Mobility of an ancient buried ice mass, Transantarctic Mountains, Antarctica

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ABSTRACT

We determined the stability of an ancient, buried ice mass in Ong Valley, Transantarctic Mountains, Antarctica. The buried ice underlies the two younger of the three successively older drifts, dated at 11–13 kyrs, 2.9 Myrs, and 4.3–5.1 Myrs, making this some of the oldest ice on Earth. The middle drift contains two stacked ice masses, which are covered by a meter-thick layer of supraglacial debris. Ice of such antiquity has the potential to extend and reveal information about the paleoclimate, that is currently poorly known. To utilize these drifts for paleoclimatological and geomorphological analyses, it is important to determine their stability. Therefore, we measured high-precision markers (~0.5 mm resolution) over a period of seven years on eight surface boulders lodged in the drifts to determine their mobility/stability. We find the stability of the three drifts to increase with distance from the currently exposed ice sheet at the valley mouth. The youngest drift, containing buried ice, appears dynamic and exhibits surface boulder movement between 0.79 and 1.10 cm/yr down the valley over the seven-year period. The middle drift and ice are considered stable, but the surficial debris is still subject to slow erosion and/or patterned ground formation. The old drift is void of buried ice and shows no signs of movement.

1 INTRODUCTION

In Antarctica, debris-covered ice is one of three main sources of old glacial ice (Bergelin et al. 2022; Bibby et al. 2016; Schäfer et al. 2000), which also includes basal ice at ice sheet domes (Jouzel et al. 2007) and blue ice at the Transantarctic Mountains (TAM) margin (Yan et al. 2019). Ice, older than 1 Myrs has the potential to extend and reveal information about the Antarctic paleoclimate, that is currently poorly known. However, to utilize these ancient, buried ice masses for paleoclimatological and geomorphological analyses, it is important to determine their long-term stability.

A debris-cover thicker than a few centimeters is known to thermally insulate glacial ice and decrease the effect of ablation (Evatt et al. 2015; Kowalewski et al. 2011; Mihalcea et al. 2006; Östrem 1959). In Alpine settings, surface features such as ice cliffs, water channels, and ponds can enhance ablation (Ragettli et al. 2016), causing the stability of debris-covered glaciers to greatly vary (Moore 2017). However, the occurrences of these surface features are limited in Antarctica due to its cold and arid climate, resulting in the preservation of old buried ice near the surface (e.g., Bibby et al. 2016).

Many buried ice masses have been identified throughout the Transantarctic Mountains, in Antarctica, with a few having the potential to harbor ancient ice (Putkonen and Mahmood 2022), and only two ancient buried ice masses have been studied in greater detail. One is found in Beacon Valley in McMurdo Dry Valleys. This buried ice mass was initially dated to be 8 Ma (Sugden et al. 1995) but its age was later questioned due to Beacon Valley's complex glacier system and potential recharge of ice (Hindmarsh et al. 1998; Ng et al. 2005; Stone et al. 2000; Van der Wateren and Hindmarsh 1995). The other is located in Ong Valley in Miller Range and dated to be 3–5 Ma (Bergelin et al. 2022).

These buried ice masses are found to be remnants of the once more extensive continental ice sheet during its previous high stand. They are formed when the continental ice sheet retreats and leaves behind isolated and stagnant smaller ice masses. As the isolated ice mass sublimates, the englacial debris within the sublimating ice slowly accumulates on the surface as supraglacial debris and begins to insulate the underlying ice from further melting.

In Ong Valley, the buried ice mass is part of a glacial drift system of debris deposited by glacial ice, separated by lateral and end moraines. The youngest two of the drifts have massive, buried ice under a thin (< 1 m) layer of loose debris completely concealing the ice. The oldest drift appears to be devoid of buried ice, which, presumably, has sublimed over extended exposure. The youngest drift has been dated to be 11–13 kyrs (Bibby et al. 2016), the middle > 1.1 Myrs (Bibby et al. 2016), and recently determined to be 2.95 Myrs (Bergelin et al. 2022). The oldest drift was initially dated to be > 2.6 Myrs (Bibby et al. 2016) and was recently determined to be 4.3–5.1 Myrs (Bergelin et al. 2022). Each drift system exhibits various age stages of patterned ground formation that appear to correlate to its age. All three drifts have related lateral moraines up on the valley walls that trace the original elevation of the expanded and elevated continental ice sheet surface during deposition. The oldest drift also has a distinct end moraine close to the head of the valley.

The long-term stability of such drifts observed in Ong Valley has been studied elsewhere in Antarctica (Putkonen et al. 2008). However, no comparable studies have been done in the central TAM. Therefore, to evaluate the stability of the drift system in Ong Valley we use high-precision GPS positioning to map the glacial moraines and drift boundaries, and the current boundary of the two buried ice masses. Mapping the distribution of glacial features and

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deposits can aid in understanding the behavior of past glacial advancements, such as the extent and dimensions, locally and potentially continental-wide. Further, we measure high-precision markers (~0.5 mm resolution) on eight surface boulders located on the drifts over a period of seven years (2010–2017) to determine the mobility and stability of these drifts and buried ice masses.

2 Methodology

Differential high-precision positioning allows for the determination of an accurate location of an object by making use of a reference point to correct for transient errors and attains a precision level of centimeter to millimeter scale. In Ong Valley, we use GPS and differential correction schemes between two receivers to acquire a high-accuracy position for (i) mapping the glacial moraines and drift boundaries and (ii) detecting surface movement to evaluate the stability of this buried ice mass and associated drift system.

