarized in the following paragraphs.

Volcanic Hazards Analysis Approach Methodology

The ongoing site-characterization field program for the CFPP site includes VHA-relevant geological and geotechnical drilling, surface and downhole shear-wave velocity surveys, seismic-reflection surveys, and geologic mapping. In addition to the standard field and laboratory investigations, LiDAR analyses will be conducted to identify volcanic features within the site vicinity (35 mile radius of the site), as will mapping of the volcanic features within the site vicinity, site area (5 mile radius of the site) and site (1 mile radius of the site), argon/argon age dating of the basalt core from a deep borehole located at the center of the CFPP site, paleomagnetic analyses of the same basalt core, and petrographic analyses of the basalt and sedimentary interbeds in the borehole. Distances cited above are consistent with the guidance of NRC Regulatory Guide 1.208 with the exception of the 35-mile radius. A 35-mile radius was selected for the site vicinity to encompass younger basalt flows and lava flow catchment. These activities will be used for estimating event frequencies, grouping basalt flows, relating flow groups to specific sources, and general correlation of basalt flow groups among boreholes.

Based on available data, a site specific tectono-magmatic conceptual model will be developed. This model will be used to inform the VHA investigators of the tectonic and magmatic processes that have occurred within the CFPP site vicinity throughout the Quaternary Period and to forecast how these processes are expected to persist or change in the future. One of the most important roles of the tectono-magmatic model is to assess how the locations and magnitudes of volcanic events that have occurred in the past are best used, in a geologically consistent way, to assess the likelihood, locations, and magnitudes of potential future volcanic events.

The tectono-magmatic model and data will be used in the screening of volcanic phenomena (***Section 4.0***) that potentially pose a hazard to the CFPP site. The screening will consider the potential for Quaternary volcanic phenomena present within the site region.

An updated database of volcanic events consisting of one or more mapped vents will be developed that informs the volcanic event recurrence rate and provides input for spatial density estimation. One or more spatial density models of volcanic events will be developed that informs the number of events per unit area and provides input for stochastic sampling of possible future volcanic events. A hazard input document (HID) will be developed to provide the necessary range of parameter values quantifying the physical properties of the volcanic phenomena that provides input for developing numerical models (***Section 5.0***) for the volcanic hazards that have a potential for impacting the safe operation of NuScale Plant at the CFPP site.

Once the data are evaluated and integrated into the relevant hazard models a series of volcanic simulations that represent eruption and eruption products will be performed to quantify the hazards at the CFPP site. Sensitivity analyses will be conducted to fully describe the impact of specific parameters and uncertainties in the results of the model analyses based on probability distributions output from the hazard models. The basis for the maximum-magnitude volcanic event(s) will be defined and documented. The outputs of these modules and sensitivity analyses will support the performance assessment of the NuScale Power Plant SSCs.

Volcanic Hazards Analysis Approach Methodology

The technical work being performed by the VHA includes the following:

- Collect new field data within the site vicinity to improve the understanding of volcanic hazards. This new data will include1) mapping of geologic features within the site vicinity, 2) drilling and examination of core at the site to characterize the basalt package, and 3) geochronology of the basalt package at the site. The analysis of the new data will result in an improved assessment of uncertainties and will lead to an acceptable definition of maximum-magnitude volcanic hazards.
- Develop a tectono-magmatic conceptual model to articulate the conceptual understanding of the geologic processes that drive the volcanic hazards, leading to improved understanding of the location, rates, and sizes of dominant volcanic hazards.
- Assess the complete range of potential volcanic hazards as part of performing volcanic hazards screening.
- Perform volcanic hazard modeling to quantify both event frequency and event physical characteristics to define the volcanic hazards as input to engineering analysis.
- Integrate the outcomes of the evaluations to develop hazard input models, including an assessment of uncertainties, leading to distributions reflecting the center, body, and range (CBR) of the technically defensible interpretations (TDI) of the input.
- Development and understanding of the key input parameters and associated uncertainties that are driving the VHA results based on relevant data, models, and methods along with sufficient sensitivity analyses.
- Document a complete and transparent record of the evaluation and integration work performed.
- Perform an independent peer review of the work completed and hazard calculation results.

The INL is separately conducting a site-wide PVHA. To ensure consistency and integration, the CFPP and INL PVHA management will periodically hold information exchange meetings. Integration and coordination is further enhanced with common team experts participating on the two teams. A memorandum of understanding related to communication and exchange of information has been adopted between the CFPP and INL management. The CFPP VHA team will benefit from the INL PVHA because of the level of the SSHAC process being performed. Likewise, the INL PVHA Team will benefit from the CFPP VHA advanced schedule and data acquisition.

Volcanic Hazards Analysis Approach Methodology

3.0 Volcanic Phenomena Screening for the CFPP Site

As data collection is ongoing, the different phenomena identified in the ESRP are being screened for potential impacts to the CFPP. The screening approach follows the guidance of RG 4.26 in that the VHA team first developed a working draft tectono-magmatic conceptual model of the region and then identified those Quaternary volcanic features within the region that may pose a hazard to the CFPP site. Following the approach developed by the INL PVHA team, the VHA team developed a site-specific matrix that relates volcanic features to volcanic phenomena. The volcanic features include those mappable geologic features that produced one or more hazardous volcanic phenomena (e.g., fissures, ash fall, lava flows) when they erupted. The VHA team is identifying those volcanic phenomena that are either present or expected to be present on the ESRP given available information and considering the location of the CFPP site. Also included on the matrix are potential distant volcanic sources (e.g., Yellowstone or Cascade volcanic eruptions). The VHA team will then assess the likelihood of future volcanic phenomena impacting the CFPP site.

To aid in the screening analysis, four screening categories were established related to assessing the potential hazards posed to the safety of the CFPP site. If they met one of these screening criteria, it was considered screened in for modeling. The screening categories are defined as those volcanic phenomena:

- Present on the ESRP and requiring numerical modeling to assess the hazard posed to the CFPP site
- Not associated with the specific volcanic feature category assessed or not present within the ESRP
- Requiring a calculation of either event frequency or a bounding calculation based on available data
- Requiring documentation to demonstrate the phenomenon should be screened out

Once the screening step was completed, the list of screened in volcanic phenomena will be prioritized for modeling to focus on those volcanic phenomena that are likely to pose a hazard to the safety of the CFPP site. This will include an initial assessment of the likelihood of the hazard, but ultimately all screened in volcanic phenomena and associated hazards will be addressed.

The hazard analysis will focus on the hazards viewed as posing the most likely to impact the safety of the CFPP site versus those hazards that may be viewed as the most dramatic, but expected to be far less likely to occur within the regulatory timeframe of concern. This analysis will be completed via the numerical modeling selected to assess these hazards.

Volcanic Hazards Analysis Approach Methodology

4.0 Tectono-Magmatic Model for the CFPP Site

A large body of work has been performed related to volcanic features (e.g., Kuntz et al. 1994, Hackett and Smith, 1992), volcanic stratigraphy (e.g., Hodges, et al., 2015, 2016; Champion et al., 2011), and origin (Anders and Sleep, 1992; Anders et al., 2014; Rogers et al., 2002; McCurry and Rogers, 2009; and McCurry et al., 2016; and Payne et al., 2013) of the ESRP and surrounding area. This body of information provides a basis for understanding the tectono-magmatic setting of the ESRP and more specifically the CFPP site vicinity. The goal of developing a tectono-magmatic conceptual model for the CFPP is to determine what aspects of this complex history of tectonism and volcanism within the CFPP site vicinity are relevant to forecasting the distribution, timing, and nature of future volcanic activity that may impact the CFPP site.

4.1 Tectono-magmatic Setting of the Eastern Snake River Plain and Surrounding Area

The ESRP and surrounding area has a long and complex history of tectonism and volcanism that is dominated by the track of the Yellowstone hot spot. The surface expression of this hotspot is a series of seven major volcanic fields extending from northwestern Nevada to southeastern Idaho, and a coincident parabola of contemporary seismicity. The track of the Yellowstone hotspot across southern Idaho (owing to westward movement of the North American tectonic plate) has progressed at a rate of 2.5 cm yr^{-1}, resulting in progressively younger volcanic fields from southwest to northeast (Humphreys et al., 2000; Leeman et al., 2009; Anders et al., 2014). Three of these volcanic fields (the Twin Falls, Picabo, and Heise volcanic fields) coincide with the ESRP and range in age from roughly 10.5 Ma to 4.3 Ma (***Figure 2***). The CFPP site lies on the northwest margin of the ESRP, at the transition from the broad flexure of the Yellowstone hotspot track (filled with Neogene- to Quaternary-aged rhyolitic and basaltic rocks) and the Basin and Range province of normal faulted early Cenozoic through Paleozoic to Precambrian sedimentary and igneous rocks.

Caldera-forming rhyolite volcanism (***Figure 2***) is most prominent on the ESRP, and on the Yellowstone Plateau, the originating source is from the current position of the hotspot and the site of Quaternary large-volume silicic magmatism (Morgan et al., 1984; Pierce and Morgan, 1992; Geist and Richards, 1993; Morgan et al., 2008).

Huang et al. (2015) seismic tomographic models summarize the basic geometry of the Yellowstone caldera and ESRP, and their relationship to magma bodies in the crust and mantle. Post-caldera basaltic volcanism during the past 4.3 Ma has largely covered the underlying caldera systems (e.g., Smith, 2004). As a result, the locations and characteristics of buried Neogene calderas are inferred from outcrops around the margins of the ESRP, and from deep borehole data. In the wake of the Yellowstone hot spot, latest Tertiary and Quaternary volcanism has been dominated by eruptions of basalt and evolved magmas derived from the parental basalt, to thickness up to 2 km in the ESRP. The continuous magmatic activity has created one of the world’s largest active continental hot spot systems (Smith et al. 2009).

Volcanic Hazards Analysis Approach Methodology

Detailed study of structures along the northern margin of the ESRP indicate 5 to 6 km of subsidence, almost all of which is accommodated by crustal flexure (McQuarrie and Rodgers, 1998; Rogers et al., 2002. Cessation of rhyolite volcanism was followed soon after by eruption of basalt lavas. The emplacement of these lavas, began approximately 6 Ma in the Columbia Snake River Plain (CSRP) and approximately 4.3 Ma in ESRP (Shervais et al., 2013; Potter, 2014; Champion et al., 2002). The basalt eruptions produced a distributed basalt-dominated field consisting of hundreds of coalesced shield volcanoes (Greeley and King 1982; Hackett and Smith, 1992; Kuntz et al., 1992 and 1994; Hugheset al., 2002), having an estimated cumulative volume of over 10,000 km^3 (McCurry et al., 2008). Accumulated basalts are up to ~2 km thick within the subsided basin of the ESRP (Shervais et al., 2013; Potter, 2014). Geophysical studies indicate that the subsidence occurred in response to intrusions of dense mafic magmas from the mantle into the lower- and middle-crust (e.g., Brott et al., 1981; Braile et al., 1982).

Regional Basin-and-Range extension began~17-15 million years ago, coeval with waxing and waning cycles of volcanism associated with the Yellowstone hotspot, and is ongoing. ***Figure 3*** shows the historical seismicity associated with Basin and Range extension around the margins of the ESRP, defining a "tectonic parabola" (Anders et al., 1992). Notably, inception of Basin and Range extension coincided with massive 17-15 million year accumulation of basalt lavas of the Columbia River Basalt, a large igneous province in southeastern Oregon (e.g., Camp et al., 2015). Basaltic volcanism also occurred southward across central Nevada.

The Pioneer, Lost River, and Lemhi Ranges north of the ESRP are primarily Paleozoic carbonate and siliciclastic rocks that are deformed by folds and faults of the Sevier and Laramide orogenies, well prior to Basin and Range extension. The Paleozoic rocks are unconformably overlain by Eocene volcanic rocks of the Challis Formation. The Paleozoic sedimentary and volcanic rocks are exposed within and on the flanks of the mountain systems north of the ESRP. These rocks have undergone late Eocene to early Oligocene and Miocene to recent extensional faulting (McCurry et al., 2016). Miocene to recent normal faulting has produced the current fault block physiography of the region. Prominent range bounding normal faults include the Lost River and Lemhi Fault systems (e.g., Janecke et al., 1993; Bruhn et al, 1992; Wu and Bruhn, 1994). The Lost River fault projects to the south into a diffuse system of small-offset normal faults and volcanic features known as the Arco-Big Southern Butte volcanic rift zone (e.g., Kuntz et al., 1992; Kuntz, 1992; Jackson et al., 2006).

Volcanic Hazards Analysis Approach Methodology

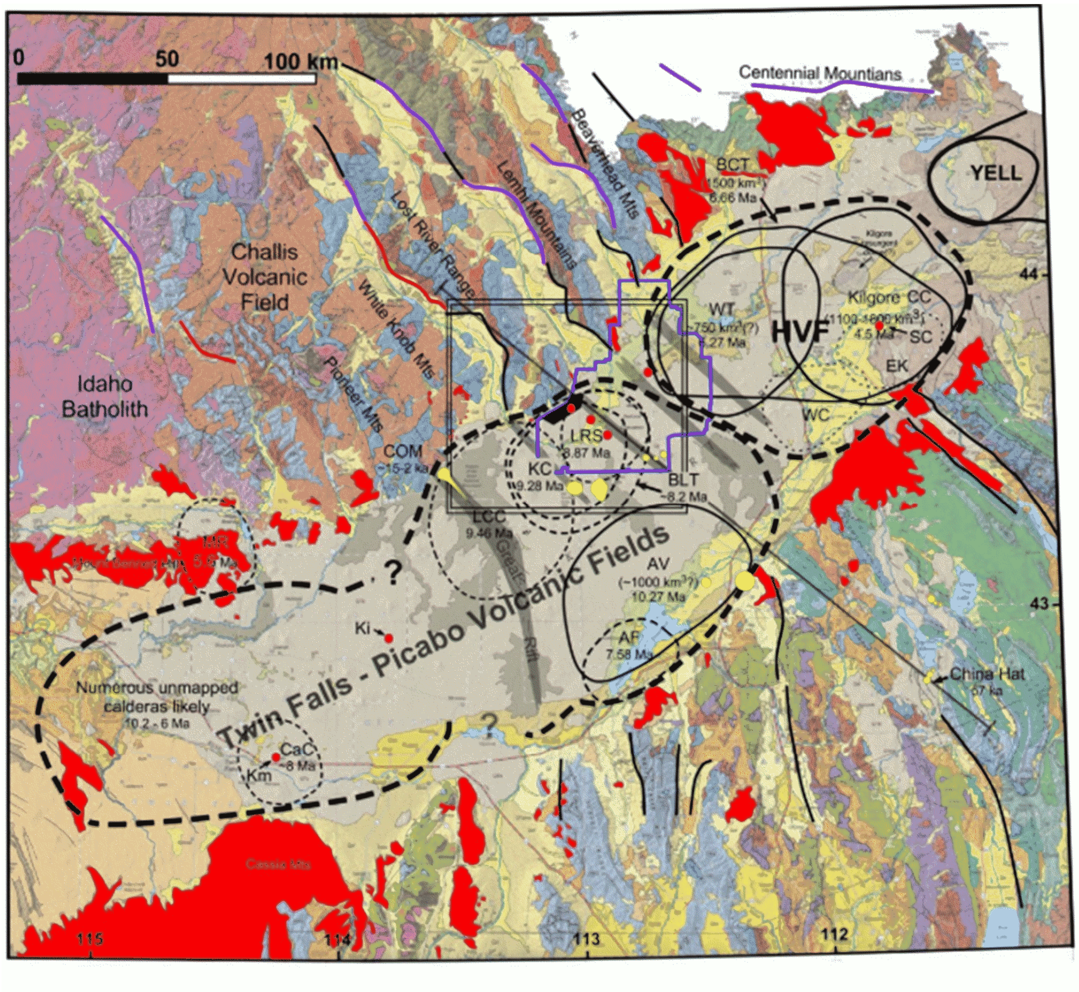

Figure 2 (From McCurry et al, 2016)

Geologic map of the Eastern Snake River Plain (ESRP) and its surroundings, emphasizing salient volcanic and tectonic features. The INL is outlined in blue with a black inset showing the location of a proposed geothermal research facility. The CFPP site is located within the black inset. The geologic base map is from Lewis et al. (2012). Shades of green, blue and purple illustrate late Precambrian to Paleozoic sedimentary rocks exposed in Basin and Range mountains north and south of the plain. Faults having late Neogene to Holocene activity are shown in bold lines (after Anders et al., 2014). Pale shades of grey on the Snake River Plain indicate Quaternary basalt lavas (Holocene in darker shade); pale yellow indicates Quaternary sediment. Yellow = Quaternary cryptodomes, lava domes and volcanic fields consisting of geochemically evolved mafic to rhyolitic volcanic rocks (e.g., McCurry and Welhan, 2012). Bold red colors indicate exposures of Neogene rhyolites (mostly ignimbrites) exposed along the margins of the ESRP. Major Neogene rhyolite volcanic fields are illustrated with bold dashed lines; HVF = Heise volcanic field. Twin Falls and Picabo fields overlap in age and are combined. Deep boreholes are shown as red dots (Km=Kimberly; Ki+Kimama; SC=Sugar City; after Shervais et al., 2013). Boreholes located within the boundaries of INL are also shown. Inferred caldera locations and ages are illustrated with solid (better defined location) and dashed (less well defined location) black lines. TF=Twin Falls, after Shervais et al., 2013; MR=Magic Reservoir, after Leeman, 1982b; AF=American Falls, LCC=Little Chokecherry Canyon, KC=Kyle Canyon, LRS=Lost River Sinks, are after Anders et al., 2014; AV=Arbon Valley (or Taber), after Kellogg et al., 1994; Kuntz et al., 1992; McCurry, 2009; WT=Walcott, BCT=Blacktail Creek, Kilgore, and CC=Conant Creek, are after Morgan and McIntosh, 2005, modified by Anders et al., 2014; WC=Wolverine Creek, Ek=Elkhorn Spring, are after Anders et al., 2014). In the ESRP, Neogene rhyolite calderas and their deposits are covered by late Tertiary to Quaternary basalts (tan map colors) and sediment of alluvial, lacustrine and eolian origins (yellow map colors).

Volcanic Hazards Analysis Approach Methodology

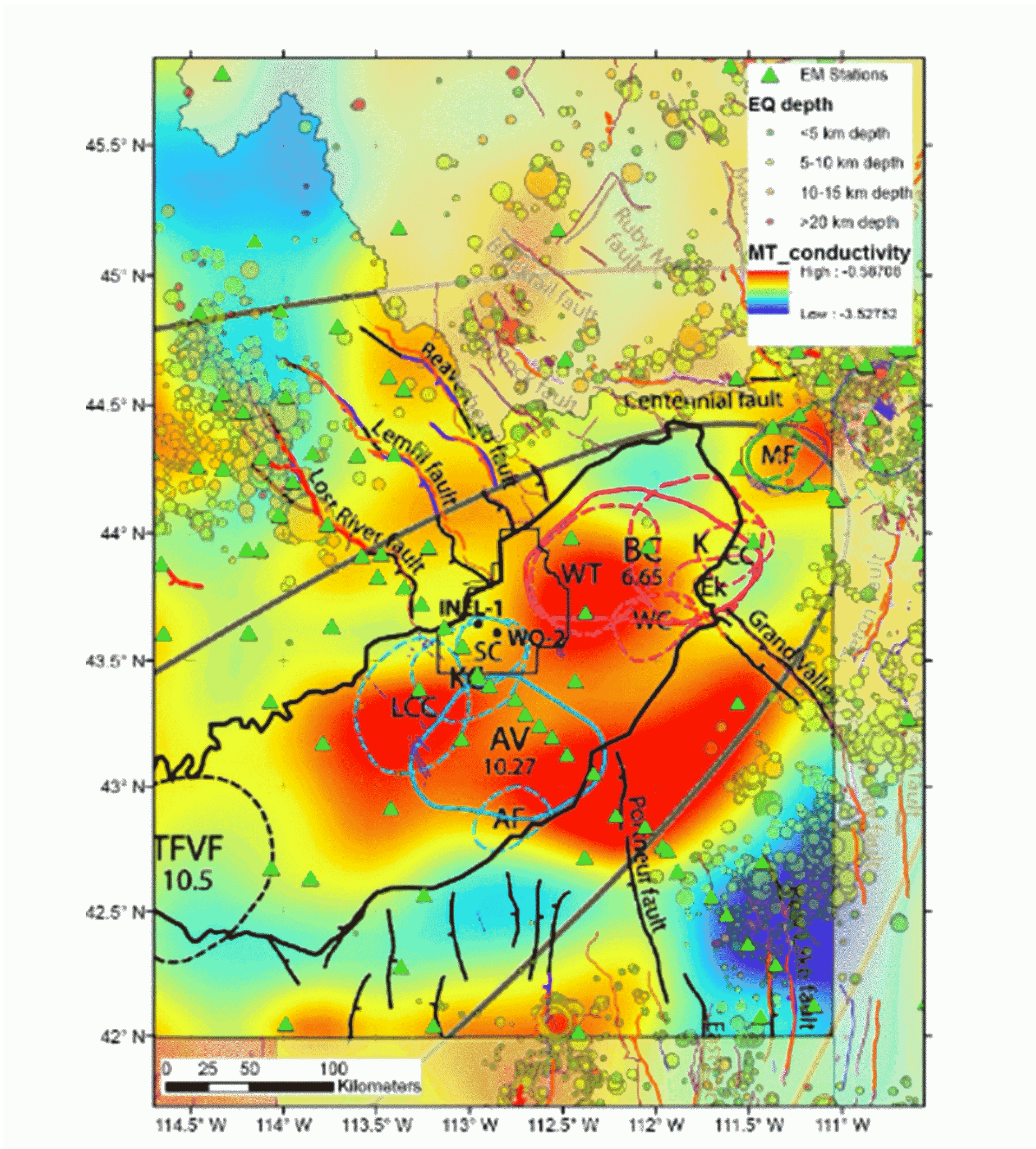

Figure 3: Historical seismicity (from Anders et al., 2014, with modifications from Liberty (2022))

A parabolic zone of historical seismicity (filled circles) occurs within the Basin and Range and surrounds the ESRP, reflecting the track of the Yellowstone hotspot to its current location. See Figure 2 for names of Neogene (ages shown in Ma) rhyolite calderas inferred beneath Tertiary and Quaternary basalt of the ESRP.

Volcanic Hazards Analysis Approach Methodology

McQuarrie and Rodgers (1997) and Rodgers et al. (2002) document progressive southward tilting of originally horizontal late Mesozoic fold axes. These structures document an approximately 20 km wide zone marginal to the ESRP in which tilts increase from zero to 20-30 degrees to the south, accommodating 4.5 to 8.5 km subsidence of the ESRP, most which occurred between ~10 and 8.5 Ma. Minor east-northeast trending normal faults are inferred to have been produced by flexure of the brittle crust.

The southern ends of the Pioneer, Lost River, and Lemhi Ranges are cut by a number of small-offset, crosscutting normal faults (***Figure 2***). Bruhn et al. (1992) indicate that those in the southern Lemhi Mountains are a product of complex fault-tip evolution of the Lemhi fault. Morgan (1984) suggested that some of the small faults could be related to normal fault ring fracture zones bordering calderas that may reside a short distance to the south of the ranges.

The pre-Neogene crust of the region consists mainly of early Precambrian crystalline rocks (Fosteret al., 2006) overlain by late Precambrian to Mesozoic sedimentary rocks of the Cordilleran fold and thrust belt (Dickinson, 2004; DeCelles and Coogan, 2006; Yonkee et al., 2014). Regional magmatic activity produced the late Cretaceous Idaho Batholith and Eocene Challis Volcanic Province (e.g., Gaschnig et al., 2011) north of the ESRP and Oligocene intrusions of the Albion Mountains region south of the ESRP (Konstantinou et al., 2012, 2013a). Strong extension in the Eocene to early Oligocene exposed mid-crustal rocks in isolated metamorphic core complexes of the Pioneer and Albion- Raft River Mountains areas (Strickland et al., 2011a,b). Coeval, less intense extension produced half graben basins over a wider region, including formation of the Arco Pass Basin located northeast of Arco (e.g.,Link and Janecke, 1999). Another, later phase of late Miocene extension and uplift occurred during volcanism along the Yellowstone-Snake River Plain (Vogel et al., 2014; Konstantinou et al., 2011, 2013b).

4.2 Volcanogenic Features of the ESRP

Petrogenetic models of magma generation and magma ascent, storage, and eruption based on magma geochemistry and mineralogy are in good agreement with geophysical elements of the ESRP. For example, McCurry and Rodgers (2009), Shervais et al., (2006); and Huang et al. 2015) present integrated models of regional tectonics, crustal structure and petrogenesis of the ESRP. Early ESRP volcanism (~10 to 4.5 Ma) involved Neogene crustal melting and caldera-related rhyolitic eruptions associated with the Yellowstone hot spot. Post-caldera volcanism on the ESRP during the past 4.3 Ma has been dominated by basalt and evolved magmas derived from parental basaltic magma. More than 95 percent of the ESRP is covered by basaltic lava flows erupted during the Brunhes Normal-Polarity Chron and therefore younger than 780 ka, and about 13 percent of the region is covered by lava fields younger than 15 ka (Kuntz and others, 1992). Most basalts of the ESRP were erupted as coalesced shield volcanoes and lava fields, each composed of many tube- and surface-fed pahoehoe-type lava flows. Deposits of fissure eruptions, cinder cones and phreatomagmatic volcanoes are present on the ESRP but comprise a minor part of its total basalt volume.

Volcanic Hazards Analysis Approach Methodology

Nearly all ESRP basalts are tholeiitic in composition and originated by partial melting of spinel lherzolite in the subcontinental lithospheric mantle (Hughes et al 2002; Leeman et al. 2009), consistent with geophysical evidence of partial melt in the lithospheric upper mantle. ESRP tholeiitic basalts are rather uniform in composition and petrography, containing sparse phenocrysts of olivine, plagioclase and Fe-Ti oxide minerals.

Batches of basaltic magma ascended from the mantle in vertical dikes as illustrated in ***Figure 4*** in two scenarios. One scenario is direct ascent from mantle depths and is supported by geochemical and petrographic data showing that erupted ESRP basaltic magma generally underwent little fractional crystallization or crustal contamination. Shield volcanoes and lava fields are typical landforms (Greeley, 1982; Hackett and Smith, 1992; Kuntz et al 1992; Hughes et al 2002) as illustrated in ***Figure 5***. Small-volume (<0.1 km^3) shields and lava fields likely formed during brief (several days) fissure eruptions and the large-volume (1 to 6+ km^3) shield volcanoes probably effused lava during several months or years (Kuntz et al. 1992; Kuntz 1992).

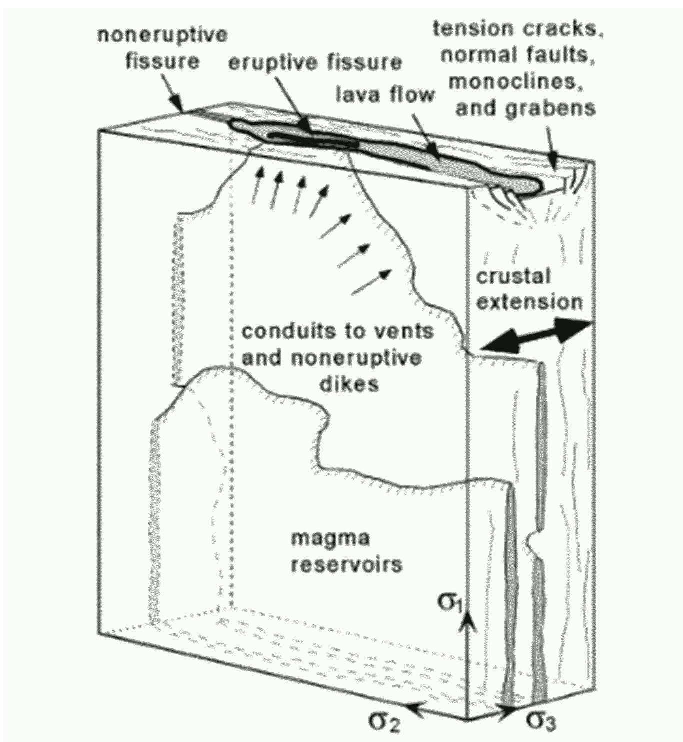

Figure 4: Illustration of blade-like dike emplacement on the Eastern Snake River Plain (from Hughes et al., 2002)

Dike propagation occurs where magma overpressure exceeds fracture toughness of country rocks, and vesiculation in the upper kilometer drives magma to the surface. Dike orientation is controlled by the regional stress field. Dikes align perpendicular to sigma-3 (direction of least compressive stress) and have a dominant northwest trend, subparallel to that of regional extensional faults in the adjacent tectonic province.

Volcanic Hazards Analysis Approach Methodology

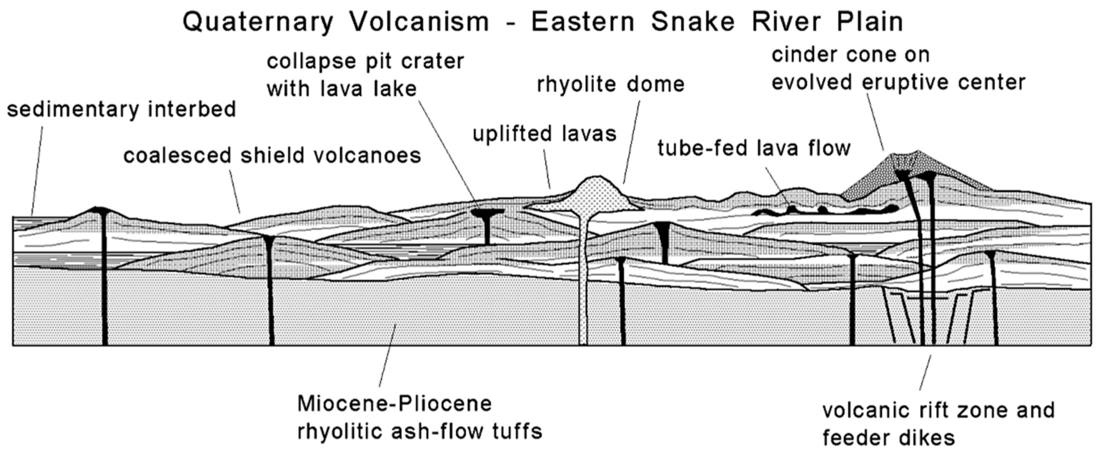

Figure 5: Volcanic features on the Eastern Snake River Plain (from Hughes et al., 2002)

Illustrates magmatic and surficial processes of the region. Low basaltic shield volcanoes and lava fields are the most common landforms.

In the second scenario, ascending basaltic magma stalls and differentiates in the crust, generating evolved magmas of intermediate to silicic composition (***Figure 6***). The evolved volcanoes occur mainly in areas of high magma production, as in the Axial volcanic zone, a region of high vent density and elevated topography near the southern and southeastern INL boundary. Rhyolite domes (Big Southern Butte and East Butte), cryptodomes (Big Southern Butte and Middle Butte), lava flows and pyroclastic cones (Cedar Butte; McCurry et al., 2008) of evolved magma, erupted along the crest of the Axial volcanic zone to the south and east of INL (***Figure 6***).

More than 600 Quaternary volcanic vents, most of them basaltic shields and lava fields with normal geomagnetic polarity (hence younger than 780 ka) are distributed on the ESRP (***Figure 7***). Eruptive fissures, noneruptive dike-induced fissures, colinear vents and slot-like pit craters indicate that most eruptions were fed by vertical dikes. Areas of high spatial density of volcanic vents (axial volcanic zone) correlate with areas of elevated topography formed by long-term constructional volcanism (**Figure 8**). The ESRP is a region of distributed volcanism, each volcano representing a single, brief geologic event that was neither preceded nor followed by eruptions from the same or nearby vents. Such volcanoes are commonly termed “monogenetic” in the published literature to distinguish from “polygenetic” volcanoes formed by multiple eruptions from central-vent complexes such as the composite cones of the Pacific rim. The preferred term “distributed volcanism” conveys that ESRP volcanic vents are distributed over a wide area and that each vent or co-erupted vent cluster represents a single geologically brief volcanic event.

