Antarctic Science 11 (2): 256–260 (1999) © British Antarctic Survey Printed in the United Kingdom

Glacial boulders 'floating' on the ice cover of Lake Untersee, East Antarctica

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Abstract: Large glacial boulders, up to several metres in diameter, resting on the lake ice are a remarkable feature of Lake Untersee (71°21'S, 13°28'E), an ice-dammed, perennially frozen freshwater lake in the Otto-von-Gruber-Gebirge (Gruber Mountains) of central Queen Maud Land, East Antarctica. A geodetic survey of such ice-rafted boulders was made over two summer seasons to determine the direction and velocity of their movement. They are transported between 3.9 and 11.1 m annually and the residence time of the boulders is estimated at approximately 500 years. Lake Untersee must have been permanently covered with lake ice for at least that long.

Received 8 July 1998, accepted 22 January 1999

Key words: Antarctica, glacial boulders, glacial geomorphology, lake ice

Introduction

A notable feature of perennially frozen lakes at glacier/rock margins in Antarctica is the presence of boulders on the ice surface (Pickard & Adamson 1983). For example, many of the ice covers on lakes in the McMurdo Dry Valleys carry surface debris ranging from sand-sized grains to 'floating boulders' several metres in diameter (Doran *et al.* 1994, and references cited therein). A number of hypotheses have been provided to account for 'floating boulders', such as direct deposition of debris from proglacial contact (Bell 1969), near-shore plucking and thrusting (Chinn 1993), mass wasting from peