Rhyolite lava emplacement dynamics inferred from surface morphology

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A B S T R A C T

The morphology of a silicic lava is created by the fluid dynamic conditions that operated during flow. Careful analysis of these features can thus be used to reconstruct emplacement processes. We used unoccupied aerial system and structure-from-motion photogrammetry techniques to collect centimeter-scale spatial resolution imagery of the surfaces of South Coulee and Obsidian Dome rhyolite lavas (Mono-Inyo Craters, USA). We supplement the newly acquired orthomosaics and digital elevation models with existing imagery of other Holocene rhyolite lavas from across the western USA, including Rock Mesa Dome (South Sister, OR), Newberry Flow (South Sister, OR), Obsidian Flow (Newberry, OR), Interlake Flow (Newberry, OR), and Banco Bonito Flow (Valles Caldera, NM). Although many morphologic features exist, we restrict our quantitative analyses to the recurrent ridges and blocks of loose rubble that are common to the flows. Ridge spacing and ridge vergence indicate the ridges are likely folds produced by compression during emplacement. Pressure ridge spacings range from 27 to 45 m at South Coulee and 18 to 34 m on Obsidian Dome. Spacing generally decreases with distance from the vent across both lavas. Ridge amplitudes range from 4 to 17 m at both lavas and show little correlation with distance from the vent. The vergence of the crest of the ridges in the flow interiors points back to the source vent, which provides strong evidence for endogenous flow and the backward rotation of folds produced by undertow of the underlying lava. Ridges near flow margins verge towards the flow front, demonstrating that exogenous flow becomes increasingly important at the point of advance. In both South Coulee and Obsidian Dome block sizes are largest near the vent, and gradually decrease towards the flow front. The gradual decrease in block size with increasing distance from the vent likely reflects decreasing effusion rates from the conduit. We interpret our high-resolution field measurements under the lens of analytical solutions to fluid dynamic models to estimate emplacement timescales and associated rates. We calculate relatively abbreviated eruptive timescales ranging from 1 month to ~2 years. Such values predict eruptive fluxes <135 m³ s⁻¹ and velocities <100 m day⁻¹, providing helpful criterion for volcanic monitoring or hazard forecasting efforts.

1. Introduction

Silicic lava flows may generate volcanic hazards during emplacement, including surface explosions, collapse avalanches, and pyroclastic density currents (Fink and Manley, 1987; Fink and Kieffer, 1993; Castro et al., 2002). These hazards are produced when the strength of the lava’s crust is overcome by internal stresses associated with continuous flow or pronounced lava vesiculation events (Cashman et al., 1994; Blake and Bruno, 2000; Magnall et al., 2017; Darmawan et al., 2018). The surface of a lava is similarly scarred by brittle and ductile deformation features caused by the accumulation and distribution of strain during eruption and subsequent emplacement (Fink, 1980, 1983; Griffiths and Fink, 1993; Castro and Cashman, 1999; Anderson et al., 1998).

Surface features of silicic lavas can be used to reconstruct lava emplacement processes. Many surface features exist, prominent among them are recurring ridges and abundant loose blocks of rubble. Ridges are commonly considered to be folds that lie perpendicular to direction of flow (Fink, 1980). If so, then they offer an opportunity to infer the crust thickness, viscosity, and strain of the formerly flowing lava (e.g., Fink, 1980). Ridge spacings have been measured using remote sensing for a variety of flows on Earth, Mars, and the Moon (Fink, 1980). Ridge amplitude and vergence angle of the antclinal crest, however, have been neglected because of the inaccessibility of sufficiently high-resolution digital elevation models (DEMs). Here, vergence is used in a structural geology sense, referring to the direction the fold is leaning (e.g. towards vent or towards flow front). Surface folds produced during exogenous tank track flow will produce a top to flow...
front vergence. In contrast, endogenous inflation flow produces folds that verge top to vent. Blocks of broken lava are another ubiquitous feature on the surface of flows. Block size distributions reflect the strain conditions during conduit effusion or emplacement (Anderson et al., 1998).

Lava surface features vary markedly in the scale of their critical dimension, ranging from the kilometer to the centimeter (Fink, 1980; Anderson et al., 1998; Kerr and Lyman, 2007). Thus, lava emplacement processes can be analyzed using a diverse array of tools, such as petrography, fieldwork, and satellite-borne remote sensing (Anderson et al., 1998; Pyle and Elliott, 2006). Recent advances in unoccupied aerial systems (UAS) and structure-from-motion (SfM) photogrammetry provide new tools to investigate macroscopic lava surface features with centimeter-scale resolution (Turner et al., 2017; Carr et al., 2019). The use of UAS enables rapid and efficient image collection across the most rugged terrain. SfM photogrammetric techniques can then be used to produce high resolution DEMs and orthomosaics from those images. Using these techniques in tandem allows for morphological and geomorphic data to be inexpensively and quickly acquired (James and Varley, 2012; James and Robson, 2012, 2014; Westoby et al., 2012). For example, here we demonstrate how UAS technology allows block size measurements to be readily quantified, which previously required arduous, immersive fieldwork (e.g., Anderson et al., 1998).

This research builds upon previous lava morphology studies by demonstrating a workflow for converting UAS imagery and topographic information into estimates for emplacement processes and timescales (Fink, 1980; Anderson et al., 1998; Castro et al., 2013; Darmawan et al., 2018; Favalli et al., 2018; Hunt et al., 2019). We present new high-resolution SfM 3D reconstructions of South Coulee and Glass Creek Dome, and high-resolution transects of Obsidian Dome (Mono-Inyo Craters, USA). We compare our data with original analyses of previously collected DEMs of rhyolite lavas from different prehistoric volcanoes across the western USA (Obsidian Dome at Inyo Craters, CA, Deadman Dome at Inyo Craters, CA, Rock Mesa Dome and Newberry Flow at South Sister Volcano, OR, Interlake Flow and Big Obsidian Flow at Newberry Volcano, OR, and Banco Bonito Flow at Valles Caldera, NM) (Fig. 1). Pressure ridges and blocks are common features on all lava flows, but their sizes and distributions vary significantly depending on the flow or the position within an individual flow. The differences preserve a record of emplacement and are used here to quantify flow dynamics. The mobility and emplacement of rhyolite lavas are estimated by interpreting the measurements through the lens of established