Volcanic Hazards Analysis Approach Methodology

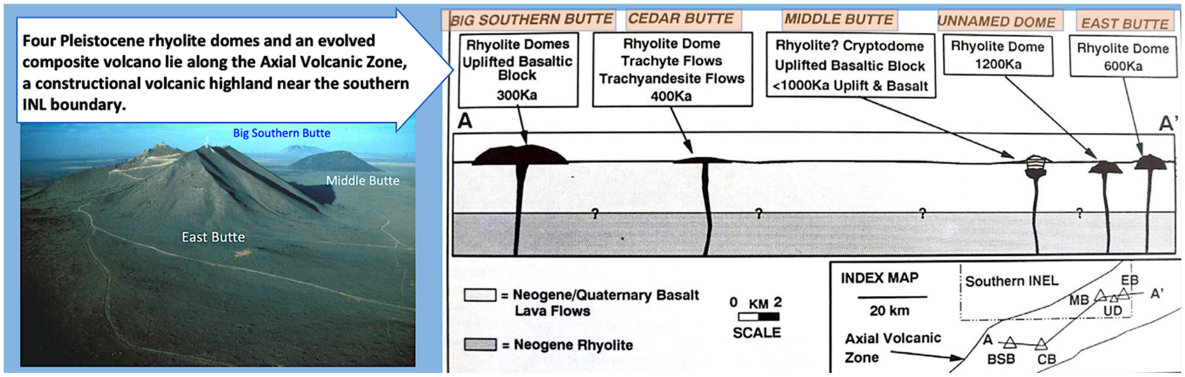

Figure 6: Rhyolite and intermediate volcanoes of the Axial volcanic zone near the southern INL boundary.

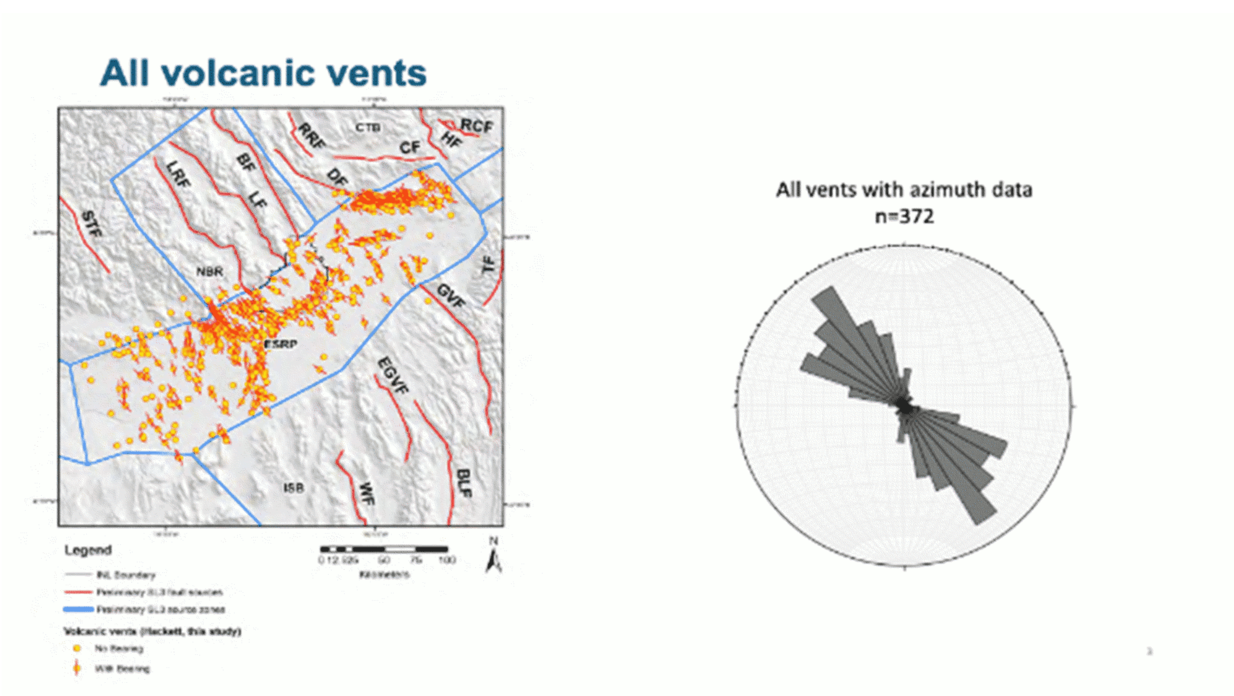

Figure 7: Map showing locations and azimuths of volcanic vents on the Eastern Snake River Plain (unpublished data from Hodges et al., 2022, in press). The rose diagram shows the orientation of the long axis of mapped volcanic features on the ESRP

Volcanic Hazards Analysis Approach Methodology

Rock cores from 33 deep boreholes of the south-central INL have been analyzed for lithology, paleomagnetic inclination and polarity, petrography, and argon-isotope geochronology, supporting a robust stratigraphic framework for Quaternary basaltic volcanism and sedimentation (Champion et al., 2011; Hodges et al., 2015; Hodges and Champion, 2016; Hodges et al., 2022 in press). The subsurface data and stratigraphic cross sections are complimentary and integrative with ESRP geologic mapping, geochronology and paleomagnetic data from surface outcrops (Kuntz et al., 1994; Kuntz et al., 2007). Many of the younger subsurface flows are correlated with mapped surface vents in the INL area. Near the CFPP site, two coreholes USGS 142 (about 2 km east of the site) and USGS 134 (about 7 km southeast of the site), are well characterized stratigraphically and geochronologically (Hodges et al., 2022 in press) as shown in ***Figure 9***. USGS 134 penetrates ~300 m of Quaternary basalt flows and sediment interbeds to total depth. USGS 142 penetrates ~430 m of Quaternary basalt flows and sediment interbeds (270 ka to 1,370 ka in age), underlain by Tertiary rhyolite tuff and tuffaceous sediment at total depth (6.3 Ma Walcott Tuff of the Heise volcanic field; Schusler et al., 2020).

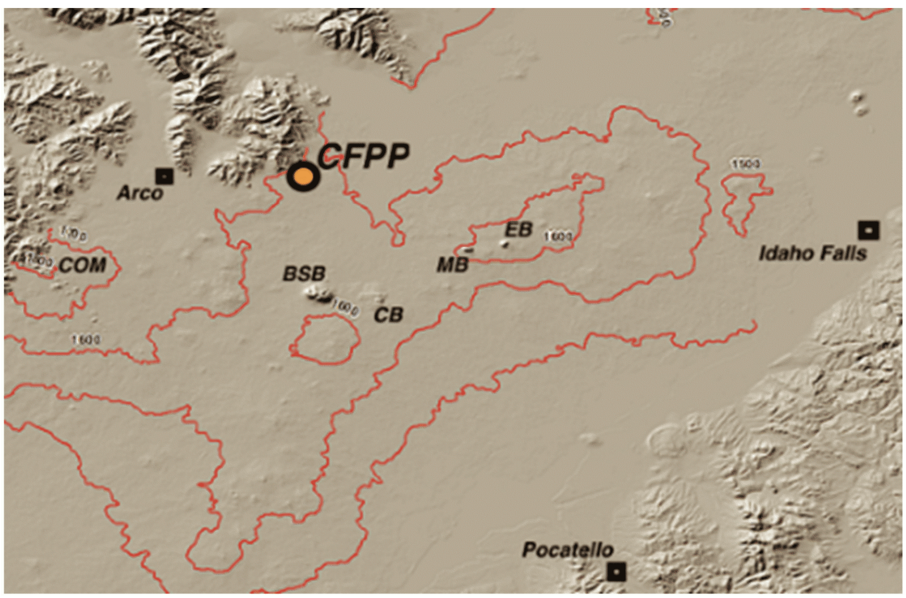

Figure 8: Shaded-relief topographic map of the ESRP with 100m topographic contour lines.

Compare with Figure 7 and note the high-elevation areas of long-term constructional volcanism that coincides with areas of high vent density to the southwest, south, and southeast of CFPP site. COM, Craters of the Moon; BSB, Big Southern Butte; CB, Cedar Butte; MB, Middle Butte; EB, East Butte.

Volcanic Hazards Analysis Approach Methodology

Based on the stratigraphic data from these two coreholes, the CFPP site vicinity was inundated by at least seven basalt lava-flow events during the past 780 ka. At least 17 inundation events occurred during the past 1.4 Ma, with an average hiatus of ~65 ka between lava-inundation events. At the CFPP site, the lava flow at ground surface is most likely either from Crater Butte (297 ± 13 ka) or Pond Butte (270 ± 46 ka). The CFPP VHA Project Execution Plan includes investigations of CFPP deep corehole B-01, to integrate its stratigraphy and geochronology with the published INL volcano-stratigraphic framework.

