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Invited research article

Global mapping of future glaciovolcanism

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ABSTRACT

We created a global database of glacierized volcanoes, using a projection optimized for each volcano, to identify locations where land ice (glaciers and ice sheets) and volcanoes co-exist on Earth. Our spatial database melds the Smithsonian Global Volcanism Database (SGVD) and the Randolph Glacier Inventory 6.0 (RGI). We identified all Holocene volcanoes within the SGVD that have glacier ice within radii of 1 km, 2.5 km, and 5 km, and thus have the potential to impact or be impacted by surrounding ice. Our analysis shows that 245 Holocene volcanoes have glacier ice within the specified radii, which are covered partly or fully by 2584 unique glaciers or the Antarctic Ice Sheet. The volcanoes are located in all major volcano-tectonic settings, although the majority (72%) are in subduction zones built on continental crust (greater than 25 km thick). They also cover the majority of the typical compositional ranges for igneous rocks (basalt to rhyolite). Twenty-nine volcanoes, or 12%, have at least 90% ice cover within 5 km, which together comprise 36% of global glacier area on volcanoes. About 20,000 people live within 5 km of a glacierized volcano, while 160 million people live within 100 km of a glacierized volcano and could be impacted by lahars and/or disruption of their water sources during future eruptions. By merging our database with existing ice thickness model estimates we find 850 ± 290 km^3 of ice within 5 km of volcanic vents globally. We compare the eruption history, ice volume, and nearby population estimates to identify the most dangerous volcanoes on Earth. The combination of volcano locations and ice thickness estimates allows us to identify 20 (out of 245) glacierized volcanoes that are most likely to experience 'thick' ice eruptions, while the vast majority are more likely to experience 'thin' ice eruptions.

1. Introduction

Glacierized volcanoes, which are volcanoes that presently host one or more glaciers, are present across the span of Earth's latitudes today and may be present on other planets like Mars (see Smellie and Edwards, 2016 for recent summary). They were undoubtedly even more abundant during the Last Glacial Maximum (LGM), and the numerous other glacial stades of the Plio-Pleistocene, and the more ancient glacial epochs on Mars. Knowing the locations and glacier extents at ice-clad volcanoes is important because the volcanoes pose unique hazards during glaciovolcanic eruptions (Smellie and Edwards, 2016), they can be used as tools to reconstruct past climate conditions (e.g., Edwards et al., 2002), and they can impact surrounding ice bodies, which themselves can be important water storage resources for local and regional communities (e.g., Kochtitzky et al., 2018). A volcanic eruption impacting large ice bodies, such as the Antarctic Ice Sheet, could also contribute to global sea level rise through melting surrounding land-based ice or acting to destabilize nearby glaciers. We use databases of volcano locations and extents of glaciers to create an inventory of glacierized volcanoes to be targeted for future studies aimed at hazard reduction, paleoclimate reconstructions, and continued monitoring.

Many previous workers have shown that volcanism can be affected by glaciation from source to surface (see Smellie and Edwards, 2016, for exhaustive bibliography). Changes in overburden pressure due to ice thickness changes can impact the depth and extent of melting in source regions (e.g., Jull and McKenzie, 1996), impede dyke formation by inducing localized stress regimes to be compressive instead of extensional (e.g., Guðmundsson, 1986; Wilson and Russell, 2020), and alter the depth of volatile exsolution and onset of explosive eruptions (e.g., Tuffen et al., 2010; Edwards et al., 2015a, 2015b). Once on the surface,

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ice can impact eruptions in a variety of ways including the eruption explosivity or characteristics of the lava flow.

Glacierized volcanoes display a variety of morphologies, dictated by their eruption and glaciation history. Longer-lived volcanic systems that have erupted through different amounts of ice cover may preserve 'inverted' flank morphologies where lavas initially confined to ice free areas between glaciers form ridges rising above glacially carved valleys (e.g., Mt. Rainier; Lescinsky and Sisson, 1998). Volcanoes formed within ice sheets may have entirely different morphologies compared to subaerial volcanoes that are intrinsically tied to formation within ice (e.g., tuyas and tindars; Fig. 1a,b). Some others have morphologies that have been influenced by the presence of periodic regional ice-sheets as well as more localized ice cover (Fig. 1c,d). Many of the presently active glacierized volcanoes have familiar volcanic morphologies, including intermediate (Fig. 1e) and mafic (Fig. 1f) composite volcanoes, formed by interactions predominantly with local as opposed to regional ice. These morphologies can help us understand past climate and eruptive history and confine future scenarios for volcano-ice interactions.

Volcanic eruptions can have significant impacts on surrounding glaciers (see Barr et al., 2018 for detailed summary) leading to either positive or negative glacier mass balance. Broad areas of elevated land surface as well as individual edifices may create topography that allow for the accumulation and formation of glaciers even within 20 degrees latitude of the equator (e.g., Mauna Kea, Hawaii; Kilimanjaro, Tanzania; Cotopaxi, Ecuador; Guliwe, Papua-New Guinea). Ash cover can expedite mass wasting by increasing absorption of solar radiation if it is thin (a few cm depending on the material) or can insulate ice and slow mass loss if it is thick (tens of cm; Kirkbride and Dugmore, 2003; Dragosics et al., 2016; Reznichenko et al., 2010; Fig. 2a). Glaciers that exist close to eruptive vents (within 1–2.5 km) can be melted by lava flows (e.g., Veniaminof, Hudson, Gigjökull, Villarrica, Llaima; Fig. 2b,c), pyroclastic density currents (Nevado del Ruiz; Mt. St. Helens (MSH)), directed blasts

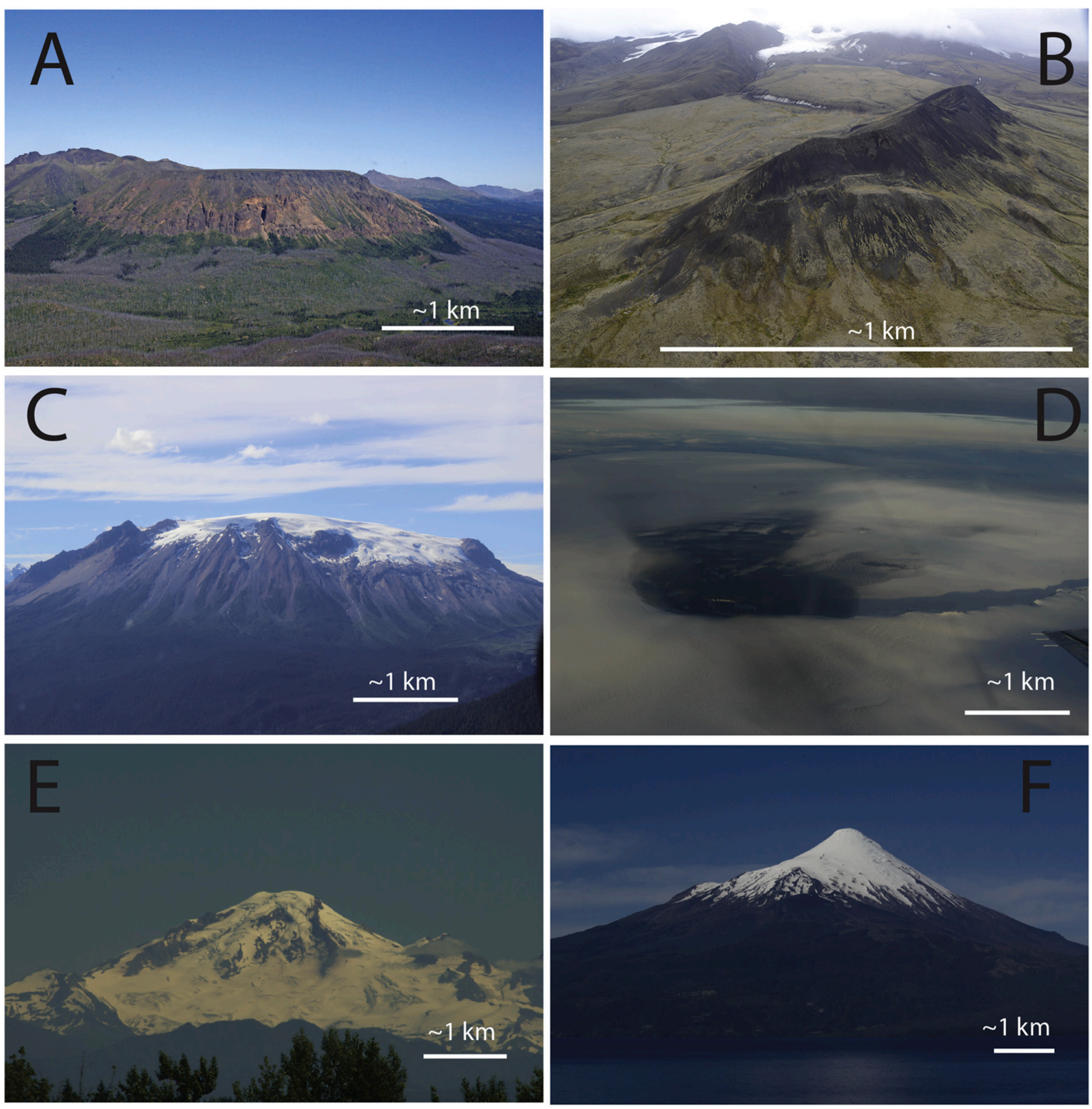

Fig. 1. Morphologies of glacierized and formerly glacierized volcanoes. A. Isspah Butte, northern British Columbia, is a classic, basaltic flat-topped tuya that formed at about 1.8 Ma during an eruption through the Cordilleran ice sheet (Edwards et al., 2020). B. Tsekone Ridge, northern British Columbia, is basaltic tindar (or linear tuya) erupted on the flank of Mount Edziza at about 60 ka (Souther, 1992). C. Hoodoo Mountain, in western British Columbia, is an intermediate composition volcano that hosts a 3 km diameter ice cap (Edwards et al., 2002). D. Grimsvötn volcano, southeastern Iceland, is a mafic volcano whose summit is entirely beneath the Vatnajökull ice cap and has erupted twice in the twenty-first century (http://icelandicvolcanos.is/). E. Mount Baker, northwestern Washington, is an intermediate composition composite (strato) volcano that last erupted in the late 1800's and is largely covered by ice. F. Osorno volcano, in southern Chile, is a large, mafic composite volcano that last erupted in the 1900's (González-Ferrán, 1995). Scales in all images are approximate and do not apply to the foreground.