2.1 Data Collection and Processing

During the 2017/2018 Antarctic field season, we mapped the crests of multiple glacial moraines throughout Ong Valley. Each moraine was measured using stop-and-go kinematic surveying. The moraines were mapped by following the crest or perimeter and measuring the positions for approximately 15 seconds, every 5–15 m. The moraine positions were collected using a Trimble receiver, with an antenna mounted to a 2 m survey pole with an attached leveler.

Six visible moraines were not accessible for direct GPS measurements because of their location up on steep valley walls. Instead, the positions of these moraines were determined using a laser ranger and a reference location on the valley floor that was mapped by a handheld GPS. A reference point was found perpendicular to each moraine crest (valley-wall) and 100–500 m away towards mid-valley, from which the distance and elevation difference between the moraine and reference point was measured.

To evaluate the stability of each of the three drifts and determine if any movement has occurred in Ong Valley, we repeatedly measured the position of eight boulders from the three drifts. The positions of the surface boulders were originally measured during the Austral summer 2010, and again in 2011 and 2017.

During the Austral summer, 2010/2011, bolts were installed in eight boulders found on the surface of the three Ong Valley drifts (Figures 1 and 2). These bolts are ~30 cm long and were manually drilled and mounted as close to vertical orientation as possible, into the upper surface of the boulders. The measurement point is a small (~2 mm diameter) dimple stamped on the middle of the flat, top surface of the rock bolt. To perform the final leveling of the antenna, a leveling mount of known shaft dimensions was screwed on the rock bolt. Once the mount was leveled the antenna was attached to the mount for determining the exact position of the stamped dimple.

Two boulders were chosen from the youngest drift, three from the middle drift, two from the oldest drift, and one near

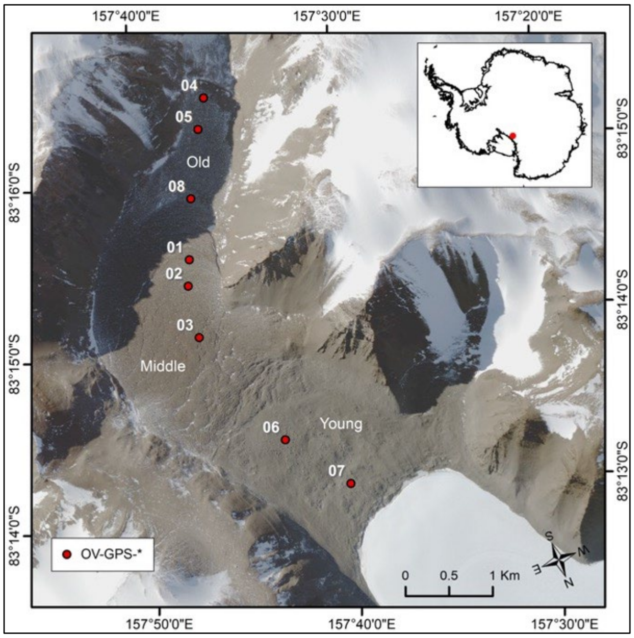

Figure 1. Satellite image of Ong Valley, Antarctica (WV2 satellite image © 2016 Maxar. Red dots indicate the locations of the 8 surface boulders. The legend shows the prefix for the boulder names.

the boundary between the middle and old drift. The boulders were originally selected based on their evidence for stability in the drift. Each boulder was > 1.5 m in the longest dimension and partially submerged in the supraglacial debris, such that any movement is assumed to be caused by either ice movement or active polygons (Figure 2). However, no ideal boulder was available at the boundary between the middle and old drift, and therefore boulder OV-GPS-08 was chosen although it is entirely perched above the drift.

The installed bolts in each boulder were revisited twice over the years. On these re-occupations, we followed the original antenna mounting procedure described above and determined the exact locations of the 2 mm diameter dimples at the top end of the stationary rock bolts. We were able to attach the antenna to a horizontal accuracy of < 1°, resulting in a centered offset of < 0.2 cm of the antenna between the years of repeating measurement. Each boulder location was recorded for a duration of 18–60 minutes for optimal accuracy.

During the initial 2010/2011 field season, a base station bolt was established in Ong Valley on an elevated bedrock outcrop central to the valley and less than 3 km from any of the eight boulders and moraines. The base station antenna was installed at the beginning of each field expedition in Ong Valley and disassembled at the end of each expedition, continuously collecting data in between.

All GPS data collected were processed using the Trimble Business Center (TBC) v5.20 software package provided by UNAVCO. The 2017/2018 Ong Valley base station was set to record daily and hourly (1Hz1Hr) positioning. The collected moraine data were processed against 1Hz1Hr hourly base data, with a horizontal and vertical precision

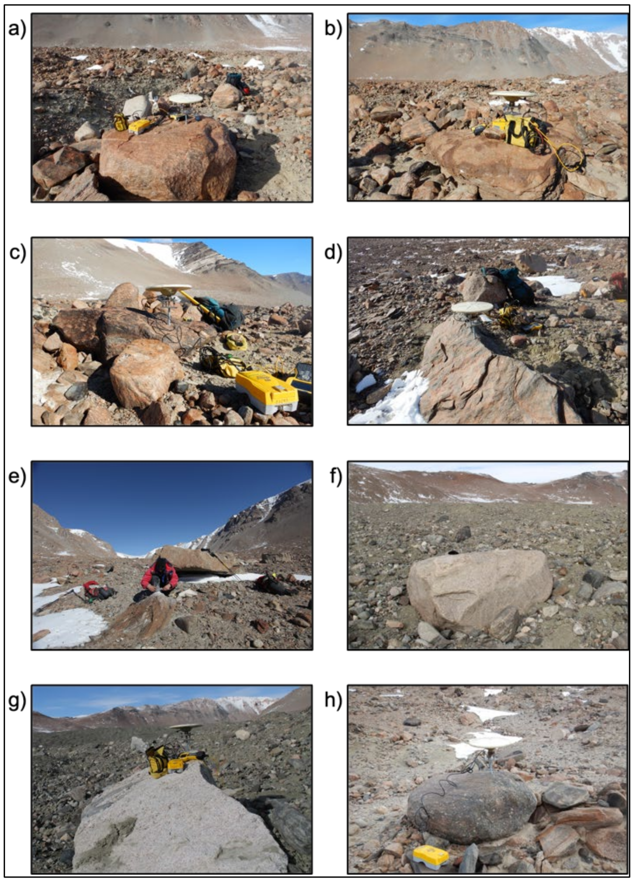

Figure 2. Photographs of surface boulders used for GNSS high-precision movement analysis. (a) OV-GPS-01, (b) OV-GPS-02, (c) OV-GPS-03, (d) OV-GPS-04, (e) OV-GPS-05, and (f) OV-GPS-06, (g) OV-GPS-07, and (h) OV-GPS-08.

failure set at 0.50 m. During field season 2010 and 2011, only daily data files were available (as opposed to hourly), and therefore only daily data files from the base station were used for all baseline processing of the boulder position.

2.2 Moraine Position Analysis

The moraine data point was imported and analyzed using ArcGIS Desktop 10.7.1. To analyze the moraine data, a 1-m resolution, Digital Surface Model (DSM) of Ong Valley was obtained from the Polar Geospatial Center's (PGC) Reference Elevation Model of Antarctica (REMA; Howat et al. 2019). Further, an 8-band multispectral, high-resolution (1.9 m) WorldView2 satellite imagery was obtained for Ong Valley. The satellite image was overlaid and visually georeferenced to the DSM hillshade raster imagery, resulting in a 2-m resolution satellite image of Ong Valley overlaying a 1-m resolution elevation data. The laser-measured moraines were manually added to the moraine point data, based on field measurements, satellite imagery, and raster elevation values.

To correlate glacial features across the valley walls in Ong Valley, an elongated two-dimensional profile of Ong Valley was created. First, a smooth curved profile line was drawn along the center of the valley, using the DSM raster for elevation values. Then all moraine data points were projected, in planar view, onto the profile line based on the nearest analysis. The resulting profile of Ong Valley is then plotted with the projected moraine points.

2.3 Boulder Movement Analysis

The movement of a boulder is determined by its change in position between the repeated measurements from 2010 to 2017. That is, we can calculate the distance between the measured location for a boulder between the years 2010–2011, 2011–2017, and 2010–2017. If the distance exceeds that of the uncertainty between two points in time, then the boulder is assumed to have moved. The position of the point is measured over a processing period in which multiple positions are continuously being recorded. The position after baseline processing is the calculated mean of x (Easting), y (Northing), and z (elevation) position during the measured period. The vertical precision is a one-dimensional component in the z-direction at the 95% confidence interval and is found by scaling the estimated 1-sigma standard deviation of all measured z-values by the coverage factor of 1.960 (Trimble 2019). The associated horizontal precision value is a two-dimensional standard error circle at the 95% confidence interval, representing the local accuracy. That is, the uncertainty in the x and y direction is represented by an error ellipse with semi-major and semi-minor axis and is combined into one horizontal precision value during baseline processing.

The calculated distance a boulder moved is that of the distance between the mean x, y, and z estimated for two separate years. Since the distance between the points is assumed to be < 10 cm, the spherical effect of Earth's curvature can be ignored, and the distance moved is calculated by the Euclidean distance between two points. The uncertainty in the Euclidean distance between the two points is that of the combined standard uncertainty expressed as the positive root of the combined covariance and is determined through error propagation using summation in quadrature, following that of Eq. B15 in Farrance and Frenkel (2012).

3 RESULTS

3.1 Moraine Mapping

It is evident from the mapping of the lateral and terminal moraines in Ong Valley that the Argosy Glacier has, during glacial advancement, expanded up and into the valley at least three times, leaving behind glacial drifts; previously identified by Bibby et al. (2016) as the old, middle and young drift (Figure 3). Using both field observations, moraine mapping, two-dimensional profile, and DSM, we can correlate between the mapped lateral and terminal moraines and assign inferred boundaries. We find that majority of the moraines can be continuously traced across the valley walls (Figure 3).

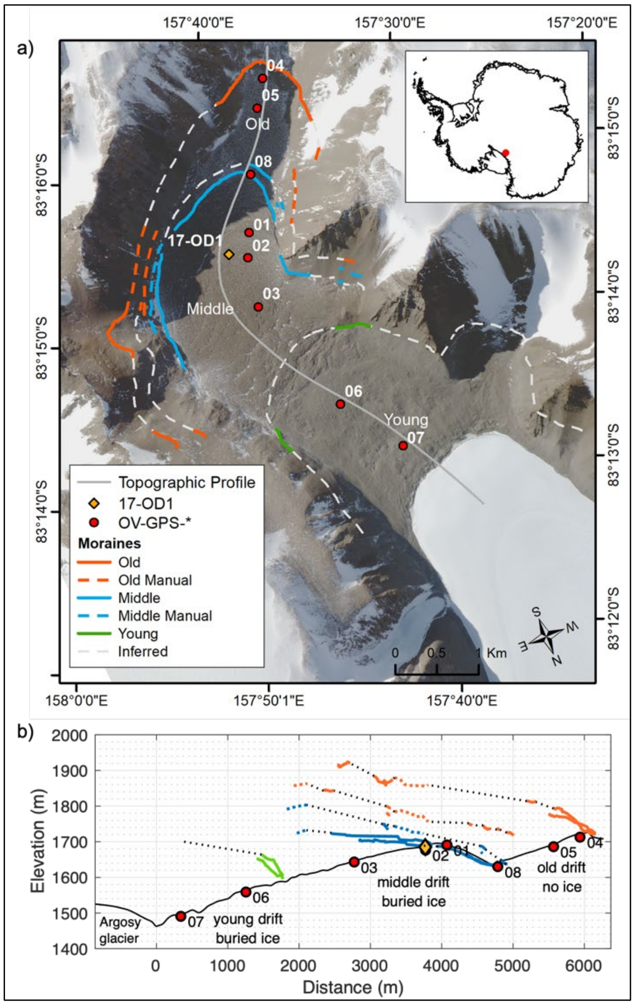

Figure 3. Moraine and drift boundaries mapped in Ong Valley, Antarctica (WV2 satellite image © 2016 Maxar). Solid lines indicate the lateral and end moraines traversed for the old drift (orange), middle drift (blue), and young drift (green). Dashed lines indicate the respective moraines mapped by laser ranger and reference point. Dashed grey (a) and black (b) lines are inferred moraine positions.

The current exposed Argosy Glacier lobe in Ong Valley is found at the valley mouth at an elevation of 1480 m a.s.l. The farthest advancement observed in the valley is that of the old drift. This advancement is well defined by a 1.8 km long, uninterrupted terminal moraine near the valley head. The old terminal moraine is found 6.2 km up valley from the Argosy Glacier lobe and at an elevation of 1725 m a.s.l. This results in at least a 245 m increase of ice surface elevation above the current in Ong Valley during the deposition of the old drift. The highest lateral moraine that can be correlated to the old terminal moraine is found at 1920 m a.s.l. on the East valley wall close to the valley mouth and is 440 m above the current ice elevation.

The extent of the middle drift is defined by a 330 m-long terminal moraine positioned on the western side of the drift. This terminal moraine is found 4.9 km from the Argosy Glacier lobe at an elevation of 1645 m a.s.l., and therefore, 165 m above current ice elevation. The current extent of the middle ice, buried below supraglacial debris, is located 110 m down valley from the middle terminal moraine at an elevation of 1636 m a.s.l., indicating that this part of the middle drift is depleted of ice. Further, we find that the highest point of the middle ice (along the topographic profile) is at 1695 m a.s.l., providing a minimum increase in elevation of the Argosy Glacier of 215 m above current during the deposition of the middle ice.

The drill site 17-OD1, used to date the age of the middle ice (Bergelin et al. 2022), is located centrally within the middle drift and found at 1685 m a.s.l., using the DSM (Figure 3). From the drill site and directly perpendicular to the valley wall, the current middle ice boundary is found at an elevation of 1699 m a.s.l. and 1694 m a.s.l. for the East and West valley walls, respectively. This results in the current boundary of the middle ice being 9–14 m above the drill site. Further, the lateral moraines associated with the emplacement of the middle ice are 1722 m a.s.l. This provides an ice surface lowering, local to the drill site, of at least 37 m since emplacement.

The most recent advancement has been dated to occur during the LGM (11–13 kyr; Bibby et al. 2016). During the LGM, the Argosy Glacier lobe expanded 2.3 km up valley reaching an elevation of 1600 m a.s.l. and, therefore, a 120 m increase in ice surface elevation above current.

3.2 Boulder Movement

We find that four of the eight boulders (OV-GPS-03, 06, 07, and 08) indicate movement in both the horizontal plane and three-dimensional space between the different periods of measurement (Table 1 and Figure 4). An additional boulder OV-GPS-01 indicates movement in the three-dimensional space only since no horizontal movement can be distinguished from the uncertainty (Table 1). The most movement was determined between 2010 and 2017, and 2011 and 2017, which are the two longest time intervals. The only movement between 2010 and 2011 occurs for boulder OV-GPS-03 and recorded in the horizontal plane only.

The young drift appears dynamic and exhibits surface movement (Table 1). The two boulders OV-GPS-06 and OV-GPS-07, located on the young drift, show distinct movement of 5.78 ± 0.91 cm and 4.85 ± 2.91 cm between the longest time interval, 2010-2017. The direction of movement is generally NNW, towards down valley (Figure 5). In three-dimensional space, the uncertainty has increased > 3 cm, resulting in a greater but less distinct movement for OV-GPS-07 (2010–2017, 7.73 ± 7.20 cm; and 2011–2017, 5.63 ± 7.89 cm), caused by the increased uncertainty in the vertical direction when measuring GPS positioning.

Table 1. Boulder movement results. The distances are reported for both horizontal and three-dimensional space, including the azimuth direction (Az.) and degrees from horizontal (From h.) representing the degree move in either upward (positive) or downward (negative) direction. Bold/grey shaded values indicate distance that are greater than the 95% uncertainty and where movement is considered.