Volcanic Hazards Analysis Approach Methodology

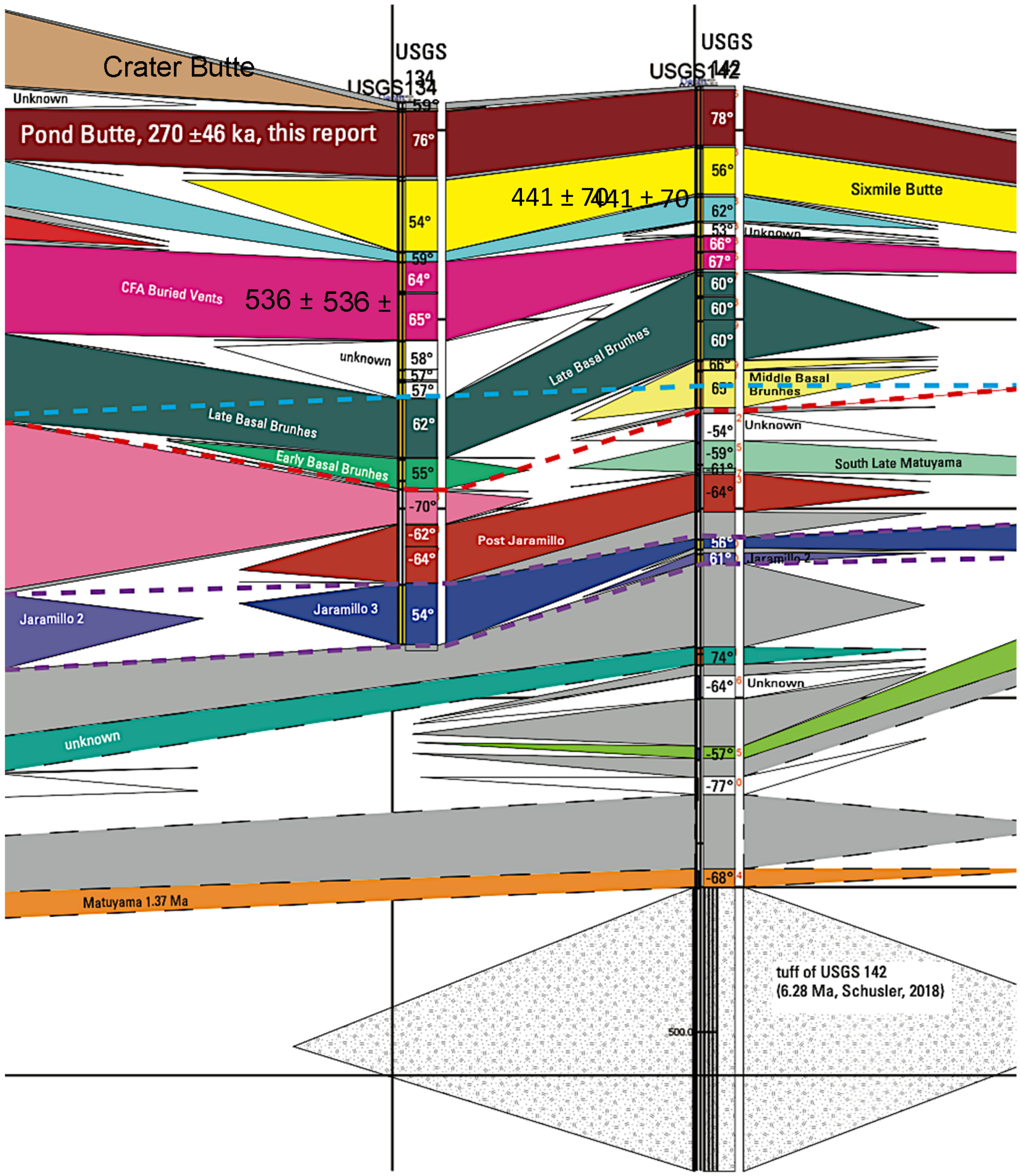

Figure 9: Stratigraphy of USGS Wells 134 and 142 near the CFPP site (Hodges et al., in press)

Basalt flows (colored and white stratigraphic units), sediment interbeds (gray), argon-isotopic age dates, and paleomagnetic inclination and polarity data for basalt stratigraphic units are shown. Each colored stratigraphic unit represents one or a few volcanic events. Each event is composed of multiple lava flows comprising a basalt shield volcano or lava field. Lava-flow thicknesses (event thicknesses) from these wells and other INL cores average 15m ± 10m (± one sigma). The three uppermost lava flows of USGS 142 erupted ca. 300-420 ka from mapped surface vents to the southwest of the CFPP site: Crater Butte, Pond Butte and Sixmile Butte, all basaltic shield volcanoes (Kuntz et al. 1994; Helmuth et al., 2019). Older subsurface lava flows erupted from buried vents at unknown locations.

Volcanic Hazards Analysis Approach Methodology

4.3 Geophysical Features of the ESRP Crust and Upper Mantle

Seismic tomographic imaging of the crust and mantle indicates a mantle plume is currently present beneath and southwest of Yellowstone caldera, at the approximate location of the Henry's Fork caldera in eastern Idaho. The mantle plume impinges on the base of lithospheric upper mantle at a depth of ~65 km and spreads southwestward along the axis of the ESRP (Peng and Humphreys, 1998). At Yellowstone, a low- velocity body is present in the lower crust, extending from the Moho discontinuity (45 km depth) to approximately 20 km depth (Farrell et al., 2014; Huang et al., 2015). This body is attributed to the presence of a zone of partial melt of basalt, and it underlies an upper-crustal body of rhyolite partial melt beneath the Yellowstone caldera. Seismic- tomography models imply that the mantle plume has also affected the ESRP sub-lithospheric mantle. This thermal anomaly is the source of heat for the magma production and distributed volcanism of the ESRP that persists today. However, there is no indication of low-velocity zone in the upper crust (rhyolitic partial melt) anywhere beneath the ESRP southwest of the Yellowstone Plateau, as would be required for a near-term caldera-forming eruption on the ESRP.

Geophysical investigations of the lower crust seek to identify zones of melt accumulation. Huang et al. (2015) identify a large low-velocity body in the lower crust beneath and adjacent to the Yellowstone caldera (***Figure 10***). They interpret this body to represent basaltic magma accumulation in the lower crust, interconnected with a shallow rhyolite reservoir (Cashman et al., 2017; Schmandt et al., 2019). Similar low-velocity bodies have not been identified in the lower crust of the ESRP.

Volcanic Hazards Analysis Approach Methodology

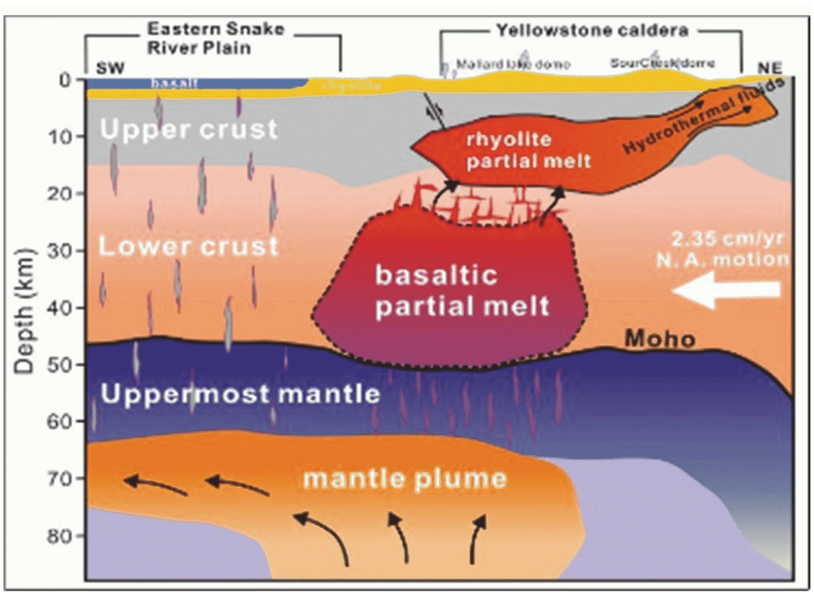

Figure 10: Schematic Cross-section of the crust and upper mantle along the Axis of the ESRP and Through the Yellowstone Caldera (from Huang et al., 2015)

Mantle plume is a source of heat. Beneath the ESRP several percent partial melt is detected by seismic topography in the upper mantle at depths of ~60 to 100 km, and near the Moho at ~45 km depth. See Figure 8 for details of ESRP crustal structure.

Anomalously high gravity has long been recognized as a geophysical characteristic of the ESRP and is interpreted as basaltic intrusions in the mid- and upper crust (Hill, 1963; Mabey, 1966 Kelbert et al., 2012). The presence of a mid-crustal sill complex is inferred from seismic- refraction experiments (Sparlin et al., 1982; Braile et al., 1982; Yuan et al., 2010), seismic models based on receiver functions (Harper, 2018), and tomography coupled with refined gravity models (DeNosaquo et al., 2009). Together these studies suggest the mid-crustal sill is a dense, crystalline, high-velocity body extending from ~10 to 20 km depth, underlying most of the region within the seismic parabola, and extending beyond the geomorphic limits of the ESRP (Shervais et al., 2006) (***Figure 11***). The mid-crustal sill occupies many times the volume of ESRP erupted magma and acts as a dense keel, explaining the positive gravity anomaly and low-lying topography of the ESRP.

Volcanic Hazards Analysis Approach Methodology

Based on seismic models and gravity data, McQuarrie and Rodgers (1998) and Peng and Humphreys (1998) proposed geodynamic models for the evolution of the ESRP, in which ~4 km of flexural subsidence on the ESRP is driven by densification of the crust due to the accumulation of mass in the mid-crustal sill. The model requires lateral flow of lower crust from beneath the ESRP to adjacent areas because the Moho is relatively flat across the ESRP (Anders and Sleep, 1992). Based on geological and geophysical arguments, McQuarrie and Rodgers (1998) suggest that the ESRP had already experienced significant subsidence ahead of the arrival of the hot spot track (~10 Ma) and continued to subside during episodes of Neogene rhyolite volcanism on the ESRP. In this conceptual model, the mid-crustal sill represents a massive accumulation of basaltic magma, prior to and during the growth of shallow rhyolite magma bodies that spawned Neogene caldera-forming eruptions.

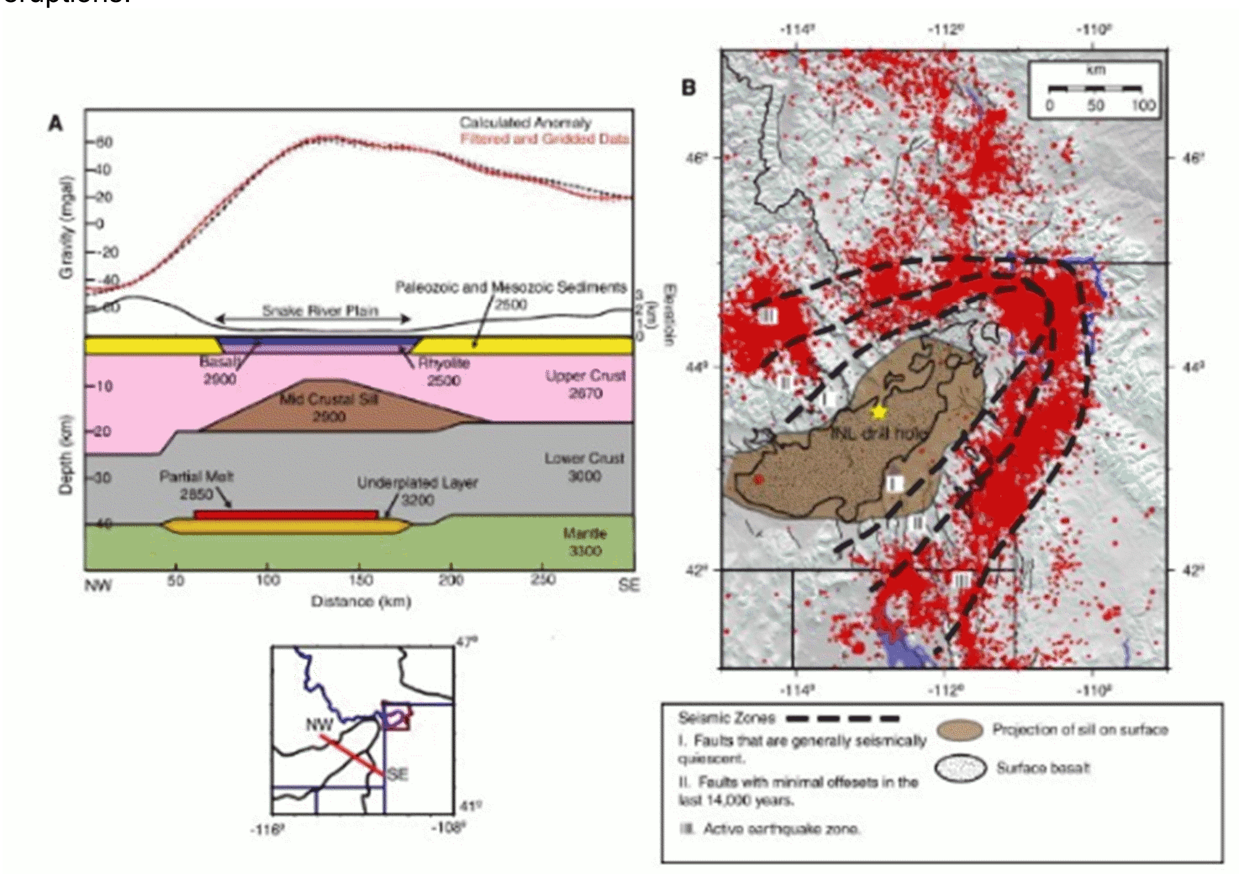

Figure 11: (modified from DeNosaquo et al., 2009)

