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Contemporary movement of rock glaciers in the La Sal and Uinta Mountains, Utah, USA

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ABSTRACT

Rock glaciers are common landforms in mountainous areas of the western US. The motion of active rock glaciers is a key indicator of ice content, offering connections to climate and hydrologic systems. Here, we quantified the movement of six rock glaciers in the La Sal and Uinta Mountains of Utah through repeat differential GPS surveying. Networks of 10–41 points on each rock glacier were surveyed in September 2021; July 2022; September 2022; and July 2023. We found that all features are moving with average annual rates of motion from 1.5 ± 0.8 to 18.5 ± 7.5 cm/yr. Rock glaciers move up to 3× faster in the summer than in the winter, and rates of motion were greater in 2023 after a winter with above-average snowfall, emphasizing the role of liquid water availability. Velocities of individual points in the winter of 2021–22 are positively correlated with velocities during the winter of 2022–23, suggesting that spatial variability of motion is not stochastic, but rather reflects internal properties of each rock glacier. Bottom temperature of snow measurements during winter, and the temperature of springs discharging water in summer, suggest that these rock glaciers contain modern permafrost. Radiocarbon data document advance of one rock glacier during the Little Ice Age. Our GPS dataset reveals complicated patterns of rock glacier movement, and the network of survey points we established will be a valuable baseline for detecting future cryosphere change in these mountains.

1. Introduction

Rock glaciers are common landforms in periglacial mountain environments (Giardino et al., 1987). Unlike alpine glaciers formed through snow accumulation, rock glaciers are composed of a mixture of perennial ice, fine sediment, and rock debris (Wahrhaftig and Cox, 1959; Berthling, 2011). Some rock glaciers, apparently evolved from alpine glaciers that become completely buried by debris (Anderson et al., 2018), contain a massive ice core (Potter, 1972). Others consist of rocks cemented by interstitial ice, likely produced as liquid water infiltrates talus and freezes (Wayne, 1981). All rock glaciers are capable of moving slowly downslope through plastic deformation of ice and localized displacement along a shear plane near their base (Giardino, 1983; Giardino et al., 1992; Serrano et al., 2006; Krainer et al., 2015). Morphologically, rock glaciers are distinctive landforms, with surface slopes characterized by wavy ridges and furrows produced by folding, thrusting, and differential movement (Kääb and Weber, 2004; Leonard et al., 2005; Cicoira et al., 2021). Side slopes and termini of rock glaciers often stand at or above the angle of repose, reflecting the presence of cementing ice (RGIK, 2023a). Relatively fast moving rock glaciers are referred to as "active," whereas "relict" features have lost their internal ice and are currently stationary (Delaloye and Echelard, 2020). Rock glaciers with low velocities (<~1 m/yr), referred to as "transitional," may be accelerating in response to climatic forcing, or slowing down as they lose internal ice and become relict (Delaloye and Echelard, 2020).

Rock glaciers have been the focus of considerable research at the intersection of periglacial geomorphology, paleoclimatology, hydrology, and geoecology. Observational studies have established that rock glaciers are significant agents of debris transport in mountain geomorphic systems (Giardino and Vitek, 1988; Knight et al., 2019). Recent work has investigated how rock glaciers function as aquifers and impact the hydrology of mountain catchments (Geiger et al., 2014; Winkler et al., 2016; Liaudat et al., 2020; Wagner et al., 2020). Other efforts have attempted to quantify the amount of water stored within rock glaciers as perennial ice (Azócar and Brenning, 2010; Geiger et al., 2014; Rangecroft et al., 2015; Jones et al., 2019; Wagner et al., 2021), and

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considered hydrochemical evidence that ice melting is influencing the amount and properties of stream water in high mountain settings (Brighenti et al., 2021a; Colombo et al., 2023; Bearzot et al., 2023). The ice within rock glaciers also buffers thermal variations in adjacent streams and springs, creating unique micro-environments for cold-adapted plants and animals (Brighenti et al., 2021b). Some studies have investigated whether rock glaciers may provide critical habitats for cold-adapted organisms in the face of warming temperatures (Millar et al., 2015).

An additional motivation for studying rock glaciers, which is particularly relevant given rapid rates of contemporary climate change in mountain environments (Adler et al., 2022), is the climatic significance of these landforms (Humlum, 1998; Frauenfelder and Kääb, 2000). To form, rock glaciers require perennial ice, therefore, they are permafrost indicators (Haeberli, 1985; Janke, 2005b). In contrast to alpine glaciers, rock glaciers persist on the landscape as obvious landforms even after they are no longer moving (Colucci et al., 2019). Thus, analyzing the spatial distribution of relict rock glaciers can yield information about past climatic conditions (Millar and Westfall, 2008). Similarly, rock glaciers that are demonstrably moving are indicators of modern permafrost (Barsch, 1992; Haeberli, 2013). Monitoring the movement of these landforms is important for documenting how the mountain cryosphere is responding to changing climatic conditions (Bodin et al., 2009), and for predicting future infrastructure impacts and hazards associated with rock glacier advance (Schoeneich et al., 2015; Marcer et al., 2019, 2020).

Considerable research on rock glacier movement has been conducted in the European Alps, yielding summaries of rock glacier velocities (Francou and Reynaud, 1992; Berger et al., 2004; Krainer and He, 2006; Delaloye et al., 2010), and significant insight into mechanisms of rock glacier advance (Kääb and Reichmuth, 2005; Cicoira et al., 2021), temporal trends in movement (Scapozza et al., 2014; Kenner et al., 2017; Thibert and Bodin, 2022), correlations between velocity and meteorological conditions (Wirz et al., 2016), and the role of liquid water in governing movement (Cicoira et al., 2019), among other things. In contrast, in North America, although rock glaciers have been inventoried (Johnson et al., 2021) and investigated for decades (Wahrhaftig and Cox, 1959), focused studies of rock glacier movement are less numerous. In some of the most prominent published examples using ground-based observations, flow rates were reported for individual rock glaciers in Colorado (Benedict et al., 1986; Leonard et al., 2005; Janke, 2005a), Wyoming (Potter, 1972; Potter et al., 1998), and for sites in Canada (Sloan and Dyke, 1998; Koning and Smith, 1999). More recently, remote sensing has also been employed to quantify rock glacier motion at mountain range-wide scales in California (Liu et al., 2013) and in Utah (Brencher et al., 2021). Despite these efforts, questions remain about spatial patterns and temporal trends in rock glacier movement, and additional datapoints are required to establish baselines against which future changes can be evaluated.

The primary objective of this study was to quantify the motion of representative rock glaciers in two mountain ranges in Utah where previous work has considered rock glacier genesis, distribution, and hydrologic significance. The secondary objective was to establish a survey protocol that could be repeated to document rock glacier change in the future. We used real time kinematic GPS (RTK-GPS) (Lambiel and Delaloye, 2004) to document the displacement of boulders on rock glacier surfaces through two winter seasons and the intervening summer. We supplemented these GPS surveys with temperature measurements of the rock glacier surface and associated springs to infer the thermal state of the rock glacier interior.