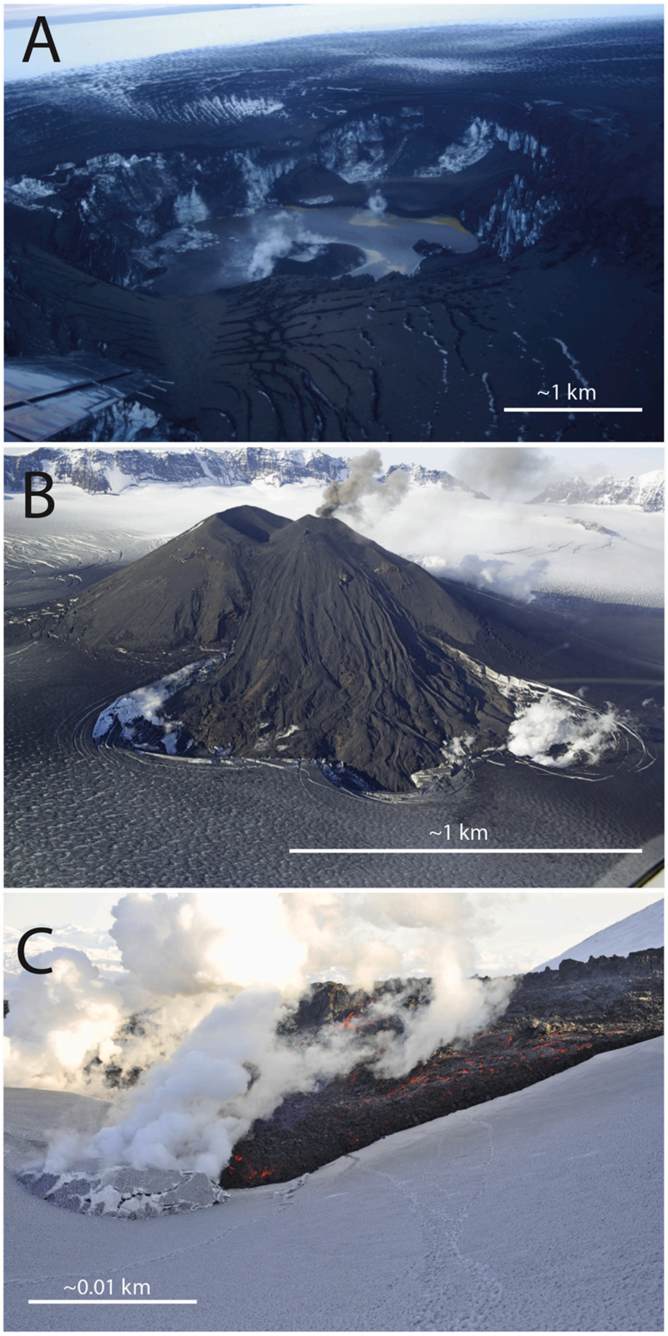

Fig. 2. Impacts of volcanic eruptions on surrounding ice. A. Eruption that begins at the base of a glacier and melts through the entire ice body (2004 eruption of Grimsvötn caldera; Jude-Eton et al., 2012). B. Eruption that begins above the surrounding glacier and produces lava flows that are emplaced on the glacier surface (2013 eruption of Veniaminof volcano, Alaska, USA, https://avo.alaska.edu/volcanoes/volcimage.php?volcname=Veniaminof). C. Lava flow inflated upwards into an overlying snow bank (2013 eruption at Tolbachik volcano, Kamchatka, Edwards et al., 2015a, b). Scales in all images are approximate and do not apply to the foreground.

(MSH), lahars generated upslope (Gigjökull), or fracturing caused by uplift associated with lava dome emplacement (summarized in Smellie and Edwards, 2016; Barr et al., 2018). Thus, monitoring glaciers on volcanoes is particularly important to predict future water resources and hazards.

Previous research on glacierized volcanoes has focused on documenting hazards from eruptions (Major and Newhall, 1989), impacts on glaciers (Barr et al., 2018) or rapid volcano-ice mapping methods (Curtis and Kyle, 2017). Major and Newhall (1989) document volcano-ice-snow interactions that produced lahars or floods at more than 40 volcanoes, some of which are glacierized and others that only have seasonal snow cover (e.g., Asama and Tokachi-dake volcanoes in Japan; Etna volcano in Italy). They concluded that explosive eruptions are mostly likely to produce dangerous lahars and floods. Curtis and Kyle (2017) developed a method to quickly identify areas where volcanoes and the cryosphere (snow, glaciers, and permafrost) could interact using the MODIS satellite. They identified 294 volcanoes that have ice or permanent snow fields with 10 km of their reported center, another 157 that might have potential for interactions between volcanism and permafrost, and they concluded that their MODIS algorithm could be useful for identifying changes in snow or ice cover for volcano monitoring. Barr et al. (2018) updated and expanded the Major and Newhall (1989) work to document the 56 volcanoes that have recently erupted beneath a glacier. They outlined in detail impacts of volcanic eruptions on surrounding glaciers. At present none of these databases has a complete inventory of every glacierized volcano that includes details of the volcanoes and of the glaciers found on or around those volcanoes.

Given the complexities of interactions between volcanoes and surrounding glaciers, a comprehensive global database of volcanoes and nearby glaciers is critical for identifying where these features co-exist. Here, we inventory the global distribution of terrestrial ice within 1 km, 2.5 km, and 5 km of Holocene volcanoes and present a database to be used for future studies of volcanoes, glaciers, and associated hazards. Our database allows for the first global examination of the petrology, tectonic settings, and nearby population of glacierized volcanoes, as well as identifying glaciers most likely to be impacted by volcanic eruptions. We have further incorporated data on ice volumes at these glacierized volcanoes to help give initial constraints on potential hazards associated with ice melting during future eruptions as well as identifying volcanoes that will show different behavior due to 'thick' or 'thin' ice cover. The new database will hopefully have a variety of immediate practical uses, but will also be impactful for more esoteric topics such as quickly identifying all terrestrial glacierized volcanoes that could be targeted as potential analog sites to develop hypotheses and data collection strategies for future Mars exobiology studies.

2. Methods

Analysis of glacier area near volcanoes was performed using glacier boundaries from the Randolph Glacier Inventory 6.0 (Pfeffer et al., 2014; https://www.glims.org/RGI/;Fig. 3a) and Holocene volcano locations from the Smithsonian Global Volcanism Database (SGVD, Global Volcanism Program, 2013; https://volcano.si.edu; Fig. 3b). Both datasets were obtained in the WGS84 coordinate system. The datasets were loaded into a PostgreSQL database with the PostGIS extension for spatial analyses. To minimize errors due to map projection distortion, all analyses were done with the PostGIS geography data type to do calculations on the spheroid.

To identify the area of glaciers near volcanoes, we created three buffers around each volcano (at 1, 2.5, and 5 km). These buffers are intended to show the impact of a direct blast mainly impacting ice within 1 km of the vent, lava flows, and pyroclastic density currents impacting ice within 2.5 km, and lahars and tephra cover likely impacting all ice within 5 km. In PostGIS, buffers were calculated using geographic data types (ST_Buffer function) after being converted to a coordinate system optimized for the individual point location (favoring UTM and Lambert Azimuthal Equal Area north/south pole projections). Doing this re-projection at the point-level using the geographic data type effectively minimizes the distortion that would be introduced by calculating the buffers in a single projection for the entire dataset. The volcano buffers and glacier boundary dataset were then intersected in PostGIS to identify the region of overlap. Areas were calculated on the spheroid for the intersecting regions at 1, 2.5, and 5 km (Fig. 3c).