Fig. 1. DEMs of all studied lava flows. a Relative location of all flows. b Big Obsidian Flow, Newberry Volcano, Oregon. c Newberry Flow, South Sister, Oregon. d Glass Creek Dome, Inyo Craters, eastern California. e Interlake Flow, Newberry Volcano, Oregon. f Deadman Dome, Inyo Craters, eastern California. g Obsidian Dome, Inyo Craters, eastern California. h Rock Mesa Dome, South Sister, Oregon. i Banco Bonito Flow, Valles Caldera, New Mexico. South Coulee, Mono Craters is shown in Fig. 2.
fluid dynamics models to calculate flow criteria, including surface and interior viscosities, strain rates between gravitational and compressional stresses, crust thicknesses, thermal gradients, flow velocity, eruption timescale, and extrusion rates (e.g., Fink, 1980; Anderson et al., 1998; Griffiths, 2000; Griffiths et al. 2000; Kerr and Lyman, 2007; Castro et al., 2013).

2. Targeted lava flows

Hundreds of rhyolite lavas have been emplaced across the western United States during the Holocene. Here, we primarily focus on South Coulee and Obsidian Dome, two of the most recent lavas that were erupted from the Mono-Inyo Craters chain, eastern CA, USA. Mono-Inyo Craters is a 25 km-long north-south trending mountain range constructively built over the past 55 kya by emplacement of >30 rhyolitic lava, domes, and related explosive centers (Bursik and Sieh, 1989; Hildreth, 2004; Bursik et al., 2014).

South Coulee is one of the largest exposed lavas in the Mono-Inyo Craters. It is a 0.3 km³ aphyric, high-silica rhyolite (76% SiO₂) that erupted 1329 ± 27 cal BP (Bursik et al., 2014). The compositions of glass and Fe—Ti oxide phenocrysts indicate that South Coulee was erupted at ~800 °C with a melt viscosity of ~10¹⁰.⁷ Pa s (Carmichael and Nicholls, 1967; Romine and Whittington, 2015). South Coulee erupted from a north-south trending fissure located along the topographic crest of the Mono-Inyo range. The flow spread both east and west from the fissure, with most of the flow traveling to the west. The surface features of some of the vent and proximal region have been removed by a pumice mining operation (Featherock, Inc.), which presents benefits and challenges. A coarse road network provides access to the entire flow. Quarry faces in the modified areas provide outcrops of flow interior. Much of the eastern lobe has been modified by mining, but the surface of the main western lobe remains largely unaffected. The 80-m-thick western lobe was emplaced as a single channel that travelled ~3.8 km from the vent. It flowed down a slope of ~3° for ~1 km before it reached a break in topography where the slope transitions to a steeper domain with a slope of ~30° for 0.5 km. The flow then reached a second break in topography and returned to a slope of ~3°. At this second topographic break, the flow expanded and split into lobes, producing a northern lobe and the continuation of the main western channel lobe, which both terminate within 1 km of the reduction in gradient (Fig. 2).

The second targeted flow, Obsidian Dome, erupted ~600 years ago from a vent in the southern portion of the Mono–Inyo Chain. It spread radially ~2 km from the centralized vent. Obsidian Dome was the focus of the Continental Drilling Program from 1983 to 1985, which led to a series of seminal publications that now guide our understanding of the magmatic plumbing system, interior structure, and emplacement mechanisms of silicic lava flows (Fig. 1g) (Eichelberger et al., 1985; Vogel et al., 1989; Swanson et al., 1989). Obsidian Dome is a 0.17 km³ rhyolite (73% SiO₂) with phenocrysts of plagioclase, sanidine, biotite, orthopyroxene, magnetite, and minor quartz, that account for 2 to 9 vol% of the flow (Miller, 1985; Vogel et al., 1989). The feldspar and Fe—Ti oxide phenocrysts indicate an eruptive temperature of ~850 °C and a melt viscosity of ~10¹⁰.⁴ Pa s (Gibson and Naney, 1992; Romine and Whittington, 2015). Obsidian Dome, unlike South Coulee, erupted onto a near constant slope of ~3°. The flow is roughly 100 m thick at the vent and thins to ~30 m at the margins.

Fig. 2. DEM of South Coulee produced with structure-from-motion UAS photogrammetry. The squares represent the 62 areas where block sizes were measured. Domains with prominent pressure ridges are highlighted with the dashed black lines.
We also analyze DEMs from seven other rhyolite lavas and domes from the western US. Big Obsidian Flow and Interlake Flow erupted from Newberry Volcano in eastern Oregon (Fig. 1b; e). Big Obsidian Flow is a rhyolite (72.6 wt% SiO₂) that erupted ~1300 years ago. It has an approximate volume of 0.13 km³ estimated using ~2 km of lateral flow at an average thickness of ~40 m (Robinson and Trumble, 1983; Castro et al., 2002). Interlake Flow is a 0.07 km³ rhyolite flow (73.9% SiO₂) that erupted ~1700 years ago (Peterson and Groh, 1969). Interlake Flow diverged into two lobes, one flowing east into the East Lake and the other west into Paulina Lake. The average flow length is 1.7 km and has an average thickness of 30 m. Newberry Flow, despite its name, is part of the Devils Chain, a contiguous north-south alignment of seven rhyolite lava domes (72.3–72.8 wt % SiO₂) that erupted ~2000 years ago on the flank of South Sister Volcano (OR) (Fig. 1c). At 0.13 km³ Newberry accounts for 60% of the total eruptive volume of the Devils Chain and has a maximum flow length of 2.5 km and an average thickness of ~40 m (Fierstein et al., 2011). Rock Mesa Dome, also located on South Sister Volcano, is a 0.5 km³ rhyolite (73.5% SiO₂) that erupted ~2150 years ago (Fig. 1h) (Fierstein et al., 2011). Rock Mesa has an average diameter of ~1.5 km and an average margin thickness of ~85 m. Banco Bonito Flow, Valles Caldera NM, is an ~0.9 km³ rhyolite (72.8 wt% SiO₂) that extends 7.7 km from the vent and has an average thickness of 59 m (Fig. 1i). The eruption age of Banco Bonito has proven difficult to constrain, with estimates ranging from 26 to 140 ka, with recent Ar/Ar estimates of 68.3 ± 1.5 ka (Miyaji et al., 1985; Phillips et al., 1997; Lepper and Goff, 2007; Pelletier et al., 2011; Zimmerer et al., 2016). Glass Creek Dome and Deadman Dome are small (~0.1 km³) rhyolites that erupted ~600 years ago in the Mono-Inyo Craters, CA (Fig. 1d; f) (Bursik and Sieh, 2013). They both have an average diameter of ~1 km and thickness of 20 to 25 m.