2. Study area

This study focused on rock glaciers in two mountain ranges in Utah (Fig. 1) selected based on an abundance of prior work on rock glacier origin, distribution, morphology, and activity. The Uinta Mountains

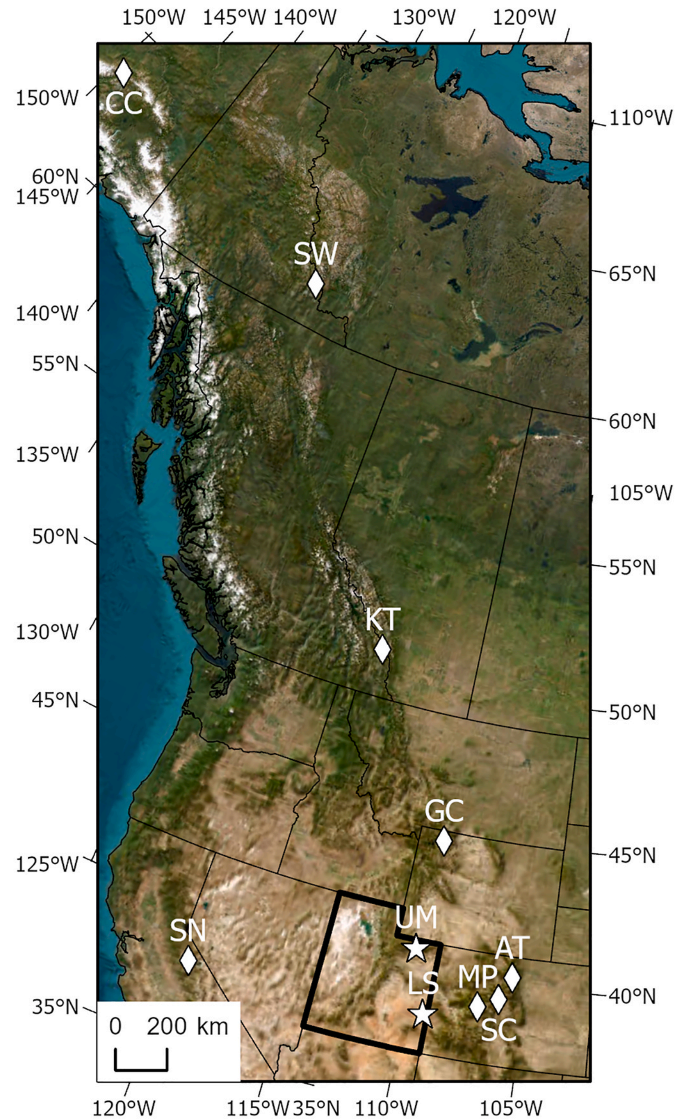

Fig. 1. Map showing the study area and other locations mentioned in the text over a background image from Earthstar Graphics. White stars mark locations in this study: LS-La Sal Mountains; UM-Uinta Mountains. White diamonds mark other notable rock glacier movement studies in North America: CC-Clear Creek (Wahrhaftig and Cox, 1959); SW-Selwyn Mountains (Sloan and Dyke, 1998); KT-Kings Throne (Koning and Smith, 1999); GC-Galena Creek (Potter et al., 1998); AT-Arapaho, Taylor, Fair (White, 1971; Janke, 2005a); MP-Maroon and Pyramid (Bryant, 1971); SC-Spruce Creek (Leonard et al., 2005); SN-Sierra Nevada (Liu et al., 2013). The state of Utah is outlined in bold.

(Fig. 1) are a Laramide-age uplift of Precambrian sedimentary rocks (Sears et al., 1982; Hansen, 1986; Dehler et al., 2007). These mountains were extensively glaciated during the Pleistocene (Munroe and Laabs, 2009), but alpine glaciers disappeared at the Pleistocene-Holocene transition (Munroe and Laabs, 2017). Maximum summit elevations are in excess of 4 km, and elevations above ~3100 m have mean annual air temperatures <0 °C (PRISM Climate Group, 2023) and likely host modern permafrost (Obu et al., 2019). Previous work has inventoried several hundred rock glaciers in the Uinta Mountains (Munroe, 2018; Brencher et al., 2021; Johnson et al., 2021), characterized their motion over seasonal and multi-annual time scales using satellite radar (Brencher et al., 2021), and examined their hydrologic significance (Munroe and Handwerger, 2023a).

Two tongue-shaped rock glaciers on cirque floors were studied in the headwaters of the West Fork Whiterocks River. These features were selected because of their accessibility and prior work on their age and hydrology (Munroe, 2018; Munroe and Handwerger, 2023a, 2023b). RG-1, which is ~500 m long and 225 m wide, is located at ~3500 m asl and has a mean slope of 19.5° (Fig. 2 and S1[2], Table 1). RG-2, located 6.5 km to the southeast, is ~550 m long and 180 m wide, is slightly lower in elevation (~3350 m, Fig. S1, Table 1), and more gently sloping (17.5°). Both are composed of quartzite blocks up to 5 m in diameter, feature surfaces characterized by prominent ridges and furrows, and are demarcated on their sides and terminus by steep slopes >10 m tall (Fig. 2).

The La Sal Mountains are laccolithic bodies of Oligocene-age trachyte (Hunt and Waters, 1958; Ross et al., 1998) intruded through sedimentary rocks of the Colorado Plateau. Rising to maximum elevations >3800 m, these mountains were glaciated repeatedly in the Pleistocene (Richmond, 1962), but no glaciers are present today. Mean annual air temperatures at all elevations are >0 °C (PRISM Climate Group, 2023). The origin of rock glaciers in the La Sal Mountains has been considered by previous studies (Shroder, 1987; Nicholas, 1994; Nicholas and Garcia, 1997), their impact on runoff in high-elevation hydrology (Geiger et al., 2014) and water properties (Munroe and Handwerger, 2023b) was investigated, >60 rock glaciers have been inventoried (Johnson et al., 2021; Kluetmeier et al., 2022), and their movement has been assessed by remote sensing (Kluetmeier et al., 2022).

Four features in the La Sal Mountains were investigated. Two of these are rock glaciers located on the west side of the range in an area known as Gold Basin. These rock glaciers, "Red Snow Cirque" (RSC) and "Middle Cirque" (MC), are tongue-shaped features in glacial cirques (Fig. S2). Both are ~800 m long, ~200 m wide, flow downslope to the north, span an elevation range from 3500 m to 3200 m, and have mean slopes ~22° (Fig. 2, Table 1). RSC is composed entirely of Tertiary igneous rock, whereas MC is a mixture of igneous rock and Jurassic clastic sedimentary rocks (Doelling, 2006). Two other features were studied on the east side of the range at the head of Dark Canyon (Fig. S2). In contrast to the Gold Basin features, the landforms studied in Dark Canyon are not located within cirques. DC-A is a long (750 m), narrow (<150 m) lobe of generally small (<1 m diameter) blocks of Jurassic/-Cretaceous sandstone (Doelling, 2006) descending an open slope to the south. The rooting zone of DC-A is at an elevation of 3500 m, the toe is at 3200 m, and the mean slope is of the feature is 24°. Previous work interpreted DC-A as a hybrid between a rock glacier and a landslip, with motion aided by accumulation of rock debris over layers of fine-grained Mancos Shale (Shroder, 1987). It is included in this study to provide a point of comparison for the more typical rock glaciers. DC-B is a short (350 m), wide (650 m) lobate rock glacier with a mean slope of 16° composed of igneous boulders (Doelling, 2006) up to 5 m in diameter, located at the foot of a steep cliff. All four La Sal features have steep side and terminal slopes, and their surfaces are characterized by ridges and furrows with up to 5 m of relief (Fig. 2).