Gravity model and geophysically interpreted crustal structure of the Eastern Snake River Plain. Partial melt is present at ~60-100 km depth in the upper mantle (not shown) and near the crust-mantle boundary. A dense mid-crustal sill composed of solidified mafic magma is present. B. The footprint of the midcrustal sill, evidence of long-term magma flux, is larger than the area of basaltic volcanism on the ESRP. Locations of historic earthquakes shown with red dots. The CFPP site lies west of the "INL drill hole" (yellow star) shown in the panel on the right.

Volcanic Hazards Analysis Approach Methodology

The mid-crustal sill today is likely to influence the ascent of magmas. As a dense, rigid body, the mid-crustal sill might arrest the ascent of magmas, promoting accumulation and differentiation (Maccaferri et al., 2011) and explaining compositional trends of evolved magmas observed on the ESRP (McCurry et al., 2008).The time required to densify the crust at the level of the mid-crustal sill may account for the time lag between the passage of caldera-forming rhyolite eruptions and the onset of ESRP basaltic eruptions (Leeman et al., 2008). The mid-crustal sill and its role in magma ascent make it important to understand its footprint (DeNosaquo et al., 2009) modeled gravity and seismic data to define the distribution of the mid-crustal sill, which is larger than the distribution of basaltic lavas, especially in the southeastern ESRP.

Above the mid-crustal sill at depths greater than 10 km, the crust is granitic in composition, as inferred from seismic-refraction experiments and seismic-velocity models (Sparlinet al., 1982). The granitic upper crust is topped by intercalated thick rhyolite tuffs and lava flows and finally by basalt lava flows with interbedded sediment.

The northwest margin of the ESRP near the CFPP site marks a distinctive transition from (1) Basin and Range gravity patterns associated with development of sedimentary basins and extensional faulting, to (2) the long-wavelength, generally positive gravity observed within the ESRP. DeNosaquo et al. (2009) suggest that positive gravity anomalies represent higher mass-accumulation zones, reflecting higher magma flux from the mantle. While this is generally true for the entire ESRP as a region of high magma flux, in detail the local gravity anomalies within the ESRP do not correlate with increased spatial density of volcanic vents at the surface nor the inferred positions of buried Neogene caldera complexes (Morgan et al., 1984; Morgan and McIntosh, 2005). Roots of calderas are thought to be capable of impeding or redirecting ascending magma, especially when the silicic bodies are partially molten (Karlstrom et al., 2015). However, Neogene ESRP calderas are too old (10 to 4.5 Ma) to be associated with persistent partial melt zones in the Quaternary, and it seems unlikely that the distribution of Tertiary calderas impacts the location or style of Quaternary volcanism (Jean et al., 2018).

Volcanic Hazards Analysis Approach Methodology

4.5 Volcanological Implications for CFPP Volcanic Hazard Assessment

The tectono-magmatic model has several significant implications for the CFPP VHA. These are as follows:

1. There is no tectono-magmatic evidence of long-term trends in rates of basaltic magmatism, such as waning volcanism. VHA models for the CFPP site will therefore assume that ESRP volcanism is persistent and that volcanic hazards at the CFPP site are associated with opening of new vent(s) in an area of distributed volcanism.

2. There is no tectono-magmatic evidence that future volcanic events will differ in magnitude or frequency from the types of volcanic events in the past.

3. Geophysical models indicate that a partial melt zone is likely present beneath the ESRP in the uppermost mantle. The presence of partial melt in the upper mantle provides additional evidence that volcanism is likely to persist in the future.

4. The CFPP is sited at a topographically elevated location, making it less susceptible to lava-flow inundation than low-lying areas. Source zones of Quaternary volcanism with high spatial density of volcanic vents for consideration lie to the southwest (the Arco-Big Southern Butte (BSB) volcanic rift zone) and south/southeast (the axial volcanic zone) of the site. The Axial volcanic zone includes volcanic centers that erupted during the past 15 ka. The Arco-BSB volcanic rift zone was the source area for the youngest lava flows (ca. 300-420 ka) mapped and intersected in coreholes near the CFPP site.

5. Published corehole data and surface mapping near the CFPP site show that the area was inundated by at least seven basalt lava flow events during the past 780 ka, and at least 17 inundation events during the past 1.4 Ma, with an average hiatus of ~65 ka between lava inundation events. Nevertheless, the frequency of basaltic lava flows in boreholes at the site does not reflect the probability of lava inundation at the site.

6. Significant hazards to the CFPP site are likely to be inundated by a basalt lava flow of 15m ± 10m thickness, ground deformation associated with basaltic dike intrusion, and basaltic near-vent phenomena such as the growth of a cinder cone, deposition of tephra, and volcanic-gas emission.

7. No evidence exists for large, low-velocity bodies in the ESRP, of the type currently observed beneath the Yellowstone caldera. The lack of observed low-velocity bodies is a strong indication that caldera-forming eruptions will not occur within the ESRP on timescales of interest. This observation is also consistent with the hot-spot model that explains the time-space pattern of early voluminous rhyolite-caldera eruptions on the ESRP. The implication is that VHA models need not consider potential caldera-forming eruptions on the ESRP.

Volcanic Hazards Analysis Approach Methodology

8. Based on gravity data and models, the dense mid-crustal sill represents magma flux from the mantle which may promote accumulation and differentiation of basaltic magma within the crust, and its footprint implies that eruptions are possible beyond the geomorphic limits of the ESRP. Based on gravity anomalies, the CFPP site is located at the margin of the mid-crustal sill. The VHA should consider spatial density models of volcanism in light of the footprint of the mid-crustal sill.

9. Variations in gravity within the ESRP may be caused by variation in the thickness of the mid-crustal sill, buried Neogene caldera complexes, variation in the proportion of late Tertiary and Quaternary basalt to sediment in the shallowest crust, or a combination of these factors. The VHA will consider the spatial distribution of volcanism in light of these possibilities, considering the implications of each for spatial-density models and/or eruptions of a specific magma type.

Volcanic Hazards Analysis Approach Methodology

5.0 Description of Models for Assessing Volcanic Hazards at the CFPP Site

Probabilistic volcanic hazard assessment (PVHA) involves the mathematical and statistical assessment of various types of volcanic hazards associated with volcanic eruptions within a defined area of interest (AOI) that could affect a site or facility located within this defined AOI (Connor et al., 2009). Hazards of significant interest include lava flow inundation, tephra fallout accumulation, dike propagation, new vent formation, and others (Connor et al., 2015). These three processes must be evaluated in assessment of hazards for the CFPP AOI. Codes which will model these hazards have been benchmarked and will be verified and validated consistent with RIZZO's quality assurance program for their use in the VHA.

The following is a brief discussion of these numerical models and the approach developed for VHA developed by the CFPP VHA Team. The CFPP VHA Team will use these models to assess volcanic hazards known to occur within the ESRP and that could conceivably occur at the CFPP site. These codes include (1) spatial density models for calculating the spatial density of past events and the probability of a future event, given that an event occurs within the ESRP (e.g., Connor et al., 2000; Germa et al., 2013; Connor et al., 2019), (2) a lava flow simulation tool (MOLASSES) for simulating lava flows and site inundation (e.g.,; Connor et al., 2018; Gallant et al., 2018 and 2021.Verolino et al., 2022); and (3) a tephra dispersion model (Tephra2), that calculates tephra accumulation at specific locations or over a region (e.g., Connor et al., 2001; Bonadonna et al., 2005; Connor and Connor, 2006; Magill et al., 2015; Connor et al., 2019). Each of these codes was developed to assess volcanic hazards for nuclear facilities and each has been used by various groups world-wide (e.g., Verolina et al., 2022; Jenkins et al., 2022; Wiejaczka and Giachetti, 2022; Schmidt et al., 2022; Bertrin et al., 2022). For example, these codes are specifically cited in International Atomic Energy Agency guidelines for safe siting of nuclear facilities (Aspinall et al., 2016). Each code is necessary for assessing the potential for volcanic hazards at the CFPP site.

The CFPP VHA team will provide the inputs and eruption source parameters (ESPs) for these models, specific for assessing potential volcanic hazards at the CFPP site. Depending on the outcome of the screening activity (Section 3.0) additional numerical models may be developed to address the details of specific volcanic hazards that have a probability of occurring within a time frame of regulatory concern.

5.1 Spatial Density Model

The ESRP is a distributed volcanic field. Volcanic activity on the ESRP is infrequent on the timescales of human experience, but when renewed activity occurs it results in the formation of new volcanic vents rather than reactivation of volcanic vents that have erupted in the past (Connor, 1990; Gallant et al., 2018). Purposes for calculating estimates of spatial density include (1) visualization of the density of past volcanic events within the ESRP, (2) calculations of the probability of new volcanic activity at and within a defined area around the CFPP site, and (3) combination of calculated spatial density values and recurrence rate values with specific hazard maps (area grids) to calculate the probability of the volcanic event impacting the CFPP site, with uncertainty (Connor et al., 2015).

Volcanic Hazards Analysis Approach Methodology

Spatial density assessment is done for two reasons. First, the probability needs to be estimated for the opening of a new volcanic vent within a specified area surrounding the CFPP site. For example, the near-vent environment for the opening of new vents associated with scoria cones, extends approximately 1 km from the volcanic vent (Connor and Connor, 2009). Second, spatial density must be calculated at distances greater than 1 km from the site. Vents located far from the site can produce lava flows (Connor et al., 2012), tephra fallout (Connor et al., 2019) and intrusive phenomena (Kiyosugi et al., 2012), resulting in adverse impacts on the CFPP site.