3. Methods

We used a combination of DEMs, orthomosaics, and 3D photogrammetry to analyze the surface of rhyolite lavas emplaced from different volcanic systems across the western USA (South Coulee, Obsidian Dome, Glass Creek Dome, and Deadman Dome at the Mono-Inyo Craters, Rock Mesa Dome and Newberry Flow at South Sister, Interlake Flow and Big Obsidian Flow at Newberry Volcano, Banco Bonito Flow at Valles Caldera). Orthophotos, DEMs, and 3D models of South Coulee, Obsidian Dome, and Glass Creek were generated using SFM photogrammetry from US images collected for this study, whereas the others were collected from LiDAR datasets in Open Topography and DOGAMI LIDAR (https://opentopography.org/; https://oregongeology.org/). We report new volume, length, width, and thickness measurements for each of these lavas. Flow thickness was calculated as the average difference in elevation between top of the flow surface and the base level at the perimeter of the flow, averaged at numerous locations across the flow. Volumes were calculated in both ArcMap and Agisoft. For ArcMap the raster was clipped to the surface area of the lava flow, and then each elevation pixel was summed to get an estimate on the lava flow volume. We use our datasets as input variables for established fluid dynamic models to establish a workflow that converts high resolution topographic data into estimates for eruption rates and durations.

3.1. UAS photogrammetry

Airborne imagery of the lavas was collected using a 20-megapixel digital camera built into the DJI Phantom Pro 4 Advanced. The preflight plans were created and carried out in an automated flight mapping software, Map Pilot. At South Coulee, iso-elevation flights were flown at a speed of ~6 m s⁻¹ and operated at an altitude of 90 m above the takeoff point on the flow’s surface. Photos were automatically taken every 2.5 s, resulting in an 80% overlap of the ground surface. We collected imagery across ~4 km² to produce an overlapping mosaic that covers South Coulee. A single battery allowed ~17 min of flight time, permitting us to collect photos covering an area of ~0.24 km². To obtain total coverage of the flow, we collected a total of 7874 photos from 25 flights.

Photos were processed in Agisoft Photoscan Professional 1.3.5.53649 to generate dense 3D point clouds, DEMs, and orthomosaics. The 3D point clouds were manually cleaned by removing anomalous points. South Coulee was georectified by linking to the known spatial coordinates of 40 ground control points distributed around and across the lava. We made ground control points with 40 by 40 cm porcelain tiles, each separated into colored quadrants that we manually painted. The precise location of each ground control point was established with a real-time kinematic global positioning system provided by UNAVCO. Ground control points give an average accuracy of 4 cm, 2 cm, and 7 cm in their x, y, z positions respectively. The uncertainty associated within the imagery independent of map coordinates has an uncertainty of 0.5 pixels, which corresponds to an internal uncertainty of 2 cm. When georectified, the South Coulee DEM and orthomosaic have resolutions of 7.5 and 4.5 cm pixel⁻¹, respectively.

At Obsidian Dome 170 photos were collected over a single flight which covered 0.13 km² along a transect. The flight was conducted at an elevation of 73 m, resulting in a DEM and orthomosaic resolution of 3.6 and 1.8 cm pixel⁻¹, respectively. The transect was not georectified with ground control points, but using the GPS onboard the UAS we were able to maintain an internal accuracy of 0.4 pixels, equivalent to ~1 cm pixel⁻¹. Glass Creek Dome was collected over a 1.9 km² area flow at 120 m elevation giving a total of 965 photos. The resulting DEM and orthomosaic resolution of 10.9 and 5.4 cm pixel⁻¹. Glass Creek is similarly not georectified, but has an internal consistency of 1.3 pixels, equal to 7 cm pixel⁻¹. The high-resolution DEM and orthomosaics of each of the flows was imported into ArcMap 10.6 to map, measure, and visualize lava surface features.

3.2. Surface feature measurements

Recurring ridges, or ogives, are one of the most prominent surface features on the rhyolite lavas. They occur as elongate, sinuous ridges aligned perpendicular to the inferred flow direction. Ridge measurements were performed by first establishing the topography along linear transects perpendicular to the axis of subsequent ridges across the length of a flow (Fig. 3a). Each transect creates a cross section that expresses both the convex ridge crest and cuspatute troughs that topographically define the pressure ridges.

We recorded the geographic coordinates of the crests and troughs and then used trigonometry to recreate ridge geometry (Fig. 3c). The strict linear distance was measured between the troughs on either side of a ridge (Fig. 3c; points A-B). This spacing represents a shortened, final distance between ridges after flow ceased. We also measured the arc length of the surface between subsequent troughs, which represents the initial distance between ridges (Fink and Fletcher, 1978) (Fig. 3c; points A-C-B). Ridge amplitude is the difference in elevation between the ridge crest and the average elevation of the encapsulating troughs. We also measured ridge vergence, which is equivalent to the fold hinge angle of the ridges (Fig. 3c; C-D). Ridge vergence is the angle measured by an imaginary line that connects the ridge crest to the point halfway between troughs; 90° is vertical, acute angles <90° verge towards the flow front, and obtuse angles >90° verge towards the vent. Said another way, vergence towards the flow front means the steeper side of the ridge is on the downstream side (e.g., C–B in Fig. 3c). At each lava multiple measurements were taken along individual ridges in order to represent variations along strike.
To establish the sizes and numbers of blocks across the surfaces of South Coulee and Obsidian Dome, we counted and measured block sizes within 20 by 20 m areas spaced every 40 m along vent-to-flow-front transects (Figs. 2 and 4). Orthophoto resolution within these domains allowed us to measure all blocks $\leq 12$ cm across. In sum, we counted 26,500 blocks in 62 domains on South Coulee and 4640 blocks in 10 domains across Obsidian Dome. We measured the longest axis of every block for consistency within our dataset and comparability to Anderson et al. (1998). The block size distribution measurements produce several different parameters, including block counts, largest block, and average block size.