3. Methods

3.1. GPS surveying

The rock glaciers were surveyed with real-time kinematic GPS (RTK-GPS) methodology (Lambiel and Delaloye, 2004; Fey and Krainer, 2020) using a pair of Emlid Reach RS2 GPS antennae (Fig. 3). One was deployed as stationary base station in a stable location with unimpeded sky exposure near each of the surveyed rock glaciers (RSC and MC shared the same base station). A reference point was marked in the top of a low, stable boulder using a hand drill, and the tripod supporting the base station was erected directly above the drill hole (Fig. 3). An array of 3 or 4 points was also drilled in stable boulders distributed around the base station. These points, which are assumed to not be moving, were

Fig. 2. Photographs of the studied rock glaciers: RG-1 and RG-2 in the Uinta Mountains, RSC and MC in the Gold Basin area of the La Sal Mountains, and DC-A and DC-B in the Dark Canyon area of the La Sal Mountains. The photograph of RG-1 was taken from ground level. The other five images were collected by an uncrewed aerial vehicle (UAV).

Table 1
Summary statistics for the studied rock glaciers.

Property	La Sal Mountains					Uinta Mountains	
	Units	RSC	MC	DC-A	DC-B	RG-1	RG-2
Latitude	DD.ddd	38.446	38.446	38.459	38.448	40.765	40.719
Longitude	DD.ddd	−109.259	−109.253	−109.229	−109.220	−110.130	−110.083
Mean Elevation	m	3362	3356	3379	3249	3473	3329
Mean Slope	°	23.2	21.4	23.9	15.9	19.5	17.6
Area	ha	18.0	13.5	13.4	8.0	9.9	13.0
Length	m	840	770	700	450	500	670
Est. Thickness	m	35	33	33	30	31	33
Est. Volume	$\times 10^6$ m^3	6.4	4.5	4.5	2.4	3.1	4.3
Est. Ice	$\times 10^6$ m^3	2.6	1.8	1.8	1.0	1.2	1.7
Est. Water Content	$\times 10^6$ m^3	2.3	1.6	1.6	0.9	1.1	1.6
RAD mean annual	kW hr/m^2	114	114	159	122	116	121
PPTann	mm	1035	1083	1078	1019	849	835
Peak SWE 2022	mm	500	500	500	500	287	287
Peak SWE 2023	mm	886	886	886	886	572	572
Tmeanann	°C	2.4	1.5	1.7	2.7	−0.9	−0.8
Points Surveyed	–	10	11	38	38	40	32
Point Density	m^2/point	1257	1162	589	1049	1057	838
Mean velocity, winter 21-22	cm/day	0.034	0.048	0.007	0.022	0.012	0.032
Mean velocity, summer 2022	cm/day	0.044	0.042	0.020	0.033	0.035	0.055
Mean velocity, winter 2022-23	cm/day	0.045	0.058	0.008	0.019	0.012	0.036
Accel (Sum ÷ Mean Win)	–	1.1	0.8	2.7	1.6	2.9	1.6
Velmean 2021-22	cm/yr	12.7 ± 3.3	16.9 ± 6.8	1.5 ± 0.8	6.2 ± 2.2	3.3 ± 1.9	11.3 ± 1.9
Velmean Full Record	cm/yr	14.7 ± 2.8	18.5 ± 7.5	1.6 ± 1.5	6.4 ± 1.9	3.4 ± 1.9	12.1 ± 1.7

Fig. 3. Photographs presenting the field surveying methodology. Left image shows the GPS base station set up over a marked point on a stable boulder. Rock glacier DC-B is visible in the background (see Fig. 2). Right image shows the GPS rover measuring a marked point on the RG-2 rock glacier (see Fig. 2).

used to check accuracy when the base station location was reoccupied for subsequent surveys (e.g. Lambiel and Delaloye, 2004). Given the remote locations of surveyed rock glaciers, it was not possible to tie the surveys into a formal, existing survey grid. Thus, measurements were made with reference to the constant base station locations.

The second GPS antenna was moved as a rover over the rock glacier surface to determine the coordinates of a network of points established in September 2021 (Fig. 3). Points were marked with a hand drill on the tops of large boulders, primarily located on ridge crests on the rock glacier surface. Where possible, wide boulders with flat tops were selected, and boulders on locally steep slopes were avoided. Surveying points were distributed as broadly as possible, however safety considerations precluded surveying in some locations. The total number of points surveyed on each rock glacier ranged from 10 (RSC) to 41 (RG-1), corresponding to an average of 1000 m^2/point (Table 1).

The GPS receiver at the base station was allowed to average for 2 min, after which it began to broadcast a real time position correction to the rover. Corrections were limited to <10 s old, and each point was surveyed with the rover as an average of measurements spanning 5 s. Baseline distances between the base station and rover ranged from 130 to 1170 m with a mean of 660 m. RMS errors on individual survey points on the rock glaciers averaged 1 cm in the x and y directions, and 1.2 cm in the vertical. Partial dilution of precision (PDOP) averaged 1.4, with a range of 1.1–2.2. After the initial survey in September 2021, each of the six rock glaciers was resurveyed in July 2022; September 2022; and July 2023.

3.2. Analysis of GPS results

Survey results were plotted in ArcGIS Pro to visualize the survey pattern and check for outliers. Results from repeat surveys of the reference points surrounding each base station were also plotted. Apparent offsets between the initial coordinates of the reference points and their repeat surveys (n = 39) were used to estimate the error involved in reestablishing the base station. These offsets in the x and y direction were normally distributed around a mean close to zero. The standard deviation of these offsets (1.5 cm) was therefore applied to the coordinates of points surveyed on the rock glacier to constrain their accuracy.

Distances between paired points in subsequent surveys were calculated in the horizontal plane; imprecision on the vertical coordinates of the surveyed points precluded a full 3D calculation. However, these planar displacements are considered sufficient for assessing rock glacier motion given the generally low surface slopes (Table 1), and vertical displacements that are much smaller than horizontal (Lambiel and Delaloye, 2004; Bearzot et al., 2022). Seasonal displacements were calculated for winter 2021–22, summer 2022, and winter 2022–23, along with an annual displacement from September 2021 to September 2022, and a total displacement from September 2021 to July 2023. Error estimates were calculated by determining the uncertainty on the hypoteneuse length between two points with known uncertainties in the x and y direction (1.5 cm), as derived from repeat surveys of the reference points. Daily and annual rates of movement were calculated from the number of days between each survey.

3.3. Rock glacier thermal characterization

Additional indirect methods were employed to provide information about the internal composition of the studied rock glaciers. Automated dataloggers were deployed to record the temperature of the ground surface beneath snow cover at DC-A, DC-B, RG-1, and RG-2 during the winter of 2021–22. Previous studies have established that the bottom temperature of snow (BTS) is lower (<-3 °C) for sites underlain by permafrost (Haeberli, 1973; Hoelzle, 1992; Hoelzle et al., 1999; Ikeda and Matsuoka, 1999). Loggers were deployed in duplicate on the rock glacier surface, as well as at nearby off-rock glacier control locations.

Dataloggers were also used to record the temperature of water discharging from springs at the termini of RG-1, RG-2, and RSC during the summer of 2022 (Munroe and Handwerger, 2023b). Water temperatures near freezing have been interpreted in previous studies as additional evidence of internal ice (Carturan et al., 2016; Brighenti et al., 2021a). These time-series of temperature measurements were augmented by point measurements of springs discharging from DC-A and DC-B.

3.4. Local climate, estimation of ice volume, and movement history

Climatic data are not available directly at the locations of the rock glaciers considered in this study. Instead, data from other sources were considered to represent local conditions at the six landforms. In the La Sal Mountains, snow accumulation records were download for the Gold Basin snowpack telemetry site (SNOTEL), located <2 km from RSC and MC at an elevation of 3070 m. In the Uinta Mountains, snow accumulation data were downloaded from the Chepeta SNOTEL, located at 3200 m < 10 km from RG-1 and RG-2. Estimated mean annual air temperatures and precipitation were retrieved for all study areas from the interpolated PRISM dataset (PRISM Climate Group, 2023). Estimated mean annual solar radiation for each rock glacier was obtained from the Portland State University Active Rock Glacier Inventory (Johnson et al., 2021). Thickness and volume of the studied rock glaciers, along with their possible ice content, were calculated using scaling functions presented in previous work, which scale from surface area and assume a realistic ice content (Rangecroft et al., 2015; Millar and Westfall, 2019; Jones et al., 2019). Finally, a sample of wood from a ridge of sediment pushed by DC-B during an episode of frontal advance was radiocarbon dated.