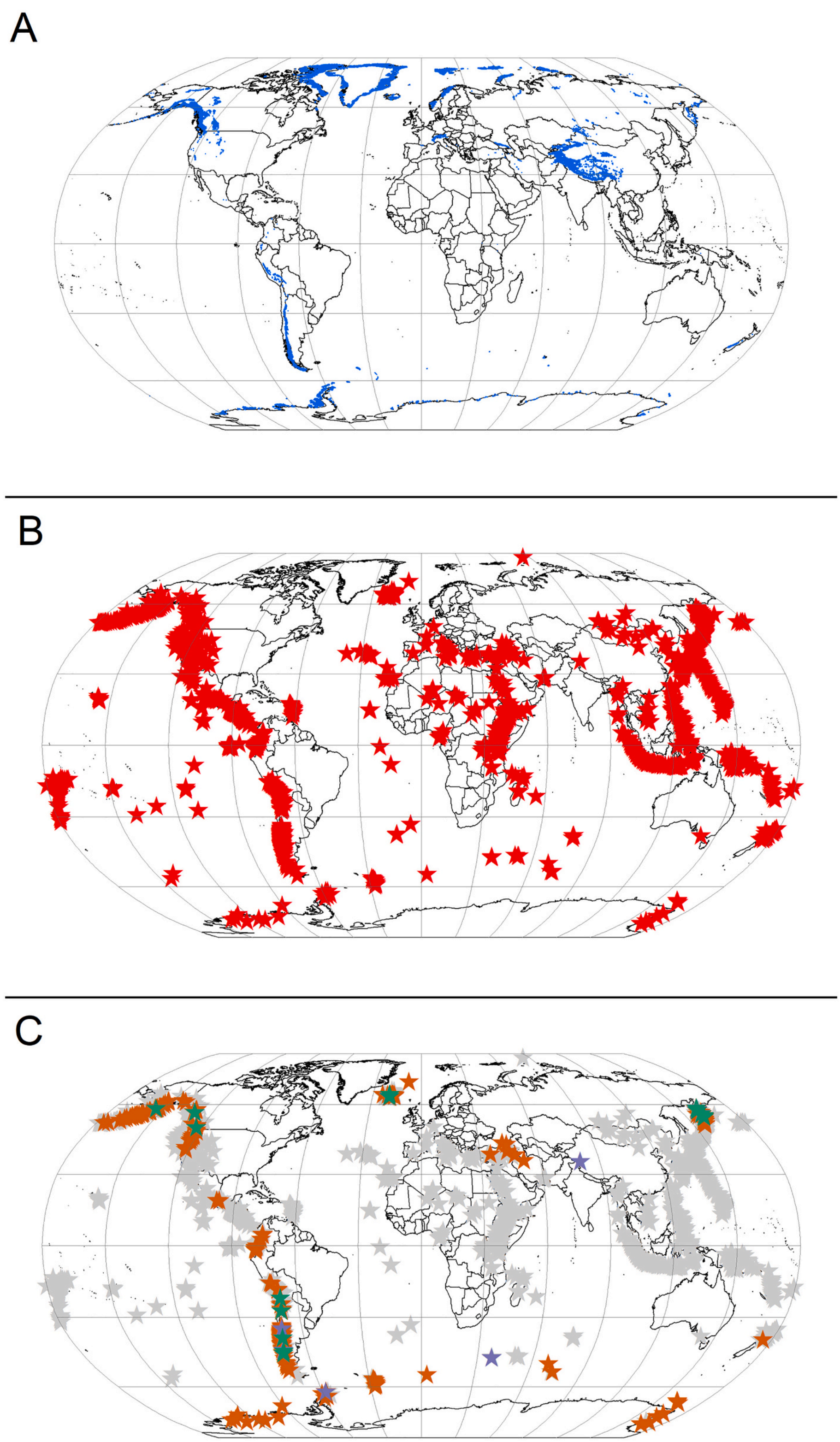

Fig. 3. Global distributions of database elements. A. Volcanoes from the Global Volcanism Program database. B. Glaciers from the RGI6 database. C. Glacierized volcanoes mapped combining figures A and B above (this work). Orange, purple, and green stars show volcanoes with ice within 1 km, 2.5 km (but not within 1 km), and 5 km (but not within 2.5 km) respectively, with a total of 245 separate glacierized volcanoes.

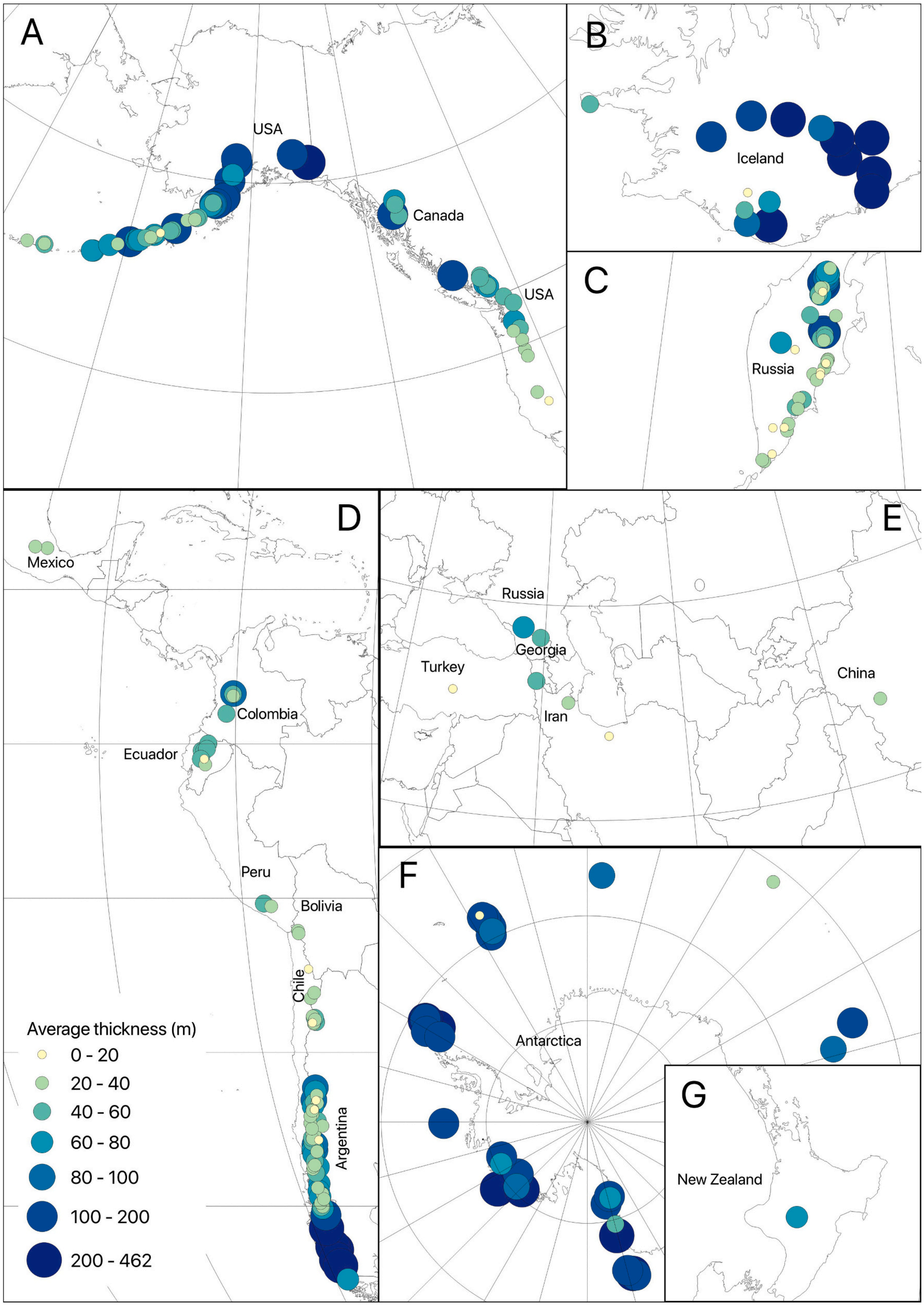

Fig. 4. Global distributions of estimated average thicknesses of glaciers on volcanoes in the database. Panels are for different geographic areas and cover all glacierized volcanoes: (A) Western U.S., (B) Iceland, (C) Kamchatka, Russia, (D) Central and South America, (E) Eurasia, (F) Antarctica, (G) New Zealand.

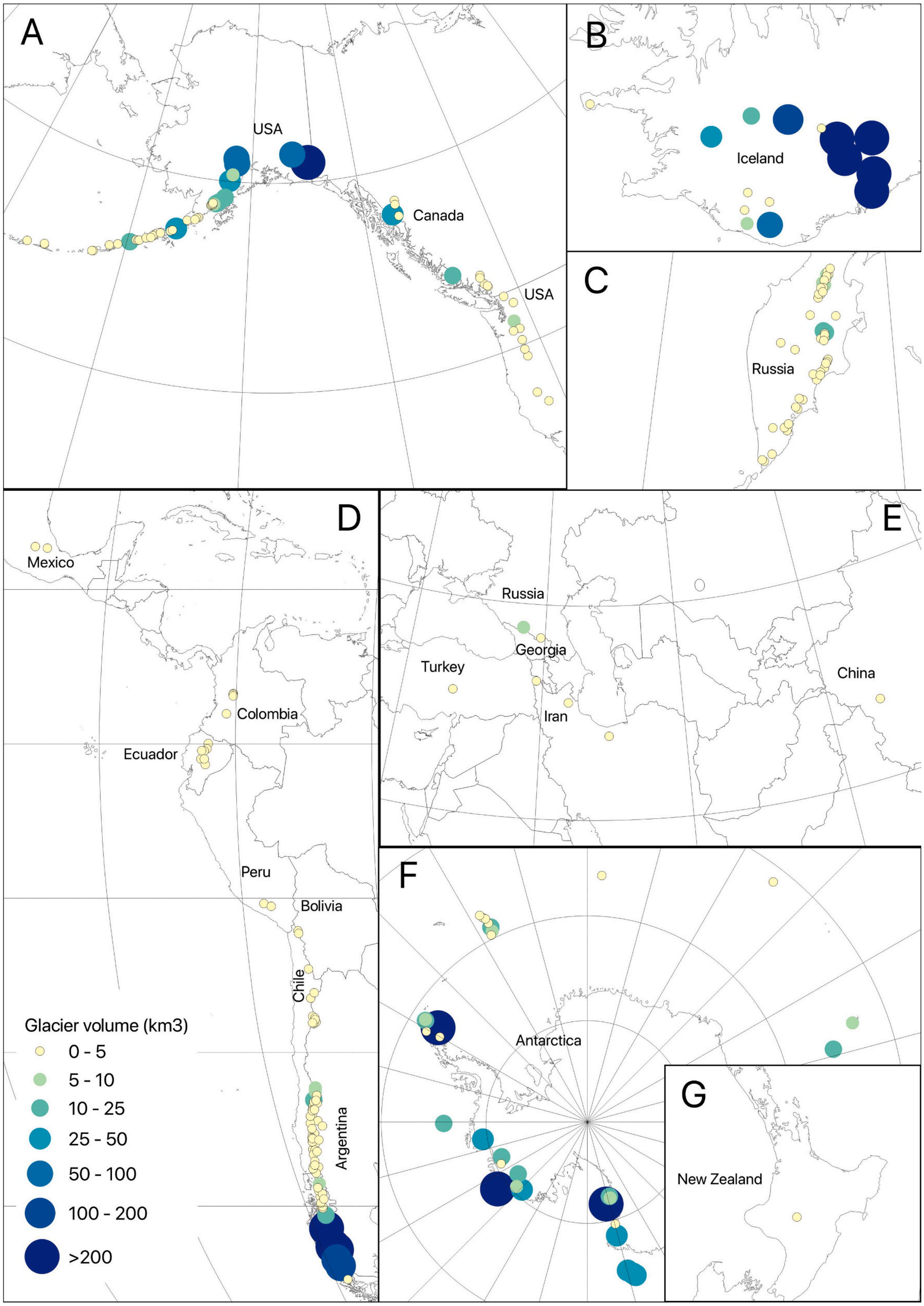

Fig. 5. Global distributions of estimated volumes from Farinotti et al. (2019) of glaciers on volcanoes in the database. Panels are for different geographic areas and cover all glacierized volcanoes: (A) Western U.S., (B) Iceland, (C) Kamchatka, Russia, (D) Central and South America, (E) Eurasia, (F) Antarctica, (G) New Zealand. Glacier volumes shown here are for the entire glacier, not just the portion within 5 km of the vent except in Antarctica where ice sheet volume is within 5 km.