		2010 - 2011				2011 - 2017				2010 - 2017			
Drift	Boulder OV-GPS-*	Horizontal distance (cm)	3D distance (cm)	Az. (deg.)	From h. (deg.)	Horizontal distance (cm)	3D distance (cm)	Az. (deg.)	From h. (deg.)	Horizontal distance (cm)	3D distance (cm)	Az. (deg.)	From h. (deg.)
Old	04	1.39 ± 5.68	6.37 ± 13.18	245	-77	1.87 ± 4.38	2.2 ± 8.27	40	31	0.84 ± 3.59	5.15 ± 11.95	356	-81
	05	0.68 ± 2.71	0.83 ± 6.58	139	35	0.87 ± 0.94	2.19 ± 4.49	299	-67	0.33 ± 2.41	1.56 ± 8.96	254	-78
	08	-	-	-	-	**0.96 ± 0.78**	**1.68 ± 1.50**	**298**	**55**	-	-	-	-
Middle	01	0.35 ± 1.43	1.32 ± 3.87	52	-75	0.14 ± 0.51	**1.94 ± 1.39**	**293**	**86**	0.31 ± 1.35	0.73 ± 3.67	29	65
	02	0.56 ± 0.84	1.76 ± 2.11	180	71	0.65 ± 1.19	0.66 ± 1.41	3	9	0.09 ± 1.4	1.77 ± 2.22	22	87
	03	**1.29 ± 1.28**	2.77 ± 3.46	49	-62	**0.78 ± 0.77**	**2.69 ± 1.86**	**327**	**73**	**1.6 ± 1.21**	**1.61 ± 1.32**	**20**	**4**
Young	06	0.51 ± 1.81	2.13 ± 4.71	23	-76	**5.55 ± 1.78**	**6.6 ± 3.75**	**318**	**33**	**5.78 ± 0.91**	**5.97 ± 1.25**	**322**	**15**
	07	1.36 ± 3.62	7.67 ± 11.04	171	80	**6.14 ± 3.12**	**7.73 ± 7.20**	**334**	**-37**	**4.85 ± 2.91**	5.63 ± 7.89	330	31

The middle drift shows a less definite movement in the surface boulders. Boulder OV-GPS-02 is located on the highest area of the middle drift and displays no movement to a position accuracy of < 1 cm. Boulder OV-GPS-01 and OV-GPS-03 are positioned on either side of the highpoint (up and down valley, respectively), and both indicate movement (Figure 5). Further, these two boulders are the only ones that display a vertical movement greater than the combined vertical uncertainty from 2011–2017 (Table 1). The vertical movement for boulders OV-GPS-01 and OV-GPS-03 is 1.94 ± 1.38 cm and 2.57 + 1.86 cm, respectively, in an upward direction. In addition, OV-GPS-03 shows horizontal movement in the NW direction and a maximum distance of 2.69 ± 1.86 cm in three-dimensional space (Table 1).

None of the boulders on the old drift surface (OV-GPS-04 and OV-GPS-05) show movement (Table 1). However, boulder OV-GPS-08 located at the boundary between the middle and old drift indicates a movement of 0.96 ± 0.78 cm and 1.68 ± 1.50 cm in the horizontal and three-dimensional space, respectively. The direction of movement is towards WNW (Table 1 and Figure 5). It should be noted that no GPS data was available for 2010, and therefore only movement analysis from the period 2011–2017 exists.

4 Discussion

Each of the three drifts in Ong Valley shows varying degrees of boulder movement and, therefore, variation in their stability. However, generally stability of the three drifts increases with distance from the valley mouth and, the age (Bibby et al. 2016; Scarrow et al. 2014).

4.1 Young drift

Movement analysis of surface boulders indicates a dynamic young drift with an average movement of 4.9–7.8 cm between 2010 and 2017 for boulders OV-GPS-06 and OV-GPS-07. We measured a supraglacial debris thickness of 14–26 cm for the young drift near these boulders. From field observations (Figures 2f and 2g), this would suggest that both boulder OV-GPS-06 and OV-GPS-07 are partially embedded in the ice and frozen in place. Therefore, any movement of the boulders is assumed to be a direct reflection of ice movement. The cause of this movement is speculative. However, from field observations, we find two possible scenarios that could lead to this distinct movement of the young drift surface boulders.

One possible scenario would suggest a stagnant ice mass, in which cryoturbation causes active movement of the supraglacial debris and surface of the buried ice. Thermal contraction of the ice during a cooling phase causes cracks to form in the ice and become filled with supraglacial debris. During a warming phase, thermal expansion of the ice causes compressive stresses and produces uplift along the crack. Over time, these cracks deepen and expand by the in-filling of supraglacial debris (Sletten et al. 2003). Such cryoturbation leads to polygon formation on the surface with an upward force of the underlying ice. A boulder on the surface of an active polygon can therefore experience movement caused by cryoturbation. However, the magnitude of movement for supraglacial debris on a polygon is dependent on its developmental stage and is unknown for the drifts in Ong Valley. Further, since the movement is caused by localized upward force of ice movement below the polygon, the direction of movement would be related to the boulder location relative to the