4. Results

4.1. Rock glacier motion

Results from RTK-GPS surveying demonstrate that the studied rock glaciers are active. Displacements measured for at least some boulders on each feature exceed the 1.5-cm measurement uncertainty quantified for the reference points. The mean horizontal displacement of all boulders surveyed (n = 167) was 12.6 ± 10.3 cm (± standard deviation) over 20 months (median of 10.6 cm), with a maximum of 65 cm (Fig. 4). The mean displacement rises to 15.4 ± 10 cm when DC-A is excluded. Mean annual velocities (2021–22) range from 1.5 cm/yr at DC-A, to 16.9 cm/yr at MC (Fig. 5), with an overall average of 6.8 cm/yr (Table 1).

The spatial distribution of surface velocities exhibits a complicated pattern within each rock glacier. At the macroscale, displacement vectors parallel the longitudinal axis of each feature and exhibit flow from high to low elevation consistent with downslope motion (Fig. 6). At finer scales, areas of faster motion tend to be located at higher elevations near rock glacier rooting zones. This tendency is particularly apparent at DC-A, where only the highest boulders exhibit detectable motion, with total displacements in excess of 5 cm (Fig. 6); lower boulders on DC-A did not move a distance greater than measurement uncertainty during the 20 months between the initial and final surveys. DC-B and RG-1 also demonstrate a clear pattern of greater velocities at higher elevations (Fig. 6). Furthermore, displacement vectors also delineate areas of diverging and converging flow on some rock glaciers, particularly on RG-1 and DC-B, where survey points were widely distributed. In contrast, on RG-2, the surveyed boulder displacements are strikingly parallel (Fig. 6).

Surface displacements vary between the surveyed rock glaciers, even for sites in close proximity (Fig. 7). The two rock glaciers in Gold Basin (MC and RSC) both exhibit high velocities (Fig. 7, Table 1), and access issues precluded surveying the uppermost sector of these features where velocities may have been even higher (Fig. 6). In Dark Canyon, however,

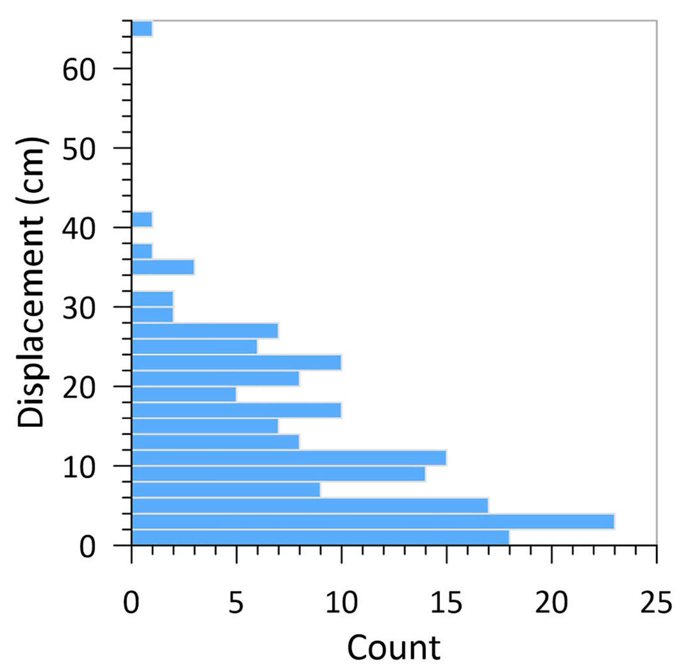

Fig. 4. Histogram of total displacements between September 2021 and July 2023 (n = 167). The majority of measurements exceed the uncertainty of ~2 cm.

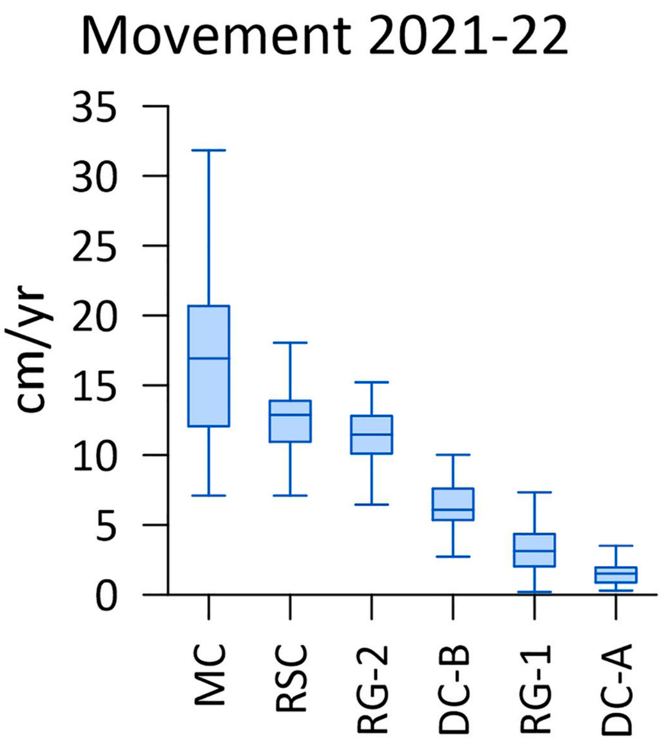

Fig. 5. Box and whisker plots presenting velocities between September 2021 and September 2022. Horizontal lines represent median values, box represents interquartile range, and whiskers represent interquartile range × 1.5.

DC-A and DC-B display very different motion, with all boulders on DC-B exhibiting measurable displacement, in contrast to DC-A (Figs. 6 and 7). Similarly, in the Uinta Mountains, RG-2 is moving >3 × faster on average than RG-1 (Fig. 7, Table 1) despite the proximity (Fig. 1) and shared tongue-shaped morphology (Figs. 2 and 6) of these landforms.

Velocities of the surveyed rock glaciers are not seasonally consistent (Figs. 7 and 8). In Dark Canyon and in the Uinta Mountains, mean summer velocities (early July through early September) are 2–3 × faster than mean winter velocities (early September through early July) (Table 1). In Gold Basin this pattern of higher summer velocities is not apparent. However, both RSC and MC moved faster during the second winter of the survey than during the first. (Fig. 8, Table 1).

Velocities measured for individual points during the winters of 2021–22 and 2022–23 exhibit correspondence to varying degrees on the different landforms (Fig. 9). At RSC and MC, calculated velocities are strongly correlated, with r^2 values > 0.88. At the two rock glaciers in the Uinta Mountains, and at DC-B in Dark Canyon, these correlations are weaker, but still positive. At DC-A, the hybrid rock glacier-landslip (Shroder, 1987), there is no correlation because very few of the survey points displaced by an amount greater than the measurement uncertainty. At all sites except DC-A correlations between velocities at specific points in the two different winters are significant ($P < 0.05$ with a Spearman's rank test).

4.2. Additional investigations

The temperature of the ground surface beneath the snowpack (BTS) during the winter of 2021–22 (December through May) on rock glacier surfaces was consistently colder than at nearby control locations (Fig. S3). At no time was rock glacier BTS warmer than the corresponding control site. Average BTS on the surfaces of DC-A, DC-B, RG-1, and RG-2 was ~-4 °C, in contrast to values between −2 and 0 °C at the control sites.