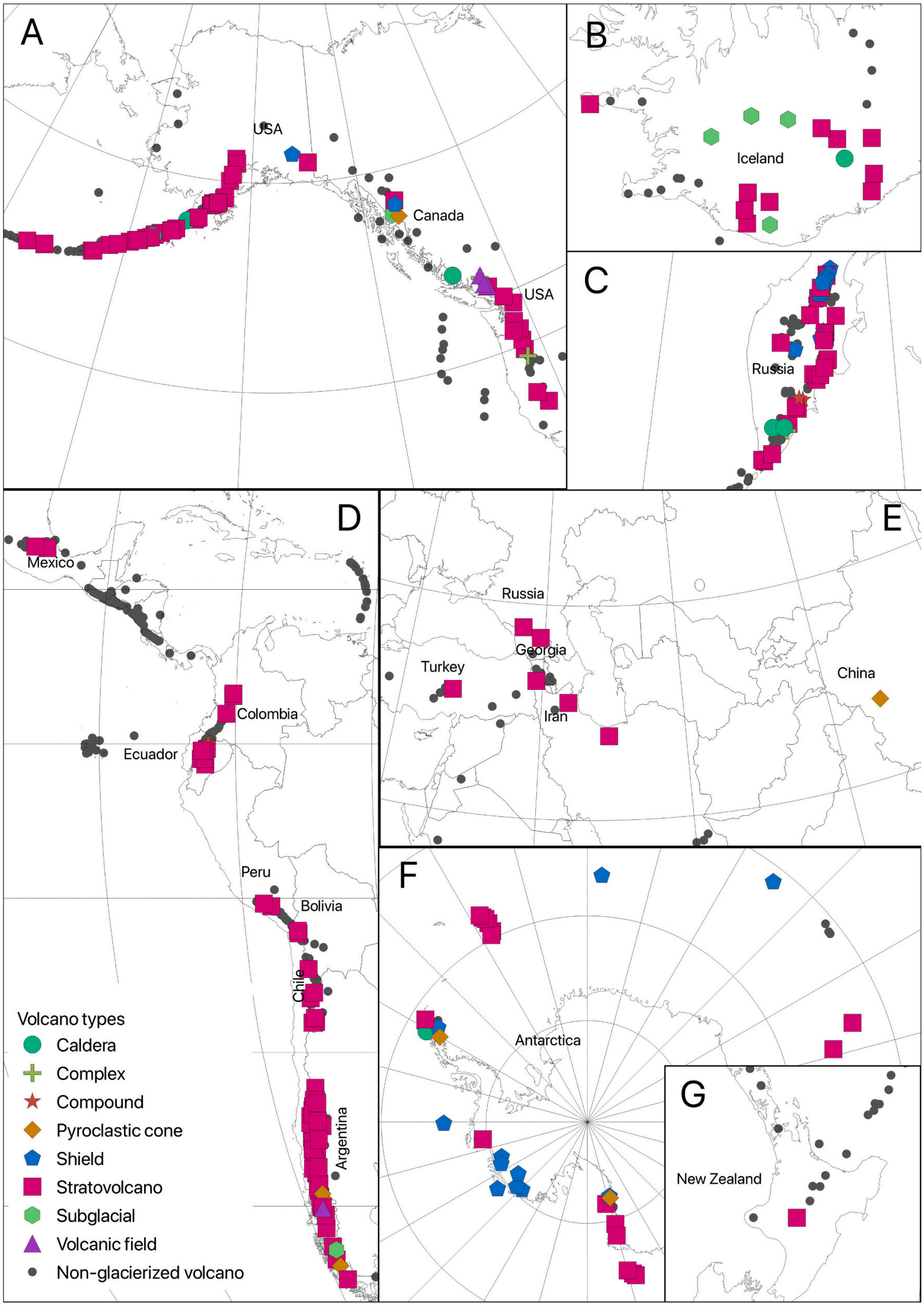

Fig. 6. Global distributions of glacierized volcanoes in the database categorized by types of volcanoes. Panels are for different geographic areas and cover all glacierized volcanoes: (A) Western U.S., (B) Iceland, (C) Kamchatka, Russia, (D) Central and South America, (E) Eurasia, (F) Antarctica , (G) New Zealand.

To calculate the volume of ice on each volcano, we used the Farinotti et al. (2019) global consensus estimate on individual glacier thickness (Fig. 4). We integrated the thickness of all the glaciers on volcanoes to calculate the total volume of each glacier within 5 km of a volcano (Fig. 5. We did this integration in each UTM zone specific to each glacier. Because Farinotti et al. (2019) present thickness estimates that are reasonably appropriate for the entire glacier, but not accurate for point measurements, we calculated the volume of every glacier within 1, 2.5, and 5 km by assuming the fraction of the glacier area covered by each buffer is proportional to the glacier volume. Farinotti et al. (2019) report a 26% uncertainty in their global estimate. Since they do not provide uncertainties at smaller scales, we assume the same uncertainty for the net volume, although individual glaciers likely have greater variability. To estimate the volume of ice around volcanoes under the Antarctic Ice Sheet we used Bedmap2 from Fretwell et al. (2013) in the same way we used the Farinotti et al. (2019) dataset.

To calculate the number of people living around each volcano, we used the Landscan 2018 dataset to compute the total number of inhabitants within a 5, 10, 30, and 100 km buffer using PostGIS.

We exclude all submarine volcanoes from our analysis, even though some are within 5 km of the Antarctic Ice Sheet and could come in contact with ice (e.g. volcano near Drygalski Ice Tongue). We assume all documented Holocene volcanoes under the Antarctic Ice Sheet are entirely covered by ice within 5 km. Our database is available as a supplemental file.

3. Results

3.1. Regional settings

A total of 217 volcanoes have ice within 1 km of the vent as defined by the SGVD, making up 416 km^2 of ice around the world. An additional 11 volcanoes have ice within 2.5 km, for a total of 2139 km^2. In all, 235 Holocene volcanoes in the SGVD have glaciers and 10 Holocene volcanoes in the SGVD are under the Antarctic Ice Sheet within a 5 km radius of their vents, for a total of 6192 km^2 of ice (Fig. 3c). We find glacierized Holocene volcanoes on every continent except Africa (Kilimanjaro has not had a documented Holocene eruption). Geographic areas (as defined by the SGVD) with glacierized volcanoes include Alaska (44), Antarctica (28), Atlantic Ocean (1), Canada and Western USA (20), Iceland and Arctic Ocean (16), Kamchatka and Mainland Asia (48), Mexico and Central America (2), Mediterranean and Western Asia (4), Middle East and Indian Ocean (5), New Zealand (1), and South America (76; Fig. 3c).

A total of 837 glaciers (excluding Antarctic Ice Sheet) are most vulnerable to a volcanic event as they exist within 1 km of a vent identified by SGVD. An additional 748 glaciers exist within 2.5 km of a vent (totaling 1943 km^2 of ice). In all, 2584 individual glaciers are within 5 km of a volcano for a total of 5407 km^2 of glacier ice. An additional 785 km^2 of ice rests on top 10 volcanoes beneath the Antarctic Ice Sheet.

3.2. Volcano types, rock composition, and eruptions

Glaciers occur on a broad range of volcano types, including small volcanic cones (9), stratovolcanoes (172), shield volcanoes (30), calderas (13), and other (21, including lava domes; Fig. 6). They also occur across tectonic settings including intraplate (34), rift zones (21), and subduction zones (190). Tropical glaciers only appear on volcanoes in subduction zones, which are all stratovolcanoes. Glacierized volcanoes span the full range igneous rocks, from felsic (25; dacite to rhyolite) to intermediate (132; andesite/basaltic andesite, trachyandesite, trachyte, phonolite) to mafic (78; basalt/picro-basalt). This classification is important for being able to identify volcanoes where more fluid, mafic lava flows are likely to erupt and produce focused but rapid melting of ice (e.g., Villarrica and Llaima, both in Chile) and felsic volcanoes where more explosive eruptions are likely and might produce larger lahars and more significant damage to surrounding glaciers (e.g., Mt. St. Helens). While many of the volcanoes in the database have limited records of Holocene activity, like Maipo volcano which has only been observed degassing, other volcanoes like Nevado del Ruiz have produced a broad range of eruptive activity including lava flows, pyroclastic density currents, phreatic activity, lava dome extrusion, debris avalanches, ash fall and lahars (volcanic mudflows) (Global Volcanism Program, 2013). A total of 1726 Holocene eruptions have been documented at these 235 volcanoes, with almost half of those having some sort of historical documentation. Villarrica volcano in Chile has the most documented Holocene eruptions in the database ($n = 152$), followed by Katla in Iceland ($n = 128$).

3.3. Volcanic explosivity index of glacierized volcanoes

Estimates of the Volcanic Explosivity Index (VEI; Newhall and Self, 1982), which is an index that is used to characterize the magnitude of an eruption and is included in the SGVD, are available for about 64% of the reported Holocene eruptions (1102 out of 1726). Lower values of the VEI (0–2) indicate eruptions that are likely to mainly have local impacts on surrounding glaciers, which can still create significant local hazards but which are not likely to cause widespread damage to surrounding glaciers. The largest reported VEIs from glacierized volcanoes in our database are 5 and 6, both of which characterize eruptions that produced more than 1 cubic kilometer of volcanic materials (lava and/or tephra) and likely Plinian eruptions, like the 18 May 1980 eruption at Mt. St. Helens (Lipman and Mullineaux, 1981). These large eruptions have the ability to almost instantaneously obliterate surrounding ice and cause significant damage to surviving glaciers. Only nine glacierized volcanoes are known to have had eruptions with Volcanic Explosivity Indices (VEI) of 6 (Aniachak, Bardarbunga, Churchill, Grimsvötn, Hudson, Michinmahuida, Mt. St. Helens, Novarupta, Veniaminof), all of which except the two Icelandic volcanoes (Bardarbunga and Grimsvötn) are in subduction zones. Another 47 eruptions have been documented with a VEI of 5 from 25 different volcanoes. Two of those, Hudson and MSH, have had a combined total of 11 documented Holocene eruptions with VEIs of 5 or 6.

3.4. Ice thickness and volume

Our database includes average ice thicknesses derived from the

Table 1
Glacier volume by region and globally. Glacier volume (km^3) calculated from average thickness at each buffer distance from mapped volcanic vent for each region. Uncertainties are propagated from Farinotti et al. (2019) with 26% uncertainty.