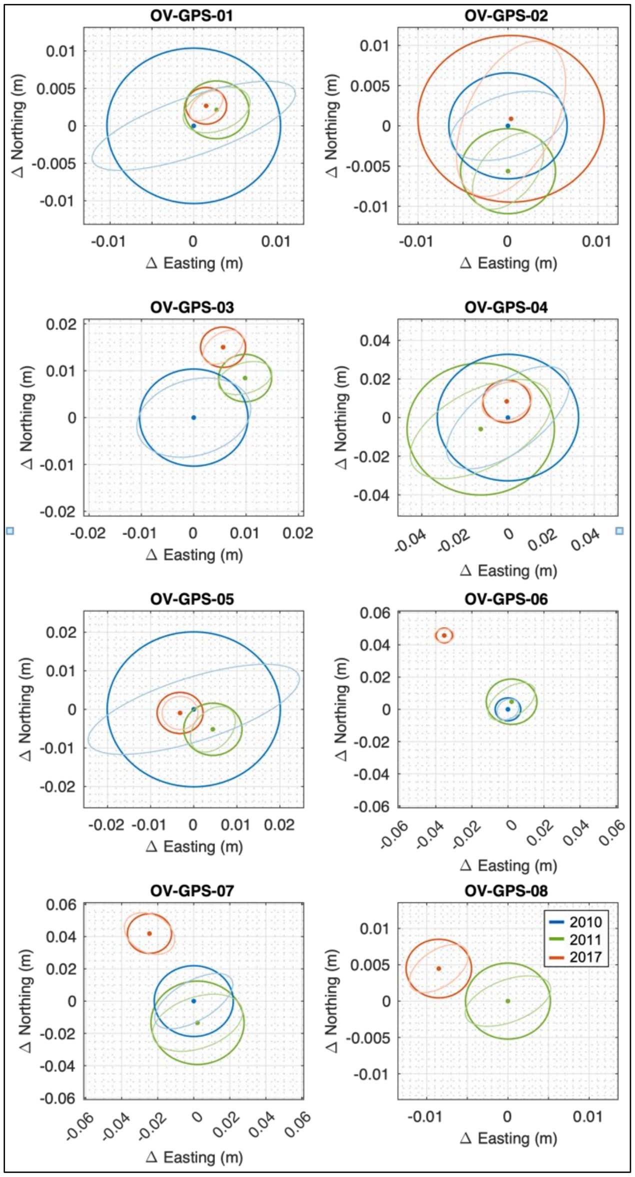

Figure 4 Horizontal boulder GNSS positions. An initial zero position is assigned to the 2010 boulder location, with 2011 and 2017 being the position relative to the initial point. Thick line represents the 95% error circle with a radius being the horizontal precision. Thin line represents the 95% error ellipse.

polygon's center. However, both boulder OV-GPS-06 and OV-GPS-07 are centered within the polygon, and therefore the direction of movement could be considered coincidental.

A second possible scenario would suggest that the young ice mass below the young drift is retreating and, therefore, not stagnant. Advancement of the Argosy Glacier deposited the young drift during the LGM, 11–13 kyrs ago (Bibby et al. 2016). During deposition, the Argosy Glacier extended 2.3 km farther into Ong Valley at an elevation of 120 m higher than the current. Since then, retreat and sublimation

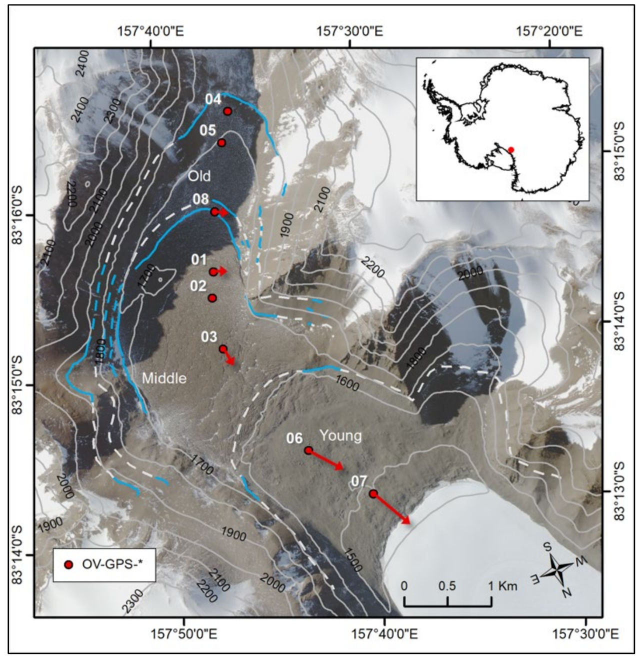

Figure 5 Directional movement of surface boulder in Ong Valley, Antarctica (WV2 satellite image © 2016 Maxar). Red arrows indicate the average direction of movement for the period 2010-2017 and 2011-2017, with arrow length indicating the average relative magnitude moved. Lines indicate lateral and end moraines mapped from traverses (blue solid line), elevation laser measurements (blue dashed line), and inferred from continuously tracing the moraines (white dashed line). Contour lines are shown in solid grey.

of the glacier lobe have created a buried ice mass experiencing an elevation difference between the maximum extent of the young drift buried ice and the current exposed glacial ice at the valley mouth (Figures 3 and 5). Boulders OV-GPS-06 and OV-GPS-07 both show movement in the NNW direction. This direction coincides with the direction of the slope gradient towards down valley, caused by a downward surface slope of ~5%. Therefore, the movement of boulders OV-GPS-06 and OV-GPS-07 could be caused by a downward flow of this young, buried ice towards the valley mouth. However, the movement is not considered an average flow rate of the ice. If this were the case, then this would suggest that the ice has moved several km since its deposition 11–13 kyrs ago and disagrees with observations in Ong Valley.