The RSC, RG-1, and RG-2 rock glaciers discharge consistently cold water throughout the summer (Fig. S4). At all three sites during the summer of 2022, minimum daily temperatures were <~1.0 °C. Maximum daily temperatures were several degrees higher due to solar heating; minimum daily temperatures are considered to better represent the actual water temperature at the point where it emerges from the rock glacier. Point measurements of springs at DC-A and DC-B also revealed water temperature near freezing, corroborating previous observations of water temperatures <1.0 °C at DC-A (Shroder, 1987).

Field surveys of the rock glaciers in the summers of 2022 and 2023 followed winters with contrasting snowfall (Fig. 7). The winter of 2021–22 was relatively dry, with a peak snow water equivalent (SWE) of 500 mm at Gold Basin and 287 mm at the Chepeta SNOTEL in the Uinta Mountains. In contrast, the winter of 2022–23 was much wetter, with peak SWE at Gold Basin of 886 mm, and 572 at Chepeta (Table 1). The PRISM dataset reveals that the rock glaciers in the La Sal Mountains receive an average of 1054 mm of annual precipitation; the locations of RG-1 and RG-2 in the Uinta Mountains are correspondingly drier, with a mean annual precipitation of ~840 mm (Table 1). The La Sal Mountain rock glaciers are also warmer, with mean annual temperatures of 2.1 °C, compared to −0.9 °C at RG-1 and RG-2 (Table 1). As the two studied rock glaciers in the Uinta Mountains are at similar elevations to those in the La Sal Mountains, this difference appears related to regional climate. Mean annual solar radiation is similar at the five true rock glaciers, averaging 118 kW h/m^2; the hybrid feature DC-A has a higher value of 159 kW h/m^2, reflecting its southerly aspect and open position (Table 1).

5. Discussion

5.1. Velocities

Excluding DC-A, annual rates of motion on the surveyed rock glaciers are 3.4 (RG-1) to 18.5 (MC) cm/yr (Table 1). This range is consistent with information available from published studies using ground-based observations (Table 2) at other rock glaciers in western North America (Fig. 1). For instance, work on similar rock glaciers in Colorado reported velocities from 5 to as much as 63 cm/yr, with most reports in the 5–10 cm/yr range (Bryant, 1971; White, 1971; Benedict et al., 1986; Leonard et al., 2005; Janke, 2005a). The Galena Creek rock glacier in Wyoming, which is known to be ice-cored, exhibits motion across a wide range of velocities (6.5 to 80 cm/yr), with the lower part of this range overlapping with the results reported here (Potter et al., 1998). Farther to the north, rock glaciers in western Canada have been documented to move 5–18 cm/yr (Sloan and Dyke, 1998; Koning and Smith, 1999), and an ice-cemented feature in Alaska studied in the seminal rock glacier investigation moves 57–64 cm/yr (Wahrhaftig and Cox, 1959). Collectively, this array of results suggests a general range of North American rock glacier velocities, for both ice-cemented and ice-cored features, of <1 m/yr. Similar velocities have been reported by remote sensing studies employing satellite radar interferometry (InSAR) to document rock glacier movement at the range scale (Liu et al., 2013; Brencher et al., 2021).

On the other hand, the rock glaciers surveyed in the La Sal and Uinta Mountains appear to be moving slower than similar features in the European Alps. For instance, GPS measurements made using an approach identical to that employed in the current study, yielded velocities ~1 m/yr on a rock glacier in northern Italy (Fey and Krainer, 2020). Three rock glaciers in the Austrian Alps were documented through field surveying to move ~3 m/yr (Krainer and He, 2006). Rock glaciers in the Swiss Alps identified as currently destabilizing are moving ~10 m/yr (Delaloye et al., 2010), and a destabilizing rock glacier in northern Italy is moving at 4 m/yr (Scotti et al., 2017). The significance of this contrast is unclear. A partial explanation is the longer observation periods of many studies in the Alps, which could capture intervals of faster movement not seen in our ~2-year record. Alternatively, some North America rock glaciers may move at velocities equivalent to those in the Alps, yet have not been identified, or are not accurately captured by InSAR studies that are

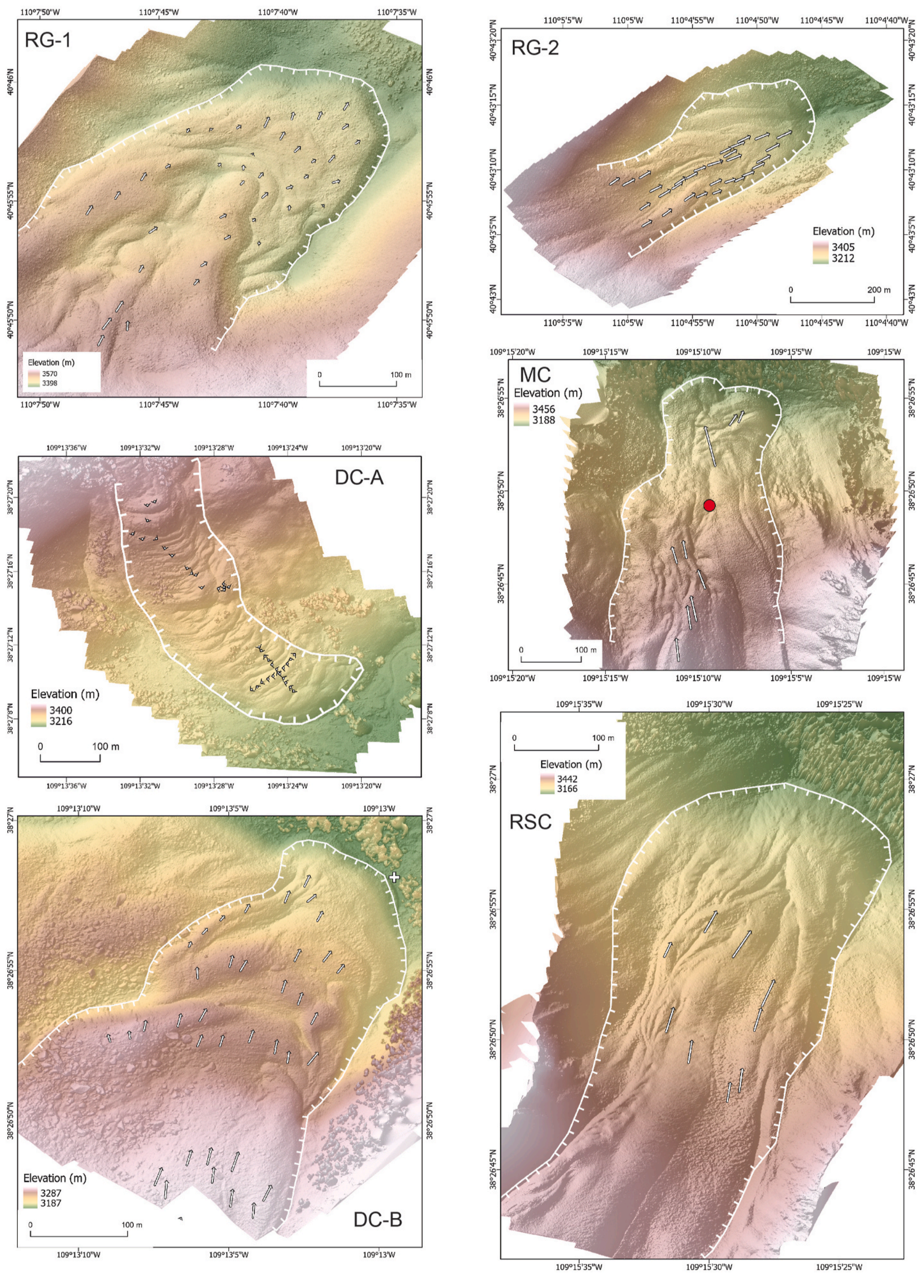

Fig. 6. Maps showing displacement vectors on the six rock glaciers between September 2021 and July 2023. Vectors are magnified 100 × the map scale for clarity. Background images are surface models derived through structure-from-motion from photographs collected with an uncrewed aerial vehicle (UAV). Warmer colors represent higher elevations. White hachured line delineates the boundary of each rock glacier. White cross on the map for DC-B denotes where wood from a push lobe was dated to 200 ± 40 ^{14}C years (see Fig. S3). Red circle on MC denotes the location where extensional cracking was observed (see Fig. 10).