Region	Volume within 1 km	Volume within 2.5 km	Volume within 5 km
Alaska	7.9 ± 2.1	49 ± 13	160 ± 43
Antarctica (ice sheet)	3.3 ± 1.5	27 ± 16	160 ± 110
Antarctica (outside the ice sheet)	5.7 ± 1.5	33 ± 8.5	110 ± 29
Atlantic Ocean	0.24 ± 0.060	1.3 ± 0.34	3.4 ± 0.88
Canada and Western USA	1.7 ± 0.45	8.7 ± 2.3	24 ± 6.1
Iceland and Arctic Ocean	7.0 ± 1.8	41 ± 11	165 ± 43
Kamchatka and Mainland Asia	2.2 ± 0.57	12 ± 3.2	37 ± 9.5
Mediterranean and Western Asia	0.48 ± 0.13	2.3 ± 0.60	6.6 ± 1.7
Mexico and Central America	0.040 ± 0.010	0.050 ± 0.010	0.050 ± 0.010
Middle East and Indian Ocean	0.75 ± 0.19	3.9 ± 1.0	12 ± 3.0
New Zealand to Fiji	0.14 ± 0.040	0.39 ± 0.10	0.39 ± 0.10
South America	10 ± 2.7	54 ± 14	160 ± 42
Global totals	40 ± 11	230 ± 70	850 ± 290

Table 2
Estimated global population around glacierized volcanoes based on LANDSCAN 2018 data (population within specified distance). See Fig. 7 for a map of these data.

Distance (diameter in km)	5	10	30	100
Estimated population	20,000	140,000	6,700,000	160,000,000

Farinotti et al. (2019) model results (Fig. 4). Twenty of the volcanoes have estimated ice thicknesses that are greater than 200 m, and most of those are located in Iceland ($n = 7$), Antarctica (n = 7), and Chile ($n = 4$). Another 39 volcanoes host glaciers with average ice thicknesses of 100 to 200 m. Based on the Farinotti et al. (2019) dataset the large majority (79%) of glacierized volcanoes have ice with average thicknesses of less than 100 m (186 of 235).

We find a total volume of 850 ± 290 km^3 of glacier ice with 5 km of a SGVD vent, with a much larger volume of glacier ice (9200 ± 2400 km^3) contained in glaciers whose perimeters at least partially intersect the 5 km buffer surrounding a mapped volcanic vent and so could be indirectly impacted by future eruptions. An additional 160 ± 110 km^3 of ice are located within 5 km of a volcano on the Antarctic Ice Sheet. Iceland, Alaska, and South American are tied for the regions with the most ice volume on volcanoes within 5 km (Table 1; excluding the Antarctic Ice Sheet; Fig. 5) but South America has the most ice volume within 1 km of a vent. This is due to the high number of glacierized volcanoes in South America (76), which is nearly double the number in the next most numerous region.

3.5. Population centers near glacierized volcanoes

Approximately 167 million people live within 100 km of a glacierized volcano (Table 2), potentially putting them at risk from hazards of future eruptions. For example, 30 million people live within 100 km of Iztaccihuatl, in Mexico, the most of any glacierized volcano, although Iztaccihuatl ranks 213th out of 235 volcanoes with respect to ice volume and so may not pose a great threat to the inhabitants of nearby Mexico City (Fig. 7).. A more widespread risk to large populations is from lahars generated during glaciovolcanic eruptions, which can travel 10's of km from the vent. For example, Nevado del Ruiz has 500,000 people living within 30 km (Fig. 7). Some of the catastrophic lahars produced by a relatively small eruption of this volcano in 1985 traveled more than 50 km from their summit starting points, and caused more than 23,000 fatalities (Major and Newhall, 1989; Naranjo et al., 1986). Fortunately, the three volcanoes that host the highest volume of ice (all in Iceland) do not have any permanent residents within 30 km (Fig. 7), even though large lahars or floods produced from eruptions at these volcanoes do have the potential to damage infrastructure such as roads (Larsen and Guðmundsson, 2016). This highlights the inverse relationship between glacier volume and population. Even small settlements near voluminous glaciers on volcanoes do not exist on Earth.

4. Discussion

4.1. Importance of projections

How global data are projected onto a plane is fundamentally important because the world is a spheroid and incorrect projection choices can lead to large uncertainties (Battersby et al., 2016). To demonstrate this point, we provide an example from Mt. Edziza, British Columbia, Canada (Fig. 8). Using a geographic projection, such as WGS84, to calculate the area of ice within our chosen radii of an edifice vent location can lead to substantial errors. For Mt. Edziza we find that a WGS84 projection overestimated glacier area within 5 km by 19% when compared to area calculations using the local UTM projection (Fig. 8). This error is exacerbated for north-south trending glacier-volcano complexes near the poles.

Other studies have suffered from not properly addressing and/or explaining the global projections used to construct their analyses. Curtis and Kyle (2017) provide the most comparable database to ours, although their goals were different. However, studies like this that do not calculate buffers on the spheroid cannot accurately map the spatial relationship of these features. Future studies, combining these databases and others, must do these calculations on the spheroid to ensure their accuracy.

4.2. Strengths and weaknesses of input datasets

We combine the RGI and SGVD datasets to calculate the glacierized area of each volcano on Earth. While these datasets are both unique and the only such available sources, several improvements are still needed for a more robust global glaciovolcanism database. The RGI dataset is the only source that maps every glacier on Earth (GLIMS does this as well and is a related data source with different temporal attributes; Pfeffer et al., 2014). The RGI comprises contributions from a number of different users, which is a necessity given the need to digitize ~215,000 glaciers on Earth. As such, RGI has two main shortcomings. First, it is poorly temporally controlled. As glacier boundaries are changing in the face of current global warming, the glacier outlines are also changing. While RGI aims for outlines from ~2000 CE, this is not always the case (Pfeffer et al., 2014). Second, RGI relies on community members to accurately interpret glacier outlines, which leads to errors and inconsistencies. This is particularly true for debris covered ice and may be more problematic for glaciers on volcanoes given the higher probability of being covered in volcanic ash. This is also true for snow cover, as discerning snow versus glacier can be challenging when not using the most appropriate imagery (Kochtitzky and Edwards, 2020). Determining glacier outlines is particularly challenging in low latitudes, where snowfall can be unpredictable. The RGI database will continue to improve with each iteration, providing new opportunities to improve this glacierized volcano database. Even though RGI has some weaknesses, it is the only source of global glacier boundaries and is subregionally accurate.

The SGVD database mainly suffers from the complexity of volcanoes and its need to assign one geographic coordinate to each volcano (Siebert et al., 2010). While the SGVD has gone through multiple iterations, each one improving the accuracy of locations and the number of Holocene volcanoes, larger volcanic complexes can have multiple vents that are separated by distances of several kilometers (Siebert et al., 2010). Because all of our buffers are centered around the point in the SGVD, our analysis will be particularly sensitive to future changes in vent location in the SGVD. Our database may not accurately capture the exact glacier area and volume that is most likely to be impacted by future volcanic events, particularly among large volcanic centers where the edifice may be more than 5 km long (e.g., Mount Edziza; Fig. 8).

The consensus modeled glacier thickness estimates by Farinotti et al. (2019) currently represent the glaciology community's best estimate of glacier thickness. However, the accuracy of these estimates varies significantly. We compared all of the glacier thickness estimates made by in situ measurements in the GlaThiDa thickness dataset (Gärtner-Roer et al., 2014) with the predicted thicknesses from Farinotti et al. (2019) for volcanoes in our database (Fig. 9). The GlaThiDa dataset only covered glaciers for volcanoes in Chile, Washington State, Columbia and Antarctica. Comparing GlaThiDa and Farinotti et al. (2019) we find that the modeled thickness results overestimate observed glacier thickness by an average of 81% (Fig. 9a). For some volcanoes, such as Mt. Baker in the Cascade volcanic arc, the match between observed and modeled thicknesses are better (Fig. 9b). But, for at least one, Beerenberg volcano on Jan Mayen Island, the Farinotti et al. (2019) thickness estimates were non-sensical, with predicted thicknesses of less than 1 m (Fig. 9c). It is unclear why the difference is so large and if this pattern holds for other glaciers on volcanoes. We need more in situ thickness observations on glaciers around the world, but particularly on volcanoes, to improve