### 3.3. Numerical methods

Field measurements were supplemented with analytical solutions to fluid dynamic models (e.g., Huppert, 1982; Griffiths and Fink, 1993; Kerr and Lyman, 2007; Castruccio et al., 2013). Our field measurements establish flow length, width, and volume. We then calculate other key physical parameters to better constrain lava emplacement mechanisms. The analytical models we employ assume a Newtonian lava flow is controlled by either slope and viscosity, or the strength of a surface crust. Models can also be analyzed under constant eruptive flux or an exponentially decreasing eruption rate (e.g., commonly associated with

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**Fig. 3.** a Topographic profiles of the surfaces of lavas showing ridge wave forms. b Magnified view of ridges on Obsidian Dome and South Coulee. Emplacement direction is to the right in both a and b. c Generic geometric treatment of ridge form to demonstrate calculations. Ridge spacing is the horizontal distance from syncline to syncline, A to B. Arc length is the surface distance between A and B. Amplitude is the distance between the ridge crest, C, and the imaginary halfway point between A and B (D). The vergence is the angle between line AD and DC.
overpressure from the magma chamber. If a rhyolite lava is assumed to be erupted with a constant eruption rate, then length of a channelized lava is:

\[ L = c_\text{vs} \left( \frac{g \Delta \rho \sin \beta q^3}{\mu} \right)^{1/3} \]  

Slope—controlled  
(1)

\[ L = c_\text{c} \left( \frac{\sigma_c}{g \Delta \rho} \right) \left( \frac{2 V}{W} - 1 \right) \left( 1 - e^{-t / \tau} \right) \]  

Crust—controlled  
(2)

where \( c_\text{vs} = (3/2)^{2/3} = 1.31 \), \( c_\text{c} \) is an unknown constant of order 1, and \( q \) is erupted volume per unit flow width (Kerr and Lyman, 2007). For exponentially decreasing eruption rates the length of a channelized lava is given by:

\[ L = c_\text{vs} \left( \frac{g \Delta \rho \sin \beta V^2}{\mu W^2} \right)^{1/3} \left( 1 - e^{-t / \tau} \right) \]  

Slope—controlled  
(3)

\[ L = c_\text{c} \left( \frac{g \rho}{\sigma_c} \right) \left( \frac{2 V}{W} - 1 \right) \left( 1 - e^{-t / \tau} \right) \]  

Crust—controlled  
(4)

where \( \tau \) is the eruption timescale, \( \sigma_c \) is the crust yield strength, \( V \) is erupted volume, and \( W \) is flow width. Many rhyolite lavas do not channelize, and instead produce near-radially symmetric domes (e.g., Obsidian Dome) requiring the following radially spreading model (Huppert et al. 1982):

\[ R = 0.7 \times \frac{g V^3}{(3 \times 10^5 \tau)^{1/2} \epsilon^{1/2}} \]  

(5)

Pressure ridges can also be used as an analytical input to numerical models to estimate the ratio of surface to interior viscosities, strain rates, and crustal thickness (Fink and Fletcher, 1978; Fink, 1980). If pressure ridges form by compression in a Newtonian fluid, they must satisfy specific rheological criteria defined by dimensionless parameters \( S, R, \) and \( L_{dy} \), which relate to viscosity, stress, and wavelength, respectively (Fink, 1980; Fink, 1978; Fink and Fletcher, 1978). The ratio of the surface to interior viscosities, \( R \), must be \(< 35 \) (Eq. (1)). The stress ratios, \( S \), which describes the stress caused by the weight of the lava and the compressive stress caused by folding, must be \(< 0.02 \) (Eq. (2)). Finally, the dimensionless dominant wavelength \( L_{dy} \) should be \(< 28 \) (Eq. (3)).

\[ R = \frac{\eta_s}{\eta_i} \]  

(6)

\[ S = \frac{-\rho g \frac{1}{2} \left( \frac{1}{\epsilon} \right)}{4 \eta_s \epsilon_{\text{xx}}} \]  

(7)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Variables in fluid dynamic equations.</th>
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</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Unit</td>
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<td>( k )</td>
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<td>( C_{\text{vs}} )</td>
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<td>( C_c )</td>
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In the equations above, $\eta_i$ is the surface viscosity, $\eta_j$ is the interior viscosity, $\rho$ is magma density, $\gamma$ is gravity, $\varepsilon_i$ is the strain rate, $L_d$ is the arc length, and $\gamma$ is the exponential decay parameter of viscosity (Table 1). We estimate the finite strain by comparing the arc lengths of the folds with the ridge spacing (Fink and Fletcher, 1978). The formation timescale of the ridges is an additional unknown, thus calculating the minimum strain rate required to form ridges provides the necessary upper bounds for the timescale for ridge formation (Eq. (9)), where $H$ is the surface crust thickness.

$$L_d \gamma = \frac{L_d}{1/\gamma}$$

In its initial application, Fink (1980) used the surface-folding model to determine that the ridges on Big Glass Mountain rhyolite satisfied all three parameters, thus suggesting that pressure ridges can be formed by flow of a silicic lava. In a recent example, the 2011–2012 Cordón Caulle eruption produced a rhyolite lava with pressure ridges. Satellite imagery and direct scientific observation were unable to record ridge formation because of interference by the ash plume and its remote location in the southern Andes of Chile. As a demonstration, we apply the surface-folding model to show that the ridges on Cordón Caulle likely formed by compressive folding. Cordón Caulle is a crystal-poor rhyolite with 70 wt% SiO$_2$ that erupted at ~900 °C (Castro et al., 2013; Schipper et al., 2013). We use reported flow characteristics including $H = 4$ m, $R > 42$, $\rho = 2300$ kg m$^{-3}$, $\varepsilon_i > 5.5 \times 10^{-5}$ and $3.3 \times 10^{-7}$ s$^{-1}$, and a time scale of 1 h to 1 week. Viscosity is predicted to be $10^9$ to $10^{11}$ Pa s and $\eta_j > 10^8$ to $10^{10}$ Pa s. These values are in close agreement with the bulk viscosity of $10^9$ to $10^{10}$ Pa s estimated from the composition of the rhyolite (Farquharson et al., 2015; Schipper et al., 2015).