best-suited to quantifying slower rates of annual movement (RGIK, 2023b). It is also possible that many of the apparently faster moving rock glaciers in the Alps are ice-cored features derived from alpine glaciers, and that many of the North American studies summarized here are of ice-cemented rock glaciers that would be expected to have slower rates of internal deformation. However, some North American features, like the Galena Creek rock glacier are known from field observations and geophysics to be ice-cored (Potter, 1972; Konrad et al., 1999; Petersen et al., 2020), so that cannot be the entire explanation. Future work, particularly studies combining remote sensing and field surveying, is clearly necessary to resolve this apparent contradiction.

Correlations between velocities of individual points in different winters vary in strength, but are positive for all but DC-A (Fig. 9). This relationship indicates that locations on a rock glacier that move faster one year tend to be faster in other years. Such continuity suggests an underlying controlling mechanism, rather than random behavior. Possible explanations include pathways of water movement within rock glaciers that could preferentially enhance shear in some areas at the rock glacier sole (Jansen and Hergarten, 2006), and spatial variations in internal ice content (Krainer and He, 2006), both of which are dictated by rock glacier geometry that remains relatively consistent from year to year. Additional studies combining monitoring of rock glacier movement and hydrology in different settings are needed to further refine our understanding of these relationships (Kenner et al., 2020).

Feature DC-A in Dark Canyon is an obvious outlier; rates of motion on this landform are low (Figs. 5 and 7), and many of the surveyed points failed to move a distance greater than the measurement uncertainty, even over the full 20-month interval (Fig. 6). Shroder (1987) considered

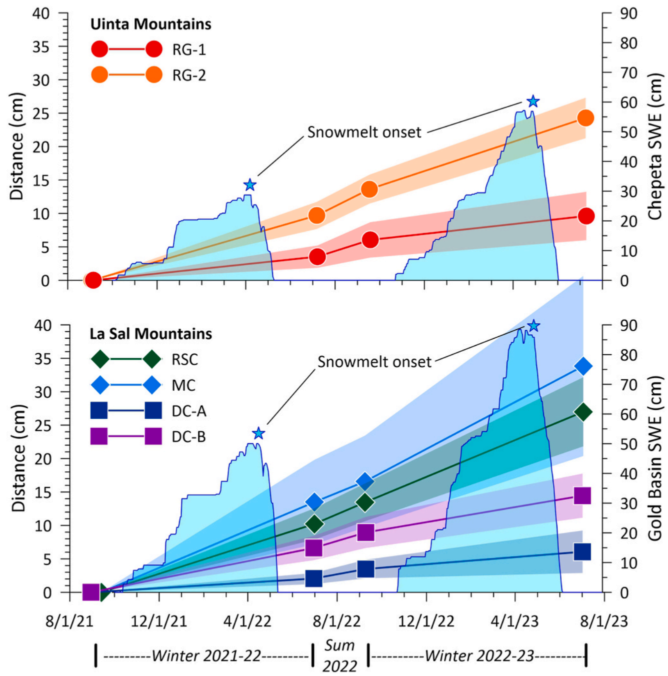

Fig. 7. Time series of cumulative movement measured on rock glaciers in the Uinta Mountains (top) and the La Sal Mountains (bottom) during winter 2021–22, summer 2022, and winter 2022–23. Symbols represent mean values, whereas the corresponding shaded envelopes represent ±1 standard deviation. Daily snow water equivalent (SWE) at the Chepeta SNOTEL (top) and Gold Basin SNOTEL (bottom) are presented (in cm). Stars denote the onset of snowpack meltout each year.

DC-A, and similar features in the La Sal Mountains, to be hybrid landforms combing the structure and kinematics of a rock glacier with those of a landslip aided by the underlying fine-grained Mancos Shale. Delivery of loose rock material to the rooting zone of DC-A by rock fall, and subsequent downslope transport of this material through creep over residuum derived from shale, could explain the location of this feature on an exposed, south-facing slope (Fig. 2). On the other hand, the low BTS values on DC-A, as well as the cold temperatures of springs discharging from DC-A noted in this study and by Shroder (1987), suggest that ice is at least locally present within this landform. Perhaps the uppermost part of the feature, where rates of movement are the fastest, is a lobate rock glacier that transitions downslope into a landslip that is either stationary or moving at rates too slow to be detected with the methods employed in this study (Fig. 6).

5.2. Rock glacier composition

The approaches used in this study to elucidate rock glacier composition are indirect, but together they provide important insights about the interior of these features. Specifically, the BTS values of ~ -4 °C measured on rock glacier surfaces during the winter 2021–22 (Fig. S3) are consistent with the presence of permafrost (Haeberli, 1973; Hoelzle, 1992), defined as earth materials maintaining a temperature <0 °C for more than two years (Dobinski, 2011). These rock glaciers, therefore, strongly suggest the presence of discontinuous permafrost in the study areas. Additionally, the maintenance of water temperatures near freezing throughout the summer in rock glacier springs (Fig. S4) supports the interpretation of ice within these landforms (Carturan et al., 2016; Brighenti et al., 2021a). Deformation of this ice, coupled with basal shear enhanced by meltwater, is presumably responsible for the surface displacements quantified with the RTK-GPS surveying (Giardino, 1983; Giardino et al., 1992; Serrano et al., 2006; Krainer et al., 2015). From the available information, it is not possible to determine whether these rock glaciers are ice-cemented, or if they contain a