The probability of new vent formation should be programmatically and objectively assessed. Kernel density estimation (KDE) is a tool used to estimate the spatial distribution of known locations of eruptive events (e.g., Duong and Hazelton, 2005 and Connor et al., 2019). A calibrated KDE can be used to make probabilistic forecasts of locations of future volcanic events. Estimates made by KDE use the mapped locations of previously formed volcanic events as a guide to the distribution of potential future events. A major task in the CFPP VHA is to determine which mapped ESRP events should be used to develop the spatial density estimate for the CFPP site. Volcano vent location data used to estimate the spatial density of future events need to be consistent with the tectono-magmatic model. The tectono-magmatic model will inform the spatial density model about how the probability should change with distance from previous volcanic events. The rate of change in the spatial density model depends both on the KDE selected for the analysis and the smoothing bandwidth of the kernel. For example, one common KDE is the bivariate Gaussian kernel function. The tectono-magmatic model can be used to bound the range of bandwidths used in the analysis based on understanding of (1) the depth to the mid-crustal sill, (2) magma focusing along faults or other discontinuities, and (3) identified regions of partial melting. Alternatively, the bandwidth can be estimated solely from the distribution of previous volcanic events, for example by maximum likelihood estimation using the log-likelihood. There are many permutations on this approach, and several will be used in the analysis, in addition to assessment of consistency with the tectono-magmatic model.

Spatial density of volcanic events changes with time. Vents are buried by subsequent eruptions. In some distributed volcanic fields activity appears to shift with time, or to occur at different rates in some areas compared with others. Craters of the Moon is an example of an area where volcanism occurs at higher rates than elsewhere on the ESRP. Vent density is also very high in the region of Spencer High Point, west of the Island Park caldera. This very high volcanic vent density is not representative of the vent density across the entire ESRP including the area closer to the CFPP site. Therefore, it is important to determine which events, or parts of the volcanic field, are most relevant to the analysis and should be included in the estimation of the spatial density at and around the CFPP site. The tectono-magmatic model is used to evaluate these decisions.

Volcanic Hazards Analysis Approach Methodology

Determining the independence of mapped volcanic events is a critical step in estimating event density. A single volcanic event can comprise several individual vents. Grouping vents into appropriate events reduces the overall number of volcanic events but increases the area they affect. Independence of ESRP volcanic events is challenging to determine. Rather than simply counting volcanoes on a geologic map, one must complete a geologic assessment of which vents are related to a single eruption or to a relatively short period of eruptive activity, and which formed during different episodes of eruptive activity. On the ESRP, mapping vents into events has been accomplished using three sources of information:

- Mapping and geomorphic analyses of volcanic vents for grouping into events
- Paleomagnetic analyses of basalt flows and vents to determine the variation in the local inclination and declination of the magnetic field of basalts as a function of time due to change in the location of the magnetic North Pole over time
- Radiometric age determinations on vents to determine which vents should be grouped as events

The approach to using volcanic events in spatial density analysis will consider the following:

- The nature of volcanic events varies spatially on the ESRP. For example, the high concentration of vents at Craters of the Moon and Spencer Highpoint are not representative of the spatial distribution of events over the entire ESRP and in the vicinity of the CFPP site.
- There is significant variation in the nature of volcanic vents on the ESRP. Some events build shield volcanoes, others form relatively small-volume crater rows. Further events will be classified by the volcanic processes that create them.
- The uncertainty associated with volcanic event classification will be assessed. Alternative event definitions will be used to calculate regionalized spatial density estimates, or hazard-based estimates depending on event type. Variations in future event probability at the CFPP site will be determined.

Once the volcanic events are determined, spatial density of potential event distribution will be estimated. The spatial density code outputs a table or grid of density estimations (probabilities) of events per square grid spacing (in km) at locations determined from the *north, south, east, west* map boundaries and *grid spacing* input parameters. The code will also calculate event density estimations at the location of the CFPP site, if this location is given. This estimation with corresponding probabilities will provide the estimated frequency of events in a given location on the ESRP.

Volcanic Hazards Analysis Approach Methodology

5.2 Lava Flow Inundation Model

Lava flows are one of the most common volcanic phenomena on the ESRP that potentially pose a hazard to the CFPP site. Lava flow inundation models simulate a range of lava flow volumes and thicknesses, calculate the area inundated by the flow, and calculate the lava volume needed for site inundation from different source locations. For the CFPP site, lava flow modeling is useful for two purposes:

- Volcanic event locations are screened out from further consideration if the largest reasonable lava flow volume erupted from that location does not reach a predefined site boundary, for example, within 1 km of the center of the CFPP site.
- For eruption locations not screened out, the probability of lava flow inundation is calculated for a list of defined effusive eruptive scenarios. These results, combined with spatial density assessment and recurrence rate assessment, yield the probability that a site will be inundated by lava flows within a time period of interest.

In the following, the modeling approach for lava flow hazard assessment using MOLASSES is described.

MOLASSES is a lava flow simulation tool, designed to forecast inundation area by lava flows, and specifically, to assess the potential of lava inundation of nuclear facilities. MOLASSES is written in the C programming language and optimized to be fast and efficient so that many (1000s - 100,000s) iterations can be performed and the results analyzed statistically. MOLASSES was first developed in 2010 (a version in PERL - practical extraction and report language) to model lava inundation at a NPP in Armenia (Connor et. al, 2012). Currently, this code is being used world-wide to evaluate both past eruptions (e.g., Gallant et. al, 2018; Kubanek et.al., 2015; Connor et al., 2018; Aspinall and Woo, 2019; Wild et al., 2020; Tsang et al., 2020; Verolino et al., 2022) and currently erupting flows in Iceland and La Palma. The code has been evaluated in comparison to other lava flow modeling codes and analog experiments by Dietterich et al. (2017).

The purpose of running lava flow simulations with MOLASSES is three fold: (1) to identify the area around the CFPP site that presents a risk to the site if effusive volcanic activity were to occur, (2) to calculate, with simulations, the minimum volume of lava leading to site inundation from identified high risk locations (*i.e.,* screened in locations), and (3) to then calculate the probability, with uncertainty, of lava flow inundation at the CFPP site from defined categories or types of effusive eruptions using spatial density and recurrence rate statistical models.

Effusive volcanic eruptions on the ESRP are often more complex than simply the eruption of a lava flow from a single vent. Lava flows may erupt from multiple vent sources during a single volcanic event or episode, for example, the eruption from a fissure. Shield volcanoes, another complex volcanic event, comprise tens to hundreds of lava flows that may erupt from a single vent or from multiple distributed vents over the course of an eruptive episode. Early lava flows from such complex volcanic events, can change the topography dramatically, and subsequently direct the path for future flows, creating a scenario that is difficult to simulate. Lava flowing across this newly altered topography may move in unexpected directions relative to the anticipated flow direction based on the topography of the original, unaltered DEM.

Volcanic Hazards Analysis Approach Methodology

Complex volcanic events must be designed to accommodate the possible range of effusive eruptions observed on the ESRP.

MOLASSES is able to model complex eruptions in two ways. First, the code can simulate multi-vent eruptions. For example, basaltic volcanic events that form long fissures along which spatter cones localize and effuse lava can be modeled as a set of simultaneously, erupting vents. Second, multiple lava flows can be added to the DEM in succession, by updating the topography (DEM) between flows. A multi-flow simulation allows for the construction of complex flow features, such as the multi-flow structure of a shield volcano. Such multi-flow volcanic events are simulated probabilistically, by sampling PDFs for the input parameters before each successive simulation begins.

The MOLASSES model relies on a grid-cell based algorithm to estimate inundation area. Code execution remains fast because rheological properties of active lava flows (e.g., temperature, viscosity, composition, flow rate, crystal content) are not modeled. Nevertheless, these rheological properties are easily linked to the MOLASSES input parameters. Since the primary information available about ESRP lava flows is their thickness, area, length and volume, this model is guided by these measurable morphological parameters.

MOLASSES is a two dimensional cell-based model that sequentially adds pulses of lava to a source cell then calculates the amount overflowed into neighboring cells. Initial elevation of cells and cell size are based on the DEM chosen to be the base of the model. The source location(s) of the flow must be within the bounds of this DEM. Three flow parameters, including the lava volume to erupt, the residual or modal thickness of the flow, and the pulse size, are inputs to the model.

Models of lava inundation are simulated by running MOLASSES many thousands of times using a range of input parameters over a range of volcanic event locations. In practice, the following steps are executed in a probabilistic analysis.

- Screen out locations unable to source lava flows that could inundate the site boundary.
- Screen in a set of locations for lava flow simulation that are determined to have some probability of site inundation.
- Select DEMs of various resolutions (coarse to fine) for the analysis.
- Specify an area of interest (AOI) around the facility.
- Simulate lava flows for a range of hazardous effusive volcanic event types

The completed inundation models are collected in association with the source of those hazards to develop a relative probability of those events reaching sites in the topographic distribution of the ESRP. These models will create the basis for a likelihood of lava flows inundating the CFPP site.

Volcanic Hazards Analysis Approach Methodology

5.2 Tephra Model

Tephra fallout results from explosive volcanic eruptions, when tephra particles (micron to decimeter in diameter) are carried aloft in volcanic plumes, advected by the wind, and deposited on the ground and on engineered surfaces. The thickness and loading of tephra fallout varies widely with distance from the source of the volcanic eruption, with the intensity of the volcanic eruption, and with the volume of material erupted. Following the most intense volcanic eruptions, tephra fallout may exceed 1000 kg m^{-2} in areas located within a few tens to hundreds of kilometers of the volcano. Small eruptions may result in tephra fallout of 10 kg m^{-2} kilometers from the volcanic vent. Tephra has densities ranging from approximately 800−1200 kg m^{-3}, much denser than snow. In addition, the load of tephra on roofs increases substantially if the tephra deposit saturates with meteoric water.

There are two reasons to estimate expected tephra fallout at the CFPP site:

- Renewed volcanism on the ESRP is likely to produce some tephra fallout at the CFPP site. Tephra fallout may come from new eruptions of scoria cones, phreatomagmatic eruptions that produce tuff rings and maars, and lava domes, for example.
- There are distal sources of potential tephra fallout at the CFPP site. These potential distal sources of eruptions include the Cascades range and the Yellowstone volcanic system.

In the following, the modeling approach for tephra hazard assessment is described, together with a workflow for simulating specific types of volcanic events, and a workflow for probabilistic calculations.