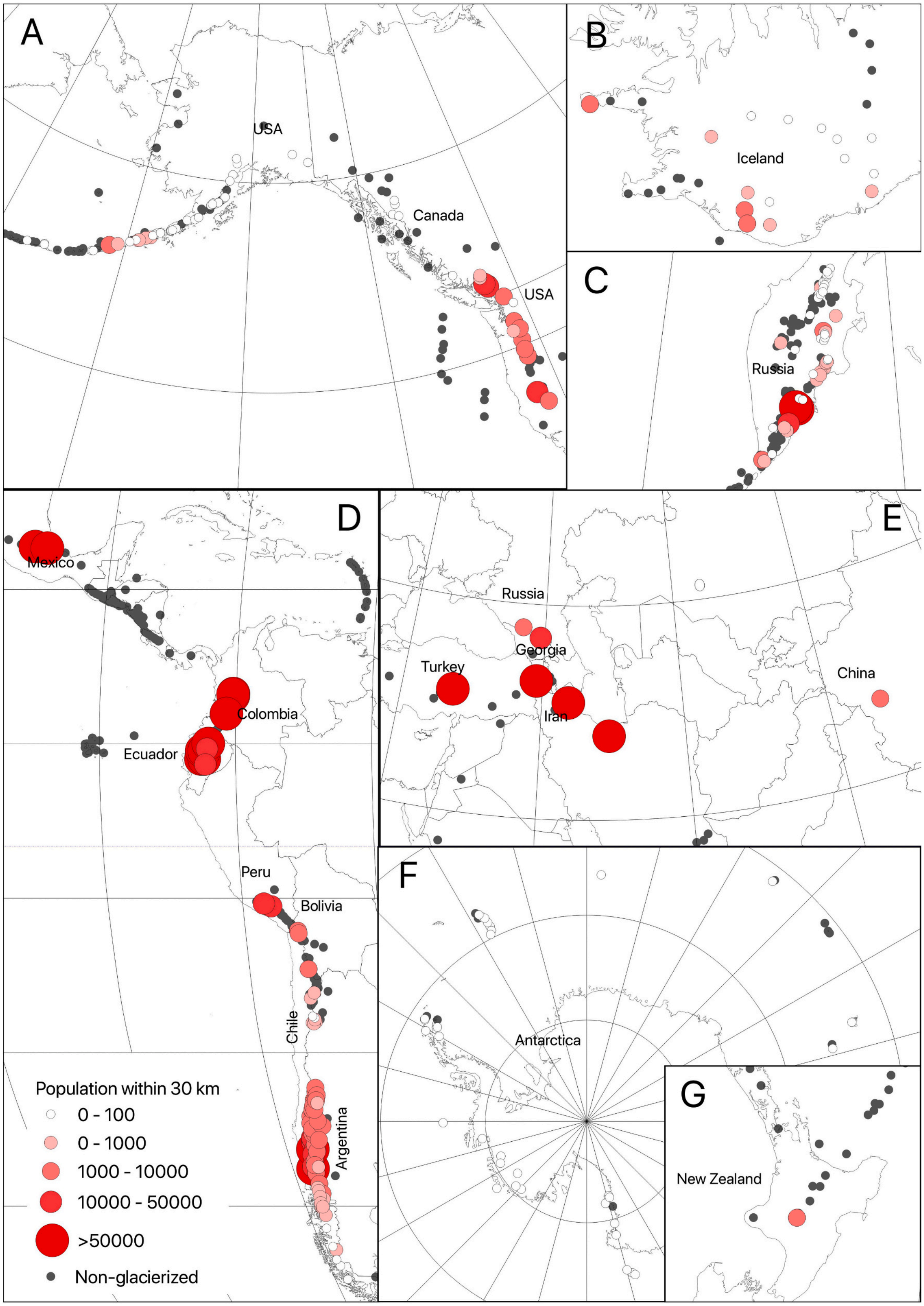

Fig. 7. Global population within 30 km of glacierized volcanoes. (A) Western U.S., (B) Iceland, (C) Kamchatka, Russia, (D) Central and South America, (E) Eurasia, (F) Antarctica, (G) New Zealand.

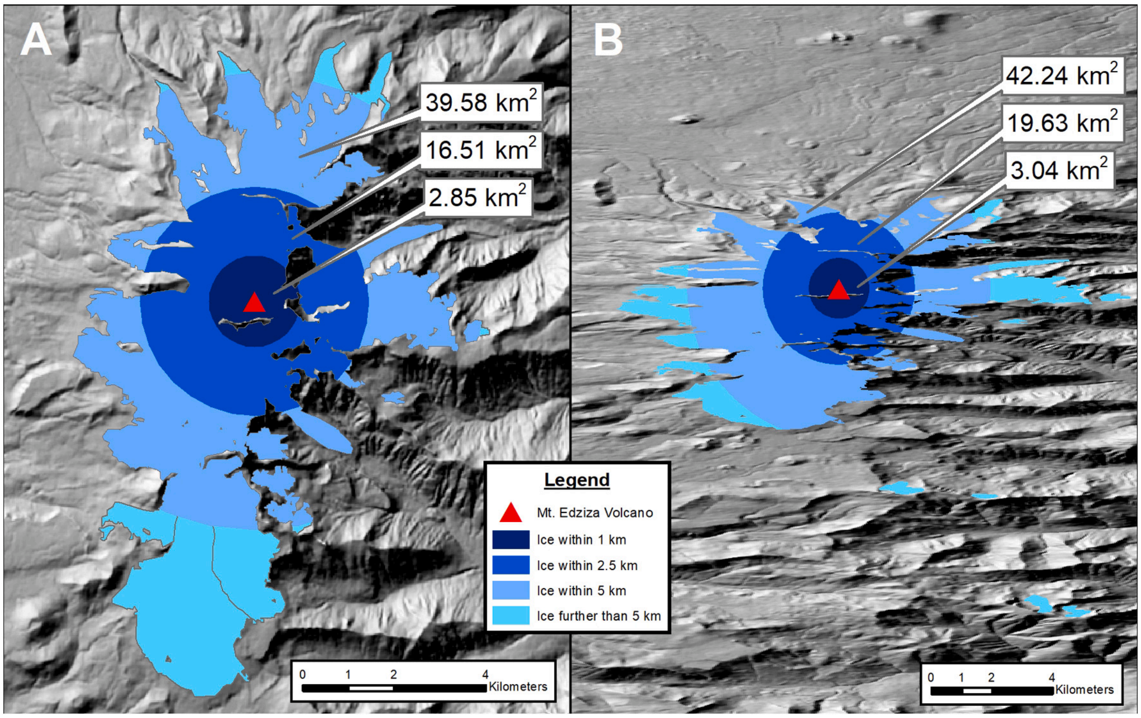

Fig. 8. Maps illustrating the importance of projections using Mount Edziza, BC, Canada as an example. (A) Our database projected in UTM 9 N. (B) Buffer done in WGS84 and clipped to RGI6.0 ice outlines.

thickness estimates and hazard predictions.

Area-volume scaling relationships have been developed to quantify regional glacier volume from regional glacier area (Bahr et al., 2015). We calculated the global volume of ice on volcanoes using the volume-area scaling law (Eq. 1)

$$V_{total} = cA^{\gamma}_{total} \tag{1}$$

where V is the glacier volume, c is the scaling parameter (we use the worldwide mean of 0.034 $km^{3-2\gamma}$ from Bahr et al. (2015)), A is the glacier area, and γ is a constant (we use a theoretical value of 1.375 from Bahr et al. (2015)). This assumes that glaciers on volcanoes are not systemically different in their flow characteristics than other glaciers. Using this scaling law we find approximately 4620 km^3 of glacier ice within 5 km of all volcanoes (excluding the Antarctic Ice Sheet), which is more than four times our volume estimate made using the Farinotti et al. (2019) data (See Table 1). This almost certainly is an overestimate, as it would indicate that ice thickness would be 850 m on average, which is more than three times the modeled average thickness estimate of 271 ± 70 m by Farinotti et al. (2019). This suggests that glaciers on volcanoes are morphologically distinct from the average glacier and merits further investigation.

One of the unique aspects of glacierized volcanoes is that they can have a range of summit morphologies, each of which has different implications for glacier thickness (Fig. 10). The most abundant volcanoes in our database are stratovolcanoes, which typically have morphologies that steepen with increasing elevation. For these volcanoes, such as Mt. Baker (Fig. 10a), glaciers are relatively thin due to the steepness of their slopes. A smaller number of glacierized stratovolcanoes have the morphology of the flat-topped tuyas (e.g. Fig. 1a), and these can host somewhat thicker glaciers on their broader and less-steep summits (Fig. 10b). The most complicated ice thickness configurations are for calderas, such as Katla volcano in Iceland (Fig. 10c). There, the much broader summits with elevated topography bounding some or all of the caldera rims, allow for the existence of much thicker ice (over 500 m locally).

4.3. Integration with existing datasets

We find good agreement between our database and other similar databases. Major and Newhall (1989) discussed hazards from volcano-ice interactions with a focus on the generation of lahars. They compiled information on volcanoes with historical eruptions that encountered snow or ice including nine volcanoes in the US, nine in South America, four in Iceland, two in Russia, and one each in the southern Indian Ocean, Antarctica, New Zealand, and Jan Mayen; all of these are identified by our new inventory, indicating they are still glacierized. Curtis and Kyle (2017) mapped 254 volcanoes within 10 km of a glacier, compared to our 235 within 5 km of glacier ice. It is difficult for us to directly compare our results to Curtis and Kyle (2017), because they do not provide details about how they handled projections and the goals of their study were different. They primarily focused on the methods to monitor changes and associated hazards of volcano-ice interactions, including in areas of permafrost with the goal of monitoring volcano-cryosphere interactions in near real-time. They suggest using existing satellites for near real-time monitoring (e.g., MIROVA project) of glacierized volcanoes. Barr et al. (2018) provide a global analysis of the 56 glacierized volcanoes that have erupted 1800 CE with a focus on the glaciological impact of eruptions at those specific sites. While some of the volcanoes differ in name between our two databases, 54 of their volcanoes also appear in our database. The remaining two, Chaitén and Gjálp fissure are not in our database. Chaitén is not presently glacierized, although the nearby Michinmahuida presently hosts 15 glaciers, which were referenced in Barr et al. (2018). The Gjálp fissure is a flank fissure between Bardarbunga and Grimsvötn central volcanoes, and not considered to be its own volcano (Guðmundsson et al., 2004; Sigmarsson et al., 2000).

Our database provides a list of glaciovolcanic hotspots around the world that need to be further investigated and monitored for hazards. For example, Edwards et al. (2015a, 2015b) divided glaciovolcanic eruptions into four different groups: Class 1A ('thick' ice greater than 500 m), Class 1B ('thin' ice less than 500 m), Class 2 (pyroclastic density currents and debris avalanches on top of ice), and Class 3 (lava-ice