Whether or not the movement of boulders OV-GPS-06 and OV-GPS-07 was caused by flow of the young ice or a shift/tilt in the position of the boulders due to cryoturbation is unclear. From the available field data, the cause of movement observed in boulders 10-OV-GPS-06 and OV-GPS-07 could be either one of the above scenarios or more likely a combination of the two.

4.2 Middle Drift

The middle ice is assumed to be stable and stagnant as it has been preserved for ~3 Ma, and also the primary assumption for cosmogenic nuclide dating of the middle ice (Bergelin et al. 2022). With a supraglacial debris thickness of ~60 cm for the middle drift, all boulders found on the surface of the middle drift are assumed to be completely detached from the buried ice. Boulders OV-GPS-01 and OV-GPS-02 are located near drill site 17-OD1 (Bergelin et al. 2022) and are considered the most stable part of the middle drift. The calculated distances between the measured boulder positions are < 1.94 cm. The distance between 2011 and 2017 for boulder OV-GPS-01 is the only distance greater than the uncertainty of 95% by ~0.55 cm, and therefore an indication of movement.

While the middle drift is considered stable, the presence of desert pavement on the surface of the middle drift polygon formations provides evidence for an active debris surface. In addition, an active surface can also be explained by a partial mixing of the supraglacial debris as observed in the cosmogenic nuclide inventory (Bergelin et al. 2022). Therefore, it is not surprising that minimal movement could be observed for any boulder from the stable middle drift. Further, Bergelin et al. (2022) find the surface erosion rate for the middle drift to be ~0.0002 mm yr^{-1}. While such low erosion rates are not detectable within a decadal time scale, it is still indicative of an active surface. Whether or not a slowly eroding surface or active polygon formations caused this movement or shift in bolt positions is unclear.

In contrast, boulder OV-GPS-03 shows a maximum movement of 1.6 ± 1.21 cm and 2.69 ± 1.86 cm for horizontal and three-dimensional movement, respectively. Boulder OV-GPS-03 is located farther down valley near a transition zone between the young and the middle drift. From field observations, this zone shows recent disturbance caused by the deposition of the young drift 11–13 kyrs. Here, the polygon formations have increased high relief (Figure 3b). The surface exhibits larger-scale extensional crevasses perpendicular to the valley direction, with a down-sloping trend toward the Argosy Glacier, as observed in the topographic profile in Figure 3b. During the deposition of the young drift into Ong Valley, the upward pushing force of the advancing Argosy Glacier lobe would potentially cause the lower part of the middle drift, the transition zone, to be compressed. Since then, a retreat of the Argosy Glacier would cause relaxation and extension of this zone. As discussed above, if the young ice below the young supraglacial debris is active and moving down valley, this could potentially influence the middle ice found in this zone as an elevation difference is created from a recently (11–13 kyrs) retreating glacial deposit, causing a gravitational relaxation of the ice topography.

Boulder OV-GPS-08 is located near the boundary between the middle and old drift. More specifically, this boulder is positioned on the middle drift but beyond the current extent of the middle ice. Therefore, boulder OV-GPS-08 is part of the middle drift surface that has been depleted of ice and is considered to be relict. The stability of boulder OV-GPS-08 is questionable, as it is positioned on top of a debris mound and not partially embedded in the debris (Figure 2h). These debris mounds are left behind when the ice below polygon formations completely sublimates. On a million-year timescale, these debris mounds are expected to erode and flatten slowly, as observed on the surface of the old drift. Given the instability of boulder OV-GPS-08, such erosion could contribute to a tilting in the bolt position and result in a general upward movement of 1.68 ± 1.50 cm. However, this is speculative.

4.3 Old Drift

The old drift is completely depleted of buried ice based on the field observations and the valley cross-sectional profiles (Figure 3b). If the separate, older ice mass below the middle ice is that of the old drift deposit (Bergelin et al. 2022), then the oldest drift was deposited 4–5 Myrs ago and is considered an ancient, relict surface. Boulder OV-GPS-04 and OV-GPS-05 agree with such, as no movement is detected.

5 Conclusions

We evaluated the stability of an ancient, buried ice mass and its associated drift system in Ong Valley, Transantarctic Mountains, Antarctica. The glacial drift system comprises three successively older drifts, dated at 11–13 kyrs, 2.9 Myrs, and 4.3–5.1 Myrs, in which buried ice underlies the two youngest. We used high-precision GPS positioning to map the glacial moraines and drift boundaries, and the current boundary of the two buried ice masses. Further, we measured high-precision markers on eight surface boulders located on the drifts over a period of seven years (2010–2017) to determine the mobility and stability of these drifts and buried ice masses.

We find the stability of the three drifts to increase with distance from the valley mouth. The youngest drift appears to be dynamic and exhibits surface boulder movement between 0.79 and 1.10 cm/yr down the valley over the seven-year period, indicating active movement of the ice below the supraglacial debris. The middle drift and ice are considered stable with a potential boundary relaxation and adjustment because of the loss of buttressing by the now retreating Argosy Glacier since the LGM. The middle drift surface is still subject to slow erosion and/or polygon formations. However, no ice movement was detected during the observed seven-year period. The old drift is void of buried ice and shows no signs of movement.