Because the ESRP is a distributed volcanic field, tephra fallout is most likely to come from new vent locations, rather than existing, previously active volcanoes. A wide spectrum of volcanic activity occurs on the ESRP, so new volcanic events may be of different types, and these types of volcanic events are capable of producing different magnitudes of tephra fallout. Types of tephra producing eruptions that occur on the ESRP include:

- Basaltic fissure eruptions and rows of craters: these phenomena produce local tephra fallout from fire-fountains.
- Scoria cone eruptions: tephra eruptions from scoria cones produce tephra fallout that, over time, creates thick accumulation within 10 km of the volcanic vent.
- Basaltic shield volcano eruptions: like basaltic fissure eruptions, these volcanic events can produce local tephra fallout from fire-fountains.
- Phreatomagmatic eruptions: explosive activity due to magma-groundwater interaction produces tephra fallout. The areal extent of tephra fallout is similar to, although often less voluminous, than scoria cone eruptions.
- Lava dome eruptions: intermediate to silicic eruptions that form lava domes on the ESRP have explosive phases that can produce widespread tephra fallout.

Volcanic Hazards Analysis Approach Methodology

Different types of explosive eruptions are capable of producing different tephra volumes and dispersion patterns of tephra fallout. The tephra fallout will be modeled for each defined eruption type as a function of distance from the CFPP site. The models will include expected accumulation and the grain size distribution of tephra particles at the site. Model results can be multiplied by the spatial density of past volcanism to obtain the expected tephra accumulation given an eruption on the ESRP, and then multiplied by the recurrence rate for future volcanic events, to obtain a probability of tephra accumulation at the site from renewed ESRP volcanic activity.

Distal sources of possible tephra fallout hazards include the Cascades and Yellowstone caldera. Explosive eruptions from Cascades volcanoes are expected during the performance period of the CFPP site. Renewed explosive Yellowstone activity is not expected but is possible during the performance period of the CFPP site. Numerous caldera-forming and intra-caldera eruptions have occurred in the Quaternary. Eruptions from these sources will be modeled.

Tephra2 is a tephra dispersion model that estimates the mass of tephra that would accumulate at a site or over a region, given explosive eruption conditions and a wind field. Tephra2 has an extensive history of world-wide use to forecast and model tephra fallout hazards (Connor & Connor, 2019; Biass et al., 2016; Alfano et. al., 2011; Connor & Connor, 2006; Bonadonna et al., 2005). The purpose for using Tephra2 for the CFPP VHA is to model expected tephra accumulation at the CFPP site for the range of explosive volcanic events that may occur on the ESRP or associated with possible distal sources, and to estimate the probability, with uncertainty, of exceeding various hazardous mass loadings of tephra at the CFPP site.

The Tephra2 model calculates the grainsize distribution of tephra particles and the expected mass loading per unit area at a given location. This numerical simulation is based on an analytical solution to the advection-diffusion equation, which is simply a mass-conservation equation that relates the mass distribution of tephra on the ground to the distribution of tephra mass within the eruption column as a function of column height and particle size, modified by wind velocity and diffusion.

Diffusion is a Gaussian process. Tephra particles of various sizes originate from a point-release source in the eruption column. Particles diffuse through different layers of the atmosphere. Particles are advected by the wind away from the erupting column. Thus, the point-release source of tephra from the column is modified by advection from the wind and diffusion through the atmosphere to deposit in various amounts at locations around the vent.

Particle sizes have different settling velocities in the atmosphere. Tephra2 uses the particles settling velocity model developed by Bonadonna et al., (1998), which is based on Stoke's settling with Reynold's number dependence. This model replaced inaccurate settling velocity model developed by Suzuki (1983) and used in older tephra dispersion models, such as ASHPLUME (Jarzemba et al., 1997). Particle fall time is measured, beginning with a particle's release height from the column until its deposition on the ground. If particles are released from the same column height, larger particles with faster settling velocities will be less dispersed in a deposit than smaller particles with slower settling velocities. Similarly, uniformly sized particles with similar settling velocities will be more dispersed when released from higher in the column than when released lower in the column.

Volcanic Hazards Analysis Approach Methodology

Tephra2 employs a column model using the beta distribution (Connor et al., 2019) not found in earlier tephra codes such as ASHPLUME (Jarzemba et al., 1997; Hill et al., 1997; Keating et al., 2008). ASHPLUME, did not include these diffusion models, which have been found to be necessary to model moderate to large volume plumes (e.g., Bonadonna et al., 2005; Connor et al., 2019; Constantinescu et al., 2021, 2022).

The following parameters are inputs to the Tephra2 model. The variable from the equations that relates to each parameter is listed with the parameter.

- ***Vent location***: Easting and northing, in geographic coordinates, and height of the vent above sea level.
- ***Plume height***: Maximum height of the eruption column.
- ***Eruption mass:*** The total mass of tephra erupted from the volcano is input in kilograms. Tephra2 calculates the mass fraction at locations around the vent.
- ***Column steps, Particle steps:*** The eruption column is discretized in to atmospheric layers. Particle sizes are divided into bins.

The following input parameters describe properties of the distributions used to estimate the populations of tephra particles that comprise the erupted mass in the model.

- ***Min, Max, Mean, Standard deviation:*** Tephra2 assumes that the total population of tephra particles follows a lognormal distribution, i.e., a Gaussian distribution and a specified mean and standard deviation.
- ***Alpha, Beta:*** alpha > 0 and beta > 0, are the two shape parameters for the beta distribution. When $\alpha = \beta = 1$, the distribution is uniform random. Using various combinations of α and β, particle release can be skewed toward the upper part of the column, as found with strong buoyant plumes, or skewed toward the bottom, as found with weak, bent-over plumes.

The following input parameters are used to guide the advection and diffusion of tephra particles through the atmosphere.

- ***Lithic density, Pumice Density:*** Tephra2 uses a linear model to approximate the change in particle density as a function of particle size. The density of small lithic particles and large pumice particles can be set (units = kg m^3) uniquely. Particle density and particle diameter together affect the settling velocity of particles.
- ***Fall Time Threshold:*** The fall time of a particle, in seconds, that determines whether a particle uses a linear atmospheric diffusion model *(i.e.,* particle falls as a coarse particle) or uses a nonlinear atmospheric diffusion model (*i.e.,* particle falls as a fine particle).
- ***Diffusion Coefficient (DC), Eddy Constant (EC):*** Higher values for the DC give greater diffusion away from the erupting column. Units for the DC and the EC are m^2s^{-1}. An appropriate value for the EC is 0.04 m^2s^{-1}.

Volcanic Hazards Analysis Approach Methodology

Two additional input files are needed to run the Tephra2 dispersion model.

- ***Grid file:*** The grid file is a text file containing lines of one or more locations. Tephra mass loading and grainsize distribution is calculated at each of the locations listed in the grid file.
- ***Wind File:*** Tephra2 allows the wind to vary in speed and direction as a function of height above the volcano. One simplifying assumption made is that the wind field remains constant across horizontal distances around the volcano, meaning the wind field remains the same at the source and at the deposition location(s), appropriate for short dispersal distances (< 100 km) or for probabilistic simulations. Tephra2 uses wind field data from NOAA reanalysis data sets, calculated world-wide, four times daily, at 2.5 degree intervals.

Given these inputs, the accumulated mass of tephra and the grain size distribution of tephra particles can be calculated at any location about the volcanic vent. The CFPP VHA will bound the ranges of the input ESPs to model the defined types of explosive events that have occurred on the ESRP in the past, such as scoria cone forming eruptions that are comparable to the cumulative tephra blankets observed at scoria cones like Sunset Crater (Arizona) and Paricutin (Mexico).

Tephra2 will be used to calculate complementary cumulative distribution functions (CCDFs) for tephra accumulation at the CFPP site, given a large magnitude eruption at a distal source. For example, one can calculate the CCDF for a volcano explosivity index (VEI) 6 eruption in the Yellowstone magmatic system using wind-fields sampled from the NOAA REANALYSIS database. These estimates require specifying appropriate ranges for ESPs for these large-volume eruptions, for a range of VEIs or any number of vent locations. The CCDFs provide a measure of the expected tephra accumulation at the site, given specific range of ESPs.

Probability models of tephra fallout for distributed events like scoria cone eruptions will be conducted using the following steps:

Step 1. Specify a grid for volcano event locations. The reason for using a grid, instead of randomly sampling a spatial density model is to uncouple these analyses, so the tephra fallout model results can be used with alternative spatial density models without re-calculating the tephra fallout hazard each time.

Step 2. Run simulations for different volcanic event types including fissure eruptions and crater rows, shield volcanoes, scoria cones, and phreatomagmatic eruptions and silicic dome eruptions. For each event type, create probability density functions for the input ESPs, including tephra eruption volume, column height, grain size distribution, etc. Wind fields are sampled from NOAA REANALYSIS data.

These results are used to identify the probability that a threshold of tephra fallout is exceeded for a grid of source locations, given an eruption at these source locations. This probability is multiplied by the spatial density and recurrence rate estimates for the ESRP to obtain a probability that a threshold accumulation is exceeded. Multiple thresholds of mass accumulations for engineering design considerations can be investigated without re-running the analyses.

Volcanic Hazards Analysis Approach Methodology

6.0 Conclusion

The CFPP VHA represents a new first of a kind iteration of new regulatory guidance in a subject that has little precedence so the development of this process is ongoing. The identification of volcanic hazards present that could potentially impact the CFPP site once completed will be screened and subsequently modeled in accordance with new methodologies built on best practices from prior work that has been performed in the assessment of volcanic hazards.

The identification of volcanic hazards on the site have required extensive use of both historical and new collections of data relevant to the CFPP site. The complex techno-magmatic history of the region is dominated by the Yellowstone hot spot. This resulted in a distribution of volcanic events in the setting in the Quaternary period of interest. Thus a comprehensive survey and most current understanding of the emergence of volcanic hazards has been undertaken.

From this thorough characterization of the site and the associated hazards an initial screening was performed in accordance with the guidance provided in RG. 4.26 which was applied conservatively. Ruling out potential sources of hazards prematurely would result in a nonconservative approach for the hazard assessment. Therefore possible hazards have a low threshold for screening into the hazard analysis and those that are screened out will still be analyzed in the final report.

The nature of these hazards in accordance with their potential impact to CFPP site necessitates a more comprehensive modeling of the hazards. This requires a more complicated and thorough modeling process for these hazards to determine their relevance to the site. The use of a spatial density model for vents, MOLASSES code for lava flow, and Tephra2 for tephra distribution creates the most robust modeling of the site possible in accordance with the current regulatory guidance.

This paper demonstrates the methodology the CFPP plans to use in regards to:

1. The identification of hazards
2. The criteria for screening those hazards
3. The requisite modeling and probability of those hazards impacting the site

The identification, screening, modeling, and risk assessment of potential impact will inform the next process of evaluating the performance of the NuScale Power Plant in the event of the events detailed from the models with their probabilities of occurrence informing the risk posed by those hazards, and subsequent mitigation strategies if needed.

Volcanic Hazards Analysis Approach Methodology

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