4. Results

The rhyolite lavas share many similar characteristics. They are ~1 km$^3$ flows that travelled ~8 km from their respective vents. Ridges align perpendicular to flow direction across portions of each lava. The surfaces of all flows are covered in blocks of brecciated pumice and obsidian clasts that range from a few meters to tens of centimeters in size. Outcrops of obsidian and pumice diapirs protrude through brecciated surfaces of the flows in places. Our UAS imagery provides unparalleled viewing of the surface textures and topography of the lavas (Fig. 5). We capitalize on the opportunity the technology provides to generate morphologic datasets of pressure ridges and block sizes.

4.1. Ridge characteristics

The spacing, amplitude, and vergence of 13 ridges were measured across South Coulee (Table 2). Ridges tend to be confined to specific areas of flows, and on South Coulee ridges are most pronounced just after the second break in slope where the underlying topography transitions from a steep slope of 30° to a much gentler slope of 3°, estimated from the topography of the margin. Ridge spacings range from 27 to 45 m. Ridge spacing decreases with distance from the vent and tends to increase on steeper slopes (Fig. 6a). Ridge arc lengths range from 33 to 59 m (Fig. 6b). Ridge amplitude progressively increases from 7 to 13 towards the flow front (Fig. 6c). Vergence angles decrease from 152° to 60° with increasing distance from vent (Fig. 6d). Vergence correlates positively with both amplitude and slope.

Ridges are also prominent features on Obsidian Dome. They do not occur in a clearly defined flow channel like at South Coulee. Instead, ridges occur as eroded ridges that track the radial emplacement of lava away from a central vent. Ridge spacing ranges from 18 to 34 m, with the spacing decreasing with distance from the vent (Fig. 6e). Arc length decreases from 33 to 28 m with distance from the vent, similar to the behavior observed at South Coulee (Fig. 6f). Ridge amplitudes range from 2 to 12 m, but do not correlate with position in the flow or spacing (Fig. 6g). Like amplitude, vergences do not vary systematically with position and range from 77° to 163° (Fig. 6h).

We performed a series of principal component and statistical analyses but found that no significant correlations exist between ridge characteristics at South Coulee and Obsidian Dome (Fig. 7). Distributions of measurements of ridge spacing, arc length, amplitude, vergence, and block size, from Obsidian Dome and South Coulee were compared using parametric (unpaired t-test) and non-parametric tests (Kruskal-Wallis and Kolmogorov-Smirnov) of sample means, medians, and distributions, to determine whether or not the morphological features from both flows are different from one another. Results of statistical tests suggest that the ridge spacing, arc length, amplitude, and block size measurements from Obsidian Dome and South Coulee are different, but vergence angles are indistinguishable. The uniqueness of the waveforms of the ridges suggests that small degrees of late stage faulting, deformation, or erosional degradation are sufficient to disrupt automated identification of any characteristic waveform that may have developed by folding.

We measured the geometries of 50 ridges on the 8 other rhyolite lavas (Table 2). Each ridge was measured multiple times along regularly spaced intervals along its length. The DEMs for these lava flows have a coarser resolution of 1 m pixel$^{-1}$, which is too coarse to reliably calculate ridge vergence (e.g., Fig. 5). Like South Coulee and Obsidian Dome...
Dome, ridges on the lavas vary in abundance, size, and distribution across the surfaces. The lavas have amplitudes ranging from 5 to 17 m (Table 2), with an average spacing and wavelength is 35 ± 11 m and 39 ± 13 m, respectively (Table 2). Spacing ranges from 10 to 85 m with Interlake Flow producing the smallest and Banco Bonito Flow the largest values.

Table 2
Lava flow surface morphology measurements. Number in parentheses is total measurements n. Multiple measurements were taken along individual ridges in order to represent variations along strike. Individual measurements for each pressure ridge, and block size can be found in supplemental Tables A.1, A.2, A.3.

<table>
<thead>
<tr>
<th>Lava Flow</th>
<th>Ridge spacing (m)</th>
<th>Arc length (m)</th>
<th>Amplitude (m)</th>
<th>Vergence (%)</th>
<th>Block size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>South Coulee</td>
<td>33 ± 9 (160)</td>
<td>42 ± 10</td>
<td>10 ± 3</td>
<td>121 ± 35</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>Obsidian Dome</td>
<td>20 ± 11</td>
<td>24 ± 10</td>
<td>5 ± 5</td>
<td>119 ± 49</td>
<td>0.7 ± 0.5</td>
</tr>
<tr>
<td>Glass Creek Dome</td>
<td>27 ± 8</td>
<td>30 ± 10</td>
<td>7 ± 4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Deadman Dome</td>
<td>28 ± 6</td>
<td>31 ± 8</td>
<td>5 ± 2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Rock Mesa Dome</td>
<td>43 ± 15</td>
<td>49 ± 17</td>
<td>9 ± 2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Newberry Flow</td>
<td>31 ± 11</td>
<td>34 ± 13</td>
<td>9 ± 2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Interlake Flow</td>
<td>21 ± 7</td>
<td>32 ± 10</td>
<td>4 ± 1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Big Obsidian Flow</td>
<td>11 ± 6</td>
<td>10 ± 6</td>
<td>4 ± 1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Banco Bonito Flow</td>
<td>85 ± 27</td>
<td>87 ± 28</td>
<td>12 ± 4</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 6. Relationship between ridge spacing, arc length, amplitude, and vergence with increasing distance from vent. a–d for South Coulee, and e–h for Obsidian Dome.
4.2. Block size distributions

Block size distributions preserve similar trends across South Coulee and Obsidian Dome. Block sizes are largest near the vent, and gradually decrease towards the flow front. Block sizes near the vent at South Coulee are 0.66 ± 0.12 m, which decreases to 0.39 ± 0.12 m. Average block size at Obsidian Dome vent is 0.90 ± 0.60 m, which then decreases to 0.65 ± 0.46 m (Fig. 8).