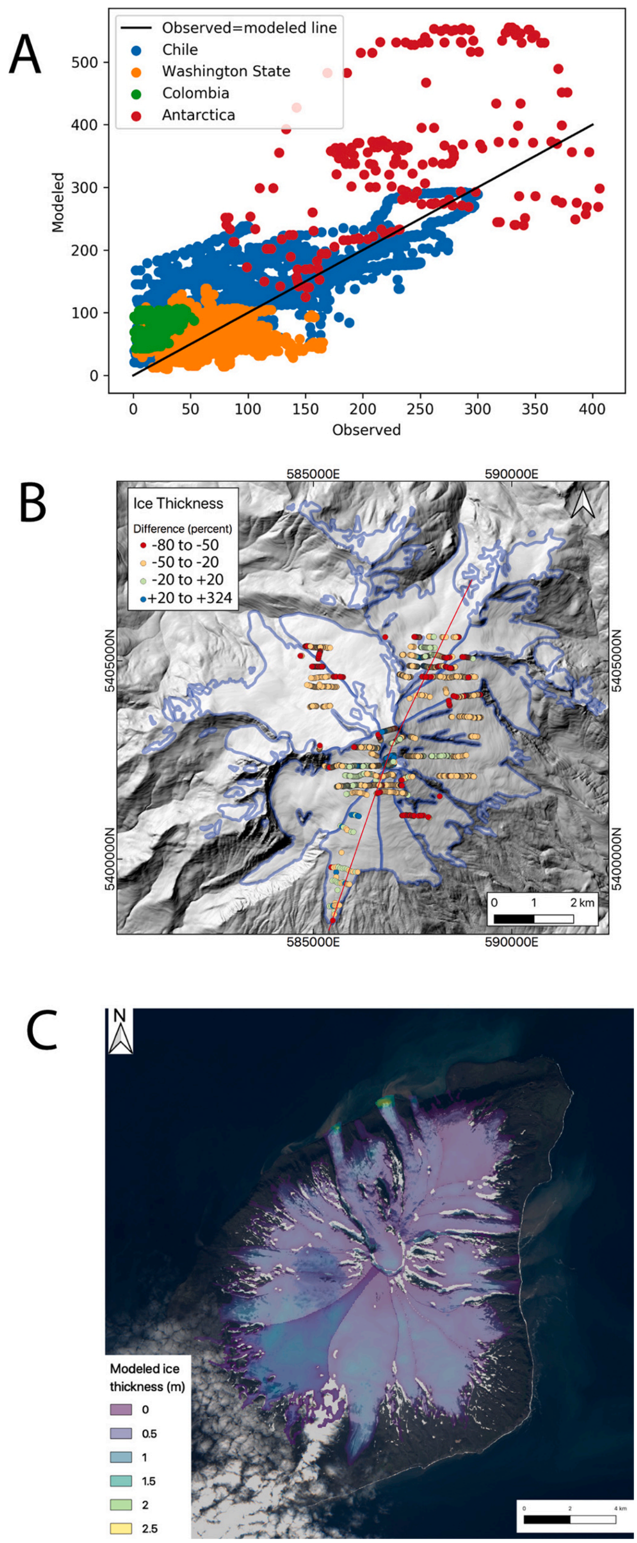

Fig. 9. Limitations on estimates for ice thicknesses from Farinotti et al. (2019). A. Observed versus modeled ice thicknesses for glaciers on volcanoes in four different regions: Chile, Washington State, U.S.A., Columbia, and Antarctica. Black line shows one-to-one correlation. B. Example from Mt. Baker volcano in Washington State U.S.A. showing the percent difference between modeled and observed ice thicknesses. C. Example from Jan Mayen Island, Norway, highlighting an extreme example of flaws in Farinotti et al. (2019) thickness estimates where ice thickness is estimated to be less than 3 m.

contact, sometimes resulting in lava flow travelling below ice). With the new database we can predict globally where we expect each of these different styles of eruption based on ice thickness and volcano type (Fig. 11). Given the uncertainties in thickness estimates, we have a subdivided average ice thickness into four ranges (0–100 m, 100–200 m, 200–400 m, 400–600 m). Even with errors of greater than 80% for some of the Farinotti et al. (2019) thickness estimates, probably most of the volcanoes with average thicknesses of less than 200 m will experience Class 2 eruptions, where volcanic debris is deposited on top of surrounding ice. These types of eruptions can be very dangerous, and included in this Class is the 1985 eruption of Nevado del Ruiz in Columbia, which resulted in over 20,000 fatalities from lahars generated by snow and ice melting from pyroclastic density currents that traveled across the surfaces of summit glaciers (Naranjo et al., 1986). At the other end of the ice thickness spectrum, Class 1A eruptions beneath thick ice are most likely at volcanoes from the 400–600 m range, although with the noted uncertainties it may well include some in the 200–400 m range also. As with the 1996 Gjálp eruption in Iceland, which melted through more than 600 m of ice (Guðmundsson et al., 2004), thick ice eruptions likely could take more than a day to melt through the overlying ice, which also means they can melt a substantial volume of ice. Thick ice eruptions are more likely to result in at least short-term storage of water within the glacier, which can subsequently be released to generate massive floods (called 'jökulhlaups' in Icelandic). This database allows for predictive mapping of volcanoes where these different classes of eruptions are most likely around the world, to warn vulnerable populations of future glaciovolcanic events, particularly with additional high-resolution elevation models. Curtis and Kyle (2017) describe methods that are appropriate for this type of monitoring. Because glaciers are unlikely to dramatically change on annual timescales (except in rare cases such as surge type glaciers), our database can serve as a hazard warning list and can be updated with each iteration of the RGI. The 56 volcanoes with glaciovolcanic activity since 1800 identified by Barr et al. (2018) provide a list of priority areas to study the impacts of volcanism on glaciers around the world.

4.4. *Impacts of glaciers on future eruptions*

While an increasing number of studies are examining links between global climate and volcanism (Huybers and Langmuir, 2009; Watt et al., 2013; Edwards et al., 2020), most of the hypotheses are still being tested. In Iceland, Schmidt et al. (2013) have proposed that rapid late Holocene deglaciation may be contributing to magma generation at some volcanoes, while preliminary studies from Chile have so far not found evidence for connections between glaciations and melt production but have suggested that changes in crustal stresses could impact tapping of magmas stored in the crust (Rawson et al., 2016). The potential impacts for volcanic hazards are mixed as rising air temperatures lead to a negative glacier mass balance. For example, while mass loss may cause changes to crustal stresses that make existing magma storage systems less stable, less ice may lower the potential for and/or volume of lahars and floods to be generated during future glaciovolcanic eruptions. On the other hand, melting of glaciers that are buttressing over-steepened volcanic flanks could increase the possibility of large mass wasting events.

This new database allows us to find volcanoes where the intersection of volcano-type and ice thickness may be cause to focus on different expected outcomes. Thus, our new inventory of glacierized volcanoes is critical for tracking these competing processes as climate change continues to impact glacier mass balance.

4.5. *Most dangerous glacierized volcanoes*

The combination of information in our new database is unique, and allows us to better understand how the distributions of glaciers, volcanoes and population intersect globally (Fig. 12). Human populations

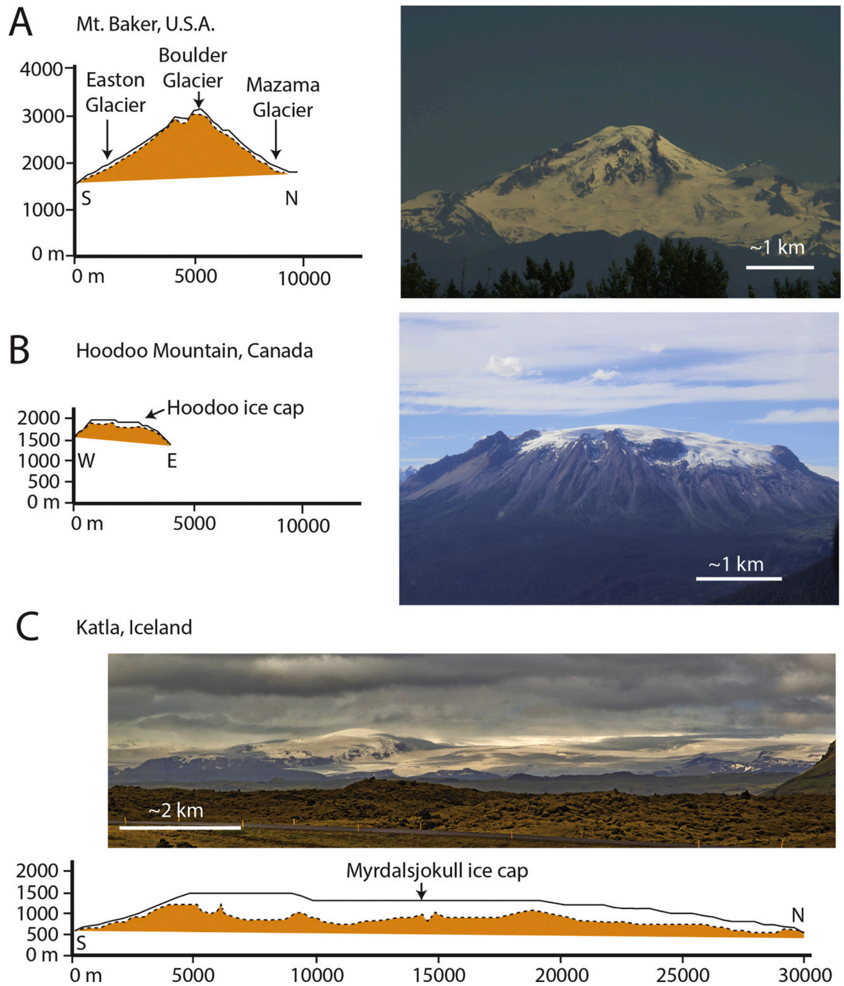

Fig. 10. Examples of some different glacier morphologies at glacierized volcanoes. A. Mount Baker in Washington State U.S.A. has a laterally extensive but thin ice cover. B. Hoodoo Mountain volcano in western British Columbia has a relatively thin ice cap on its flat summit. C. Katla volcano in south-central Iceland has thick ice cover that fills in the summit caldera. Scales in all images are approximate do not apply to the foreground.

tend to be relatively low around high latitude volcanoes (Fig. 12a), while those same high latitude volcanoes also have ice volumes that are 1–2 orders of magnitude larger than mid- and low-latitude volcanoes (Fig. 12b). About 50% of the volcanoes we have identified have more than 100 people living within 30 km (124/245) and roughly half of those volcanoes have five or more documented eruptions (41/74; Fig. 12c).

To understand which volcanoes in our new database are among the most dangerous, we ranked (1 most, 245 least) each volcano based on ice volume, number of observed eruptions (SGVD data), and 2018 Landscan estimates for population within 30 km. We added the three rankings to generate a 'danger rank' for each volcano (Table 3). We find that the top ten most dangerous volcanoes based on this ranking are Villarrica (Chile), Katla (Iceland), Llaima (Chile), Tupungatito (Chile-Argentina), Nevado del Ruiz (Columbia), Cotopaxi (Ecuador), Cayambe (Ecuador), Rainier (U.S.A.), San Jose (Chile-Argentina), and Makushin (U.S.A.). Inclusion of Nevado del Ruiz in the top ten (number 5; Table 3) is a partial validation of the simple ranking scheme since it produced the most-deadly glaciovolcanic eruption in modern history, and at least two other volcanoes in the top ten have had fatality-producing eruptions in historic times (Major and Newhall, 1989). Another six volcanoes in the database, Elbrus (Russia), Palomo (Chile), Ushkovsky (Russia), Viedma (Argentina), Coropuna (Peru), Kazbek (Georgia), have not had a documented Holocene eruption, but are all proximal to population centers and have a minimum average ice thickness of ~60 m (Table 3). If any of these six were to become active, they would also be considered very dangerous. Fortunately the volcanoes with the largest nearby populations, Iztaccihuatl (Mexico) and Erciyes Dagi (Turkey), have not had many eruptions and have small ice volumes. Similarly, the three volcanoes with the highest average ice thickness are all in Iceland (Bardabunga, Kverkfjöll, and Grimsvötn), which all have documented eruptions, but at most ~3000 people live within 100 km of them. Katla (Iceland) and Villarrica (Chile) have the most observed eruption (152 and 128, respectively), both of which make our most dangerous list. While glacierized volcanoes do pose substantial risk around the world, fortunately very few people (approximately hundreds of people) live near highly active glacierized volcanoes with thick ice.