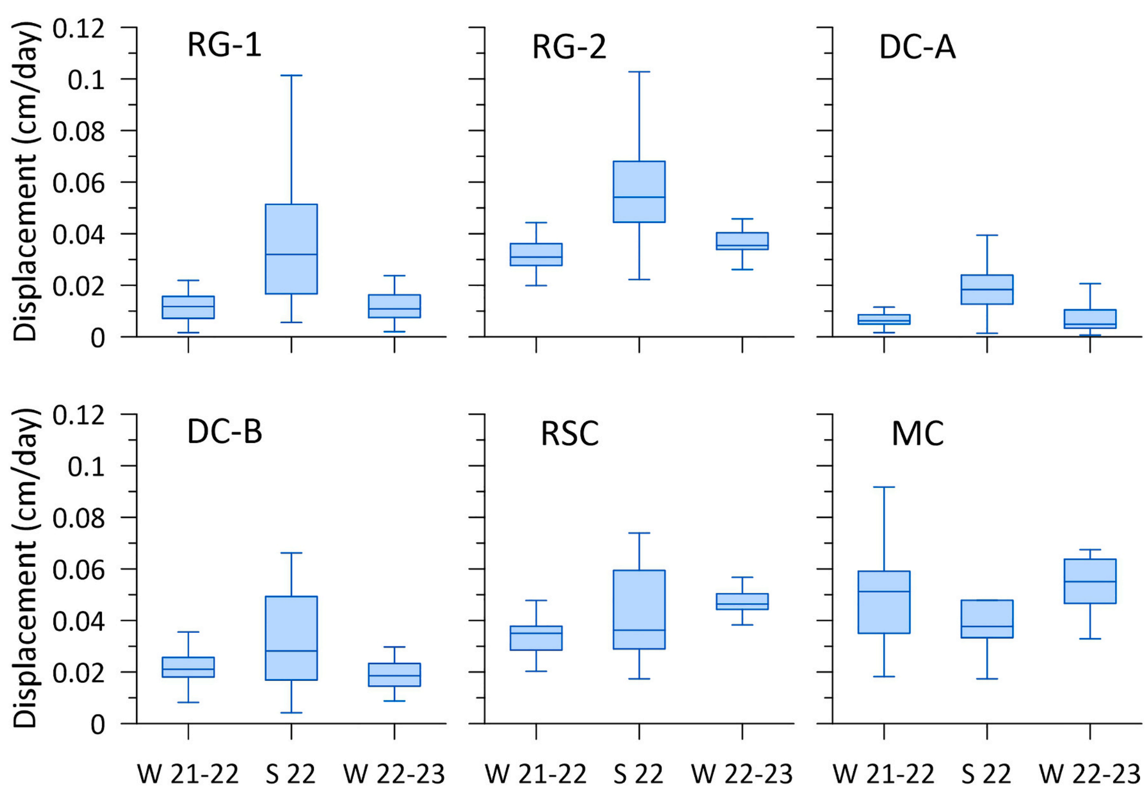

Fig. 8. Box and whisker plots presenting seasonal displacements on the six rock glaciers in cm/day for winter 2021–22, summer 22, and winter 2022–23. Horizontal lines represent median values, box represents interquartile range, and whiskers represent interquartile range × 1.5.

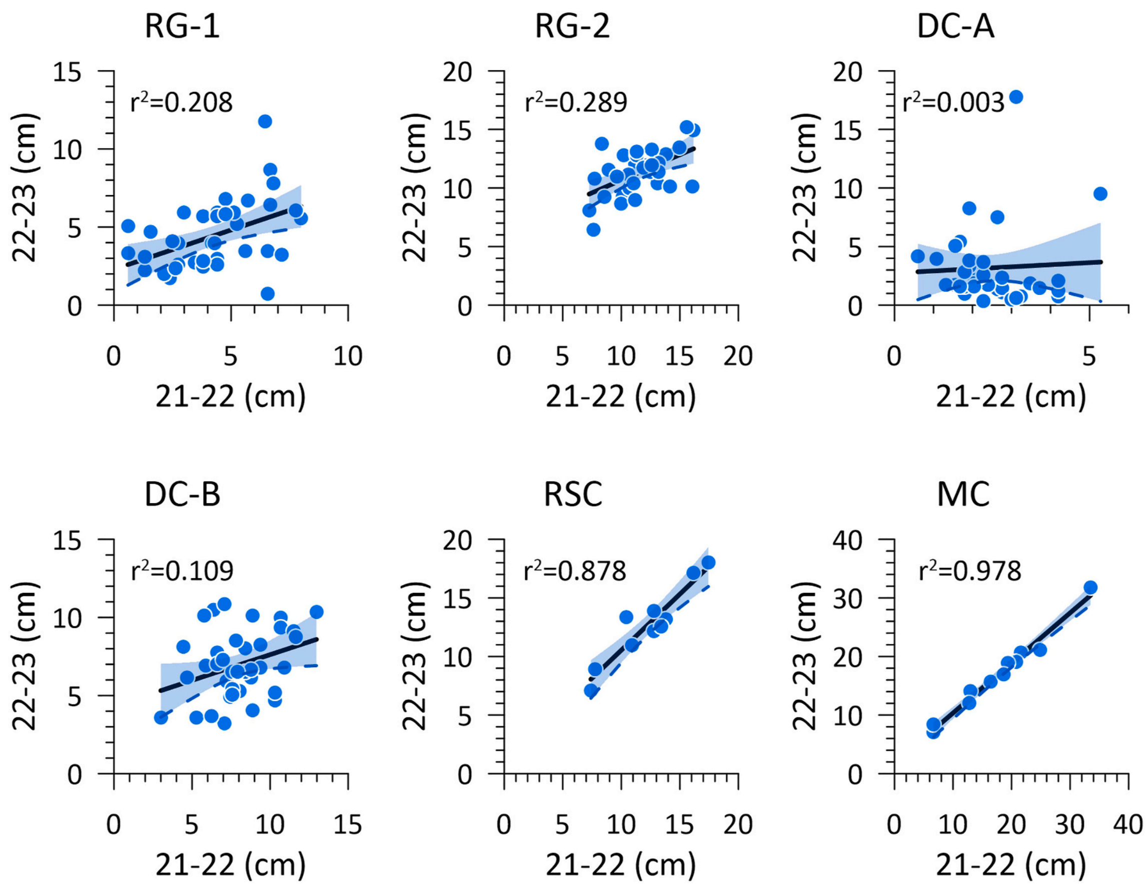

Fig. 9. Paired velocities (cm/yr) at points measured on the six rock glaciers during the winters of 2021–22 and 2022–23. Black lines are linear fits and the shaded blue area represents the 95% confidence interval.

Table 2
Selected north American rock glacier movement inventories.

Location	State/Province	Type	Number	Years	Rates (cm/yr)	Method	Reference
Clear Creek	AK	Ice-cemented	1	1949–1957	57 to 64	Transit	Wahrhaftig and Cox, 1959
Arapaho, Taylor, and Fair	CO	Ice-cored	3	1961–1966	5.0 to 9.7	Thedolite	White, 1971
Maroon and Pyramid	CO	?	2	1964–1968	63	Thedolite	Bryant, 1971
Arapaho	CO	Ice-cored	1	1960–1985	6.2 to 19.3	Thedolite	Benedict et al., 1986
Galena Creek	WY	Ice-cored	1	1960s-1995	6.5 to 80	Total Station	Potter et al., 1998
Arapaho, Taylor, and Fair	CO	Ice-cored	3	1961–2002	6.3 to 9.5	Total Station	Janke, 2005
Selwyn Mtns	YT	?	15	1983–1995	18	Thedolite	Sloan and Dyke, 1998
Kings Throne	AB	Ice-cemented	1	1988–1996	5.4	Thedolite	Koning and Smith, 1999
Spruce Creek	CO	?	1	1985–2000	4.5 to 6.7	Total Station	Leonard et al., 2005
Sierra Nevada	CA	?	59	2007–2008	14 to 87	InSAR	Liu et al., 2013
Uinta Mountains	UT	?	205	2016–2019	0.4 to 6.0	InSAR	Brencher et al., 2021
La Sal and Uinta Mountains	UT	?	6	2021–2023	1.6 to 18.5	RTK-GPS	This study

massive ice core. However, if ice within these landforms is interstitial, and porosity is ~30% (Arenson and Jakob, 2010; Jones et al., 2019), then their estimated water contents, converted from ice equivalent, range from 0.9×10^6 m^3 (DC-A) to 2.3×10^6 m^3 (RSC) for a total of 9.1×10^6 m^3 (Table 1).