4.3. Numerical modeling

Using the UAS-derived morphology measurements in conjunction with fluid dynamic-based numerical models, we estimate prehistoric lavas’ surface crust thickness, strain rates, and viscosities to constrain emplacement dynamics (Table 3). The ridges on the surfaces of each flow may be treated as compressional folds, as each lava passes the “fold criteria” (e.g., Eqs. (6) to (8), Fink, 1978, 1980; Fink and Fletcher, 1978). We calculated that the emplacement of each lava was likely modified by the formation of a significant crust ranging from 4 to 12 m thick. These crusts produced surface viscosities ~2 log units greater than interior flow viscosities. During emplacement, strain rates ranged from $10^{-7}$ to $10^{-9}$ s$^{-1}$. Because flow length is an established parameter, eruption timescales were calculated by rearranging Eqs. (1) through (5) to solve for eruptive timescale (Table 5). Looking to South Coulee and Obsidian Dome as our best imaged lavas, we calculate timescales ranging up to ~6 months. The slope-controlled model predicts that if the 3-km-long South Coulee flow was emplaced on an average slope of 7° (best guess at average slope from our measurements), then the emplacement took ~120 days, using either a fixed or decreasing eruption rate. The crust-controlled model predicts emplacement timescales ranging from 85 to 153 days, with the variability controlled by assuming a constant or exponentially decreasing flux. Obsidian Dome is not a channelized flow and thus requires the radially spreading model. We calculate that Obsidian Dome was emplaced in ~30 days. Each of the other lavas’ emplacement timescales similarly ranged from 1 month to ~2 years (Table 4).

5. Discussion

We have used high resolution UAS imagery of lava flow surfaces and topography to gain insight into emplacement processes and timescales (e.g., Fink, 1980, 1983; Griffiths and Fink, 1993; Castro and Cashman, 1999; Anderson et al., 1998). These datasets and calculations provide new opportunities for characterizing factors that strongly influence the mechanisms and hazards associated with emplacement, offering an opportunity to assess the future impact of rhyolite effusions.

5.1. Ridges to infer emplacement style

Ridges are common features marking the surfaces of many natural flows, including glaciers, debris flows, and lavas. On lavas, the length scale of ridge amplitude and spacing vary with melt composition and flow viscosity (Deardorff et al., 2019). Centimeter-scale ridges form on basaltic pahoehoe in response to compressive stresses on timescales of seconds to minutes. Ridge formation has never been observed on more viscous silicic lavas, including andesites, dacites, and rhyolites, because their eruptions are rare, often in remote locations, or are dangerous to observe first hand. They must form, however, because large ridges with spacings ranging up to 100 m and amplitudes >10 m commonly mark their surface. The similar ridged morphology on the surfaces of pahoehoe and silicic flows may form by a shared mechanism despite the difference in scale. If the ridges on silicic lavas form in response to compressional stresses then they may be interpreted as folds, ramp structures formed by thrust faulting of a brittle crust, or kinematic waves formed by surges of lava. The causal compressive stresses would be generated when the flow gradient shallows, or by
shear stresses on the channel margins producing folds in the flow channel upstream (Fink, 1980). The ridges could also form from an extensional regime, where the interior lava extrudes through regularly-spaced cracks formed during extension of the flow crust (Loney, 1968; Fink, 1980).

The pressure ridges on the surfaces of the lavas may be formed by a variety of processes, both extensional or compressional. Using the “fold criteria” introduced by Fink (1980), we tested if the ridges can be declared “pressure ridges” sensu stricto, defined as folds that form in response to compressional stresses (Fink, 1980). Indeed, the ridges on each lava flow satisfy the specific rheological criteria defined by dimensionless parameters $S$, $R$, and $L_y$, which relate to viscosity, stress, and wavelength, respectively (Fink, 1978, 1980; Fink and Fletcher, 1978).

If ridges can indeed be treated as folds, then the vergence of the fold’s axial hinge provides an additional record of emplacement processes. In the absence of shear, the vergence angle of a fold should be vertical at 90°. If the lava surface is modified by shear stress, then the ridge crest may point away from or towards the vent. Accordingly, vergence angles can be used to differentiate between the endmember emplacement styles of endogenous inflation and exogenous, tank-tread transport. These styles operate with distinctly different rotational shear stresses. Tank-tread style is characterized by top-to-flow front vergence created by overturn of the surface continuously rolling over itself. Tank-tread style is observed in block and a‘a lavas, and at the flow front of pahoehoe. The effects of an impeding, insulating crust control emplacement by endogenous inflation. After the insulating crust has formed, subsequent eruption of lava thickens under the crust and inflates the flow. The crust may become increasingly stretched if the flow is vigorous, or it may thicken with diffusive heat loss in lower flux environments. Pressure ridges that form in response to endogenous inflation will verge top-to-vent caused by the backward rotation of folds produced by undertow of the underlying lava (Walker et al., 1999).

We restrict ridge vergence to our UAS datasets at South Coulee and Obsidian Dome. On South Coulee, we measured the vergence angle of 13 ridges along a 1-km-long transect. Vergences range from 152° to 60° (Fig. 6d). Vergence is predominantly top-to-vent where the lava first interacts with the gentle 3° slope. Vergence remains consistent for ~700 m of channelized flow across gentle preexisting topography. Ridges on the eastern side of Obsidian Dome verge at 77° to 162° (Fig. 6b). Most of the ridges display verge towards the vent, again evidence for endogenous flow. In the most distal portions of South Coulee, close to the flow front, the ridges transition to top-to-flow front vergence. Channelized flow is predominantly endogenous, but transitions to exogenous emplacement close to the flow front. Such transition from endogenous to exogenous is a common behavior observed in basaltic pahoehoe and a‘a flows (Peterson and Tilling, 1980, Cashman et al., 1994), which occurs when brittle fracturing destroys crust in response to increased yield strength and viscosity attributed to the onset of groundmass crystallization (Crisp and Bologa, 1980; Cashman et al., 1994). A similar increase in viscosity in rhyolite can also be accomplished by degassing 0.1 wt% H₂O or cooling the lava by 50 °C (Costa et al., 2005; Giordano et al., 2008; Romine and Whittington, 2015). We interpret the endogenous–exogenous transition at South Coulee to reflect an increasing viscosity caused by degassing or cooling in distal positions.