Our differential GPS-based analyses of the three drift surfaces of which two younger ones are still underlain by glacial ice supports and enhances our understanding of the slowly evolving Antarctic landscape. The oldest surface on the valley floor has entered a more sedentary phase as no ice from a 4–5 Myrs old ice sheet expansion exist there any more. However, the middle drift (2.95 Myrs old) is still underlain by slowly sublimating ice and thus, currently shows signs of intermittent shifts on surface boulders. And the youngest drift is in a stage of relatively rapid landscape evolution as attested by relatively large boulder movements within the 7-year study period.

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7 References

Bergelin, M., Putkonen, J., Balco, G., Morgan, D., Corbett, L.B., and Bierman, P.R. 2022. 'Cosmogenic nuclide dating of two stacked ice masses: Ong Valley, Antarctica', *The Cryosphere* 16, pp. 2793–2817.

Bibby, T., Putkonen, J., Morgan, D., Balco, G., and Shuster, D.L. 2016. 'Million year old ice found under meter thick debris layer in Antarctica', *Geophysical Research Letters* 43, pp. 6995–7001.

Evatt, G.W., Abrahams, I.D., Heil, M., Mayer, C., Kingslake, J., Mitchell, S.L., Fowler, A.C., and Clark, C.D. 2015. 'Glacial melt under a porous debris layer', *Journal of Glaciology* 61, pp. 825–836.

Farrance, I. and Frenkel, R. 2012. 'Uncertainty of Measurement: A Review of the Rules for Calculating Uncertainty Components through Functional Relationships', *The Clinical Biochemist Review* 33, pp. 49–75.

Hindmarsh, R.C.A., Van der Wateren, F.M., and Verbers, A.L.L.M. 1998. 'Sublimation of ice through sediment in Beacon Valley, Antarctica', *Geografiska Annaler, Series A, Physical Geography* 80(3/4), pp. 209–219.

Howat, I.M., Porter, C., Smith, B.E., Noh, M.-J., and Morin, P. 2019. 'The Reference Elevation Model of Antarctica', *The Cryosphere* 13, pp. 665–674.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., et al. 2007. 'Orbital and millennial Antarctic climate variability over the past 800,000 years', *Science* 317, pp. 793–796.

Kowalewski, D.E., Marchant, D.R., Swanger, K.M., Head, J.W., 2011. Modeling vapor diffusion within cold and dry supraglacial tills of Antarctica: Implications for the preservation of ancient ice', *Geomorphology* 126, pp. 159–173.

Mihalcea, C., Mayer, C., Diolaiuti, G., Lambrecht, A., Smiraglia, C., and Tartari, G. 2006. 'Ice ablation and meteorological conditions on the debris-covered area of Baltoro glacier, Karakoram, Pakistan', *Annals of Glaciology* 43, pp. 292–300.

Moore, P.L. 2017. 'Stability of supraglacial debris', *Earth Surface Processes and Landforms* 43, pp. 285–297.

Ng, F., Hallet, B., Sletten, R.S., and Stone, J.O. 2005. 'Fast-growing till over ancient ice in Beacon Valley, Antarctica', *Geology* 33, pp. 121–124.

Östrem, G. 1959. 'Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges', *Geografiska Annaler* 41, pp. 228–230.

Putkonen, J., Balco, G., and Morgan, D. 2008. 'Slow regolith degradation without creep determined by cosmogenic nuclide measurements in Arena Valley, Antarctica', *Quaternary Research* 69, pp. 242–249.

Putkonen, J. and Mahmood, T.H. 2022. 'Twenty-four buried ice masses remotely mapped in Transantarctic Mountains, Antarctica', *Geocarto International* 38.

Ragettli, S., Bolch, T., and Pellicciotti, F. 2016. 'Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal, Nepal', *The Cryosphere* 10, pp. 2075–2097.

Scarrow, J.W., Balks, M.R., and Almond, P.C. 2014. 'Three soil chronosequences in recessional glacial deposits near the polar plateau, in the Central Transantarctic Mountains, Antarctica', *Antarctic Science* 26, pp. 573–583.

Schäfer, J.M., Baur, H., Denton, G.H., Ivy-Ochs, S., Marchant, D.R., Schlüchter, C., and Wieler, R. 2000. 'The oldest ice on Earth in Beacon Valley, Antarctica: new evidence from surface exposure dating', *Earth and Planetary Science Letters* 179, pp. 91–99.

Sletten, R.S., Hallet, B., and Fletcher, R.C. 2003. 'Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground' *Journal of Geophysical Research* 108.

Stone, J., Sletten, R.S., and Hallet, B. 2000. 'Old ice, going fast: Cosmogenic isotope measurements on ice beneath the floor of Beacon Valley, Antarctica', *Eos Transactions American Geophysical Union* 81, pp. 15–19.

Sugden, D.E., Marchant, D.R., Potter, N., Souchez, R.A., Denton, G.H., Swisher, C.C., and Tison, J.L. 1995. 'Preservation of Miocene Glacier Ice in East Antarctica', *Nature* 376, pp. 412–414.

Trimble 2019. *Trimble Business Center v5.0 – Processing and Adjusting GNSS Survey Control Networks.* Sunnyvale, California, United States.

Van der Wateren, D. and Hindmarsh, R. 1995. 'Stabilists strike again', *Nature* 376.

Yan, Y., Bender, M.L., Brook, E.J., Clifford, H.M., Kemeny, P.C., Kurbatov, A.V., Mackay, S., Mayewski, P.A., Ng, J., Severinghaus, J.P., and Higgins, J.A. 2019. 'Two-million-year-old snapshots of atmospheric gases from Antarctic ice', *Nature* 574, pp. 663–666.