5.3. Connection to climate and water

Although the distribution of survey points was not the same on the different rock glaciers (Fig. 6), it is notable that the large tongue-shaped features (Fig. 2) in the La Sal Mountains (RSC and MC) are moving faster than similar landforms in the Uinta Mountains (RG-1 and RG-2); the average velocity of RSC and MC for the full record was 16.6 cm/yr, compared to 7.8 cm/yr for RG-1 and RG-2 (Table 1). This discrepancy is striking given the otherwise similar morphology, dimensions, and elevations of these features, as well as their estimated annual solar radiation received (Table 1). Previous studies have established that rates of rock glacier movement are connected to water availability (Cicoira et al., 2019), which aids rock glacier motion by increasing pore water pressures, with a corresponding reduction in effective stress (Krainer and He, 2006; Ikeda et al., 2008). The greater velocities in the tongue-shaped La Sal rock glaciers could, therefore, reflect the wetter conditions in that mountain range (Fig. 7). Studies have also demonstrated that rock glacier movement is not strongly related to air temperature (Cicoira et al., 2019), thus the general colder climate of the Uinta Mountains is likely less a factor in controlling rates of rock glacier motion.

Furthermore, most of the rock glaciers surveyed in this study moved faster on a daily basis during the summer of 2022 and the winter of 2022–23 than during the first winter (Fig. 8). Because the rock glaciers could not be accessed for surveying until nearly all of the snow had melted each year, the winter motion intervals actually include nearly all of the annual snowmelt period (Fig. 7). In this regard, the higher velocities calculated for the winter of 2022–23 could reflect greater forward motion in the spring of 2023 when a larger snowpack was melting (Table 1). Similarly, overall higher velocities on a daily basis during summer months (Fig. 8) are consistent with the presence of more liquid water from rain along with lingering snowmelt and rain. Faster flow rates during summer have also been proposed as a diagnostic characteristic of ice-cemented rock glaciers (Knight, 2019).

A longer-term perspective provided by paleoclimate data reinforces the impression that these landforms accelerate during times of greater water availability. Shroder (1987) reported a summary of dendrogeomorphic data (Shroder, 1980) from trees growing on DC-A. These trees were disturbed by renewed or enhanced motion of the landform, preserving evidence in their rings that constrains past motion. Numerous intervals of motion were identified, including near AD 1840, the early 20th century, near 1940, and again near 1970. When plotted against reconstructed discharge of the Colorado River at Lee's Ferry (Woodhouse et al., 2006) as a reference for effective moisture in this region, peaks of motion generally align with higher reconstructed discharges (Fig. S5).

Evidence of older episodes of frontal advance comes from the DC-B rock glacier. Around the terminus of this feature are prominent push lobes (sensu Shroder, 1987) and turf rolls up to ~1 m high (Fig. S6). These vegetated ridges of fine-sediment were displaced as the rock glacier terminus plowed forward into the surrounding soil. Shroder (1987) reported an age of 690 ± 80 ^{14}C years from beneath one of these push lobes, which calibrates to ~AD 1300, providing a maximum limiting age on advance and ridge formation. During this study, an additional sample of wood retrieved from within this push lobe (Fig. 6 and S6) yielded a ^{14}C age of 200 ± 40 years. This calibrates to a median of AD 1770 (Fig. S6), indicating that DC-B was advancing during the Little Ice Age. Although the precision on this calibrated age is wider than the annually resolved discharge reconstruction for the Colorado River, it is notable that advance in the late 1700s also corresponds with intervals of increased effective moisture (Fig. S5).

5.4. Signs of recent change

The GPS surveying reported in this study provides a baseline against which future changes in the activity of these rock glaciers can be identified. Such monitoring would be particularly important given evidence suggesting that rates of rock glacier motion are changing due to ongoing climate shifts. Along the lower central axis of rock glacier MC is a narrow band of relatively stone-poor, vegetated fine sediment. This area must have been relatively stable for some time in order to allow the fine material to accumulate and for vegetation to become established. Now, however, this area is cross-cut by fresh extensional cracks that penetrate through the turf and fine soil, exposing organic-poor, stony diamicton at depth (Fig. 10). Individual cracks are up to 3 m long and 20 cm wide, and their downslope side is commonly displaced below the upslope side, resembling a series of small normal faults. Significantly, their orientation is consistent with extension along the longitudinal axis of the vegetated zone, evidencing recent stretching in this area of the rock glacier (Fig. 10). The duration of the GPS surveying efforts reported in this study is too short to evaluate whether this extension is truly recent or accelerating, however future monitoring and repeat surveying could confirm whether the motion of this part of MC, already the fastest moving rock glacier in this study, is changing. Investigations in Europe have reported recent dramatic accelerations of rock glacier velocity, in some cases leading to disintegration and slope failure (Roer et al., 2008; Marcer et al., 2019, 2020; Hartl et al., 2022). Given the climatic dependence of rock glaciers, future monitoring of the survey network established here will be important for tracking cryosphere change in these mountain ranges.

6. Conclusion

Six rock glaciers surveyed in the La Sal and Uinta Mountains of Utah are currently active. They appear to move faster during the summer months, and are also faster after winters with greater snowfall. Overall velocities of these rock glaciers are consistent with values reported from elsewhere in North America, but are slower than those reported for rock glaciers in the European Alps. Future resurveying of the landforms

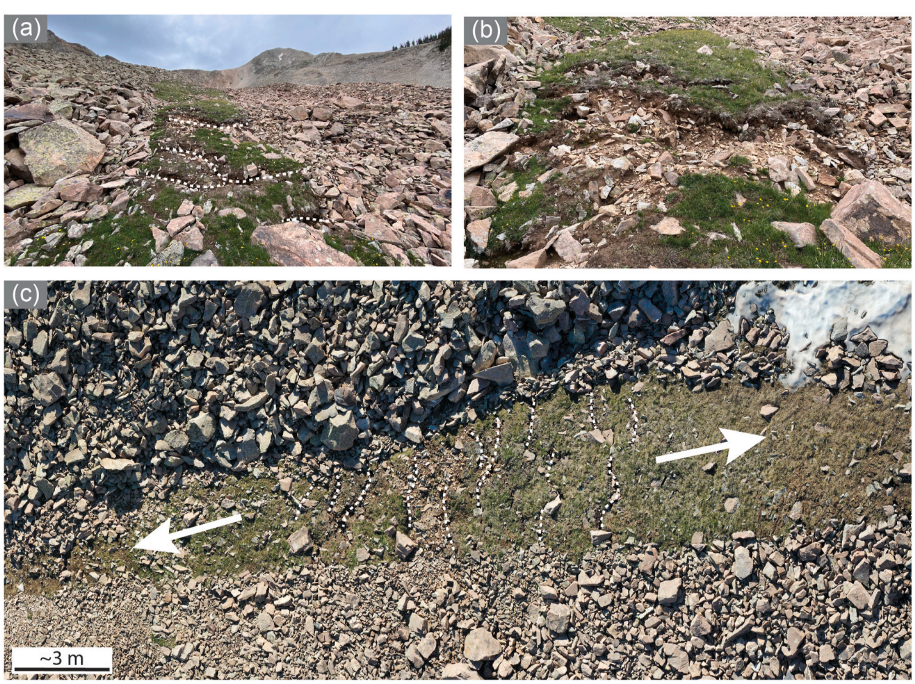

Fig. 10. Extensional cracking along the central axis of rock glacier MC (see Fig. 6). (a) Ground level view of prominent cracks, looking upslope. (b) Close-up of a large crack with ~50 cm of horizontal displacement. (c) Vertical aerial photo showing the entire crack area, with prominent examples highlighted by dashed lines. Approximate scale denoted by the bar at lower left. Large arrows emphasize the direction of tension.

reported on here will be valuable for identifying cryosphere change in these mountains.

CRediT authorship contribution statement

Jeffrey S. Munroe: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alexander L. Handwerger:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The surveying data generated in this study are available in the open Zenodo repository: https://zenodo.org/uploads/10887207

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.qsa.2024.100188.

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