Vergence measurements require precise spatial measurements of the ridge crest. Vergence is measured in degrees, with our measurements ranging from 60 to 173°. If we assume that 1° is a desired precision and that South Coulees average arc length is 42 m, then the DEM requires 0.2 m vertical resolution. Most LiDAR-generated DEMs provide resolutions of 1–5 m, thus resulting in vergence precisions ranging from 5° to 20°.

Ridge spacing provides insights into the compressive forces caused when the flow is impeded by the crust or by changes in underlying slope (Fink and Fletcher, 1978). Changes in spacing reflect the dissipation or buildup of compressive stresses. Ridge spacing thus allows us to estimate the accumulation of finite strain. Strain is calculated as the difference between ridge spacing and arc length divided by arc length. The most pronounced ridges at South Coulee occur after the break in slope, from steep to gentle. We interpret this transition as an impediment that allows for compressive stresses to accumulate in the lava. The faster velocity on the steeper slope continuously disrupts the crust, and no ridges are preserved in that domain. The velocity decreases after the flow encounters a gentler slope, allowing ridges to form. The ridges become more closely spaced with distance.

**Table 3**

<table>
<thead>
<tr>
<th>Lava Flow</th>
<th>$L$ (km)</th>
<th>$W$ (km)</th>
<th>$V$ (km$^3$)</th>
<th>$\rho$ (kg m$^{-3}$)</th>
<th>$\beta$ (°)</th>
<th>$\mu$ (log Pa s)</th>
<th>$D$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Coulee</td>
<td>3</td>
<td>1.5</td>
<td>0.30</td>
<td>2333</td>
<td>7°</td>
<td>10</td>
<td>83</td>
</tr>
<tr>
<td>Obsidian Dome</td>
<td>0.88</td>
<td>0.9</td>
<td>0.17</td>
<td>2284</td>
<td>5°</td>
<td>10.1</td>
<td>31</td>
</tr>
<tr>
<td>Glass Creek Dome</td>
<td>1</td>
<td>0.6</td>
<td>0.10</td>
<td>2359</td>
<td>8°</td>
<td>11.4</td>
<td>25</td>
</tr>
<tr>
<td>Deadman Dome</td>
<td>1</td>
<td>1</td>
<td>0.13</td>
<td>2378</td>
<td>3°</td>
<td>11.6</td>
<td>23</td>
</tr>
<tr>
<td>Rock Mesa Dome</td>
<td>1.5</td>
<td>1.5</td>
<td>0.50</td>
<td>2404</td>
<td>9°</td>
<td>10.2</td>
<td>86</td>
</tr>
<tr>
<td>Newberry Flow</td>
<td>2.5</td>
<td>1</td>
<td>0.13</td>
<td>2379</td>
<td>18°</td>
<td>9.8</td>
<td>39</td>
</tr>
<tr>
<td>Big Obsidian Flow</td>
<td>1.9</td>
<td>1.3</td>
<td>0.38</td>
<td>2380</td>
<td>9°</td>
<td>10.4</td>
<td>43</td>
</tr>
<tr>
<td>Interlake Flow</td>
<td>1.7</td>
<td>0.04</td>
<td>0.07</td>
<td>2395</td>
<td>6°</td>
<td>9.7</td>
<td>30</td>
</tr>
<tr>
<td>Banco Bonito Flow</td>
<td>7.7</td>
<td>1.7</td>
<td>0.90</td>
<td>2350</td>
<td>8°</td>
<td>12.5</td>
<td>59</td>
</tr>
</tbody>
</table>

Fig. 8. Block sizes decrease along transects across South Coulee and Obsidian Dome. Dashed trend lines are provided as a guide.
downstream from this point. Compressive stresses as high as 23% occur at the break in slope, which decrease to 13% nearing the flow front. The ridges on Obsidian Dome were measured on the eastern flank. Ridge spacing decreases with distance.

From the vent, which correlates to an increase in compressive strain from 6% to 10%, Obsidian Dome was erupted onto a preexisting topography with a near constant slope. The impediment to flow is thus attributed to the growth of a surface crust.

5.2. Block size distribution

The rhyolite surfaces are covered with a jumbled assortment of loose blocks. This block-scrawled surface form is the brittle crust of a lava fracture in response to stresses accumulated during flow (Anderson et al., 1998). The block size distribution is an artifact of past stress conditions within the lava’s crust, causing the numbers and sizes of blocks to be an integrated record of the strain imparted during extrusion at the vent and/or progressive mechanical fracturing during emplacement (Anderson et al., 1998). High eruptive flux rates generate high strain rates which in turn produce many, smaller blocks. Low extrusion rates produce fewer, larger blocks and slabs near the vent. With progressive transport away from the vent during flow, block sizes may change in response to mechanical fracturing (decreasing size) or the addition of blocks added by processes associated with surface features such as pressure ridges, crease structures, pumice diapirs, or surface explosions (Anderson et al., 1998).

Obsidian Dome is an exceptional field location to investigate how block sizes change across a rhyolite lava. Anderson et al. (1998) physically mapped the block size distribution across the surface of Obsidian Dome and found that the average block size gradually decreases from 0.7 m at the vent to 0.3 m at the eastern flow front. This consistent, gradual decrease in block size with increasing distance from the vent could possibly reflect a decreasing effusion rate, but Anderson et al. (1998) could not definitively distinguish this from mechanical fracturing of blocks during transport down flow except in cases of a sudden change in block size associated with the cessation of an eruption. We reproduced the field measurements of Anderson et al. (1998) by measuring block sizes from orthomosaics created from UAS photogrammetry. We found that block size does indeed decrease away from the vent, with average block size decreasing from 0.9 ± 1.3 m at the vent to 0.6 ± 0.4 m at the flow front (Fig. 8). Although the trend is the same, our average size is larger at each position because we measured blocks within a larger 20 × 20 m area, making the larger blocks easier to include. Following Anderson et al. (1998), we also did not count blocks <12 cm because small blocks tend to slip towards the interior of the flow in fractures and thus do not accumulate as ‘fines’ on the flow surface.

At South Coulee block sizes gradually decrease from 0.7 ± 0.4 m at the vent to 0.4 ± 0.2 m at the flow front (Fig. 8). The block sizes on South Coulee were on average ~20 cm smaller than those measured on Obsidian Dome for any given position. The smaller block sizes at South Coulee could be attributed to a faster extrusion rate compared to Obsidian Dome (Anderson et al., 1998). The overall decreasing trend suggests that the extrusion rate was initially high and waned with time. Decreasing extrusion rate arises when a volcanic system is controlled by overpressure in the underlying magma chamber (Scandone, 1979; Wadge, 1981; Stasiuk et al., 1993). If extrusion rate did not decrease with time, then the block size distribution may instead reflect increasing thermal-mechanical fracturing downslope of the vent. With an increase in slope, we would predict the velocity of the flow to increase thus providing more stress and creating smaller block sizes. The formation of pressure ridges is also associated with increasing compressive stresses on the surface of the flow, so we would also predict smaller blocks to be found in this region. But, block size does not correlate with slope nor the presence of pressure ridges. As an alternative mechanism, mechanical fracturing may instead occur because of increased transport time and accumulated stresses. We cannot rule out the relative impact of this mechanical fracturing during transport.

5.3. Emplacement timescales and flux rates

Fluid dynamic properties can be used in tandem with flow volume and length to infer emplacement timescales. Timescales can then be used to estimate other emplacement parameters including mass flux, velocity, and strain rate. We calculate that each of the targeted lavas were likely emplaced in <2 years (Table 5). Using our best fit pre-existing topography, rheology, and assume an exponentially decreasing flux, then we calculate that South Coulee was emplaced in ~120 days. Such result is similar to the observed 285 days for Cordón Caulle,
whose slightly higher viscosity of $10^{10.1}$ to $10^{10.6}$ Pa s may account for the longer emplacement time (Farquharson et al., 2015). We calculate that Obsidian Dome was emplaced in ~30 days, similar to the emplacement duration of Chaitén that was observed to have erupted in 60 days. Rock Mesa at South Sister volcano also yields a comparable emplacement timescale of ~45 days.

With the emplacement time and final volume estimated, eruption rates can be calculated by:

$$V(t) = \frac{V}{1 - e^{-\frac{t}{\tau}}}$$

where $V(t)$ is the volume as a function of time, and $V$ is final volume. If we assume that South Coulee was emplaced in ~120 days, we calculated exponentially decreasing eruption rate with an initial lava flux of 112 m$^3$ s$^{-1}$ (48 m$^3$ s$^{-1}$ if constant flux) (Eq. 10). Obsidian Dome is predicted to have erupted with a constant flux of 60 m$^3$ s$^{-1}$. No models specifically treat exponentially decreasing flux for a dome, but comparison with South Coulee suggests an initial flux of 140 m$^3$ s$^{-1}$ for Obsidian Dome. Exponentially decaying eruption rates coincide with the predictions set forward by block size distributions, magma reservoir models, and observations of recent rhyolitic eruptions. Cordón Cauile was found to have an average flux of ~50 m$^3$ s$^{-1}$, with the highest flux of 72 ± 6 m$^3$ s$^{-1}$ early in the eruption (Bertin et al., 2015). Chaitén erupted with an initial flux of ~66 m$^3$ s$^{-1}$, which decreased to average 45 m$^3$ s$^{-1}$ for the first four months of the eruption (Pallister et al., 2013). Our estimates for eruptive timescales and known length measurements, allow for average advance rates to be calculated. The average velocity of flow front advance ranges from 4 to 100 m day$^{-1}$. These durations and flux estimates appear to be realistic, falling in line with observations at other volcanoes (Fig. 9). We acknowledge our calculations use many simplifications and assumptions but are unavoidable per the scope of this study. However, these estimates do provide important constraints on prehistoric flows and add to our understanding of rhyolite emplacement dynamics (Table 5).

5.4. Final considerations

We have built upon the legacy developed by previous lava morphology studies by demonstrating how high resolution UAS imagery and topographic data can be used to increase understanding of emplacement mechanisms (Fink, 1980; Anderson et al., 1998; Castro et al., 2013; Favalli et al., 2018; Hunt et al., 2019). Using that approach, we provide first order estimates into the emplacement dynamics of prehistoric rhyolite lavas. Ridge spacing, amplitude, and vergence measurements indicate that the eruptive timescales of the analyzed lavas ranged from 1 month to ~2 years, suggesting eruptive fluxes and velocities of <135 m$^3$ s$^{-1}$ and < 100 m day$^{-1}$, respectively. Gradual decreases in block size with increasing distance from the vent likely reflects decreasing effusion rates from the conduit, suggesting these eruption rates similarly decreased with time. The lavas were emplaced via endogenous processes, with limited exogenous behavior near flow fronts. Only 2 active rhyolitic lava flows have been observed in the scientific era, thus our understanding of rhyolites is largely biased towards those lavas from the Chilean Andes. Detailed studies of Holocene flows and analog modeling of flows in the western US, like those herein, are very important for conceptual models. Computational fluid dynamic models for viscous rhyolite lavas remain an additional undeveloped avenue. In contrast, basalt lavas can be readily simulated with a number of robust numerical models (e.g., Dietterich et al., 2017). These fluid dynamic simulations of basaltic lavas are built upon decades worth of extensive field-based datasets and experiments. Similar observational datasets are needed for rhyolites, which will then be used as benchmarks to establish the anticipated parameter space in future models. Our contribution thus provides an important step towards a wholistic understanding of rhyolite lava flow emplacement.

CRediT authorship contribution statement

Tyler N. Leggett: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. Kenneth S. Befus: Conceptualization, Investigation, Writing - review & editing, Supervision, Funding acquisition, Resources, Visualization. Stuart M. Kenderes: Formal analysis, Visualization, Writing - review & editing.

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