5. Conclusions

We used unique local projections on the spheroid that minimize errors due to projection distortion to map every Holocene volcano on earth presently covered by a glacier or ice sheet. We find 245 Holocene volcanoes partially or fully covered by 2849 unique glaciers or the Antarctic Ice Sheet, totaling 850 ± 290 km^3 of ice within 5 km of a volcano. We find a total area of 6192 km^2 of ice within 5 km of global volcanoes, 416 km^2 of which is within 1 km of a mapped vent. This represents substantial hazards to surrounding populations from lava flows, ash, and lahars. In all, approximately 6.7 million people live with 30 km of a glacierized volcano, and 163 million people live within 100 km globally.

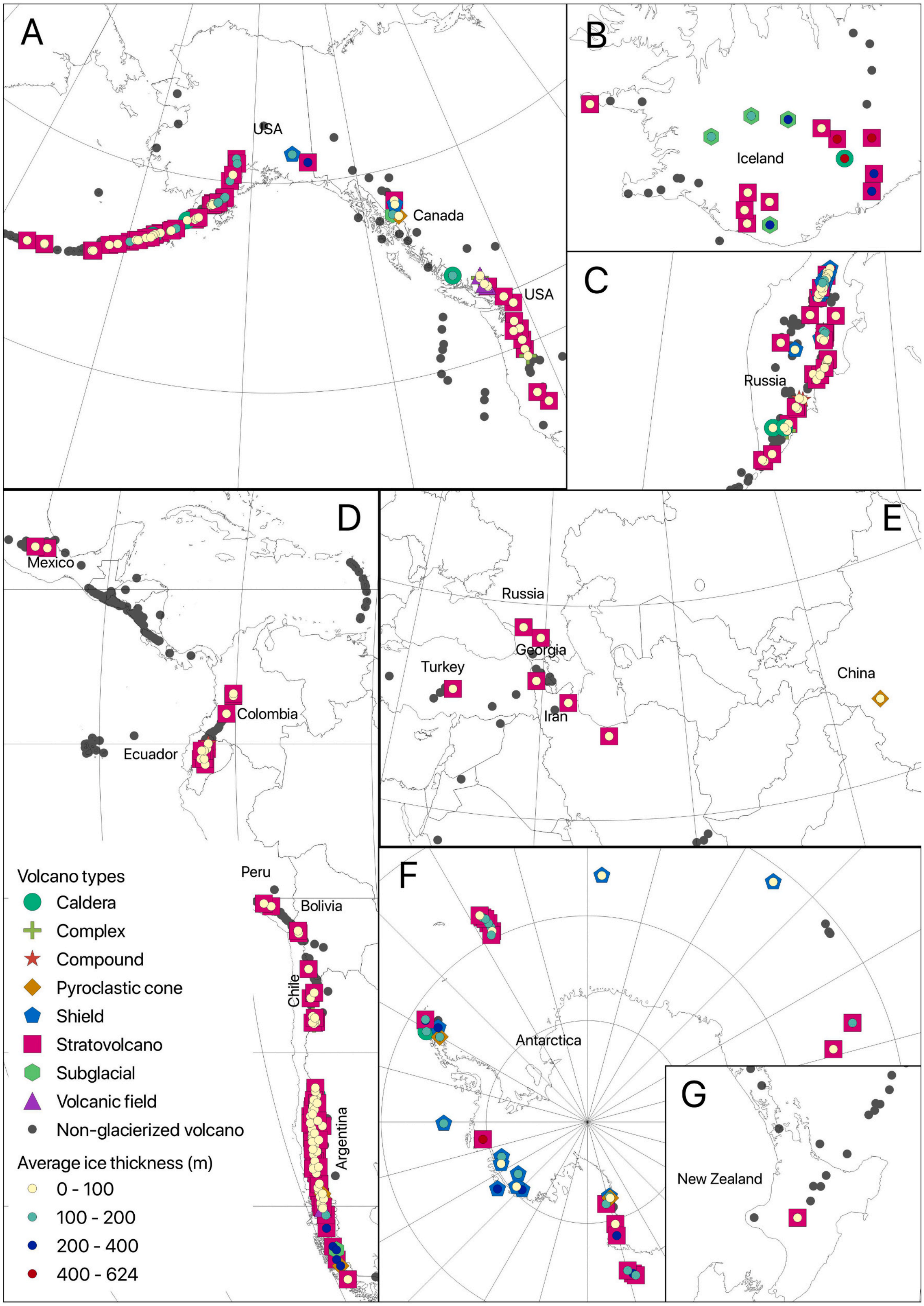

Fig. 11. Global distributions of volcano types and average ice thicknesses. Ice thickness estimates of Farinotti et al. (2019). Panels are for different geographic areas and cover all glacierized volcanoes: (A) Western U.S., (B) Iceland, (C) Kamchatka, Russia, (D) Central and South America, (E) Eurasia, (F) Antarctica, (G) New Zealand.

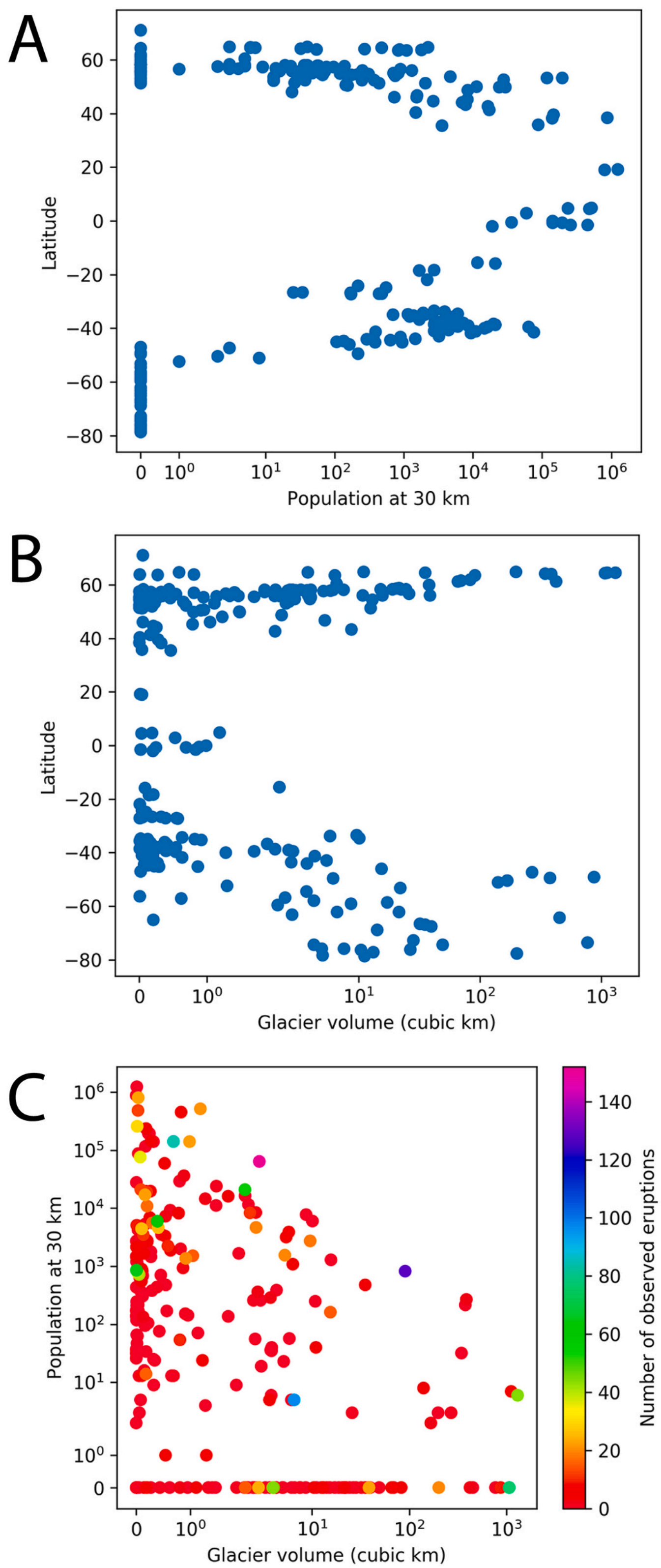

Fig. 12. Database parameters used to evaluate relative danger from eruptions at glacierized volcanoes. (A) Estimated human populations within 30 km of a glacierized volcano based on our analysis of the Landscan 2018 global population dataset as a function of volcano latitude. (B) Estimated glacier ice volumes on volcanos as a function of latitude. (C) Estimated human populations within 30 km of a glacierized volcano compared to estimated glacier ice volumes. Points are colored based on the number of documented Holocene eruptions at each volcano. Note that most axis are log scale.

Table 3
Ranking system used to identify the danger rank for glacierized volcanoes.

Volcano	Ice volume rank (out of 245)	30 km population rank (out of 245)	Eruptions rank*	Danger rank (out of 245)
Villarrica (Chile)	83	18	1	1
Katla (Iceland)	16	86	2	2
Llaima (Chile)	100	25	8	3
Tupungatito (Chile-Arg)	50	59	28	4
Nevado del Ruiz (Columbia)	116	4	23	5
Cotopaxi (Ecuador)	133	12	4	6
Cayambe (Ecuador)	120	13	21	7
Rainier (U.S.A.)	63	72	24	8
San Jose (Arg)	61	53	49	9
Makushin (U.S.A.)	88	49	27	10
Elbrus (Russia)	51	40	125	26
Palomo (Chile)	49	43	125	27
Ushkovksy (Russia)	38	77	125	46
Viedma (Arg)	9	111	125	50
Coropuna (Peru)	95	33	125	55
Kazbek (Georgia)	99	30	125	56

We used our newly compiled database to identify volcanoes where populations, glacier volumes and number of documented eruptions intersect and applied a simple ranking to locate the 10 most dangerous glacierized volcanoes on Earth.

Declaration of Competing Interest

We have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2020.103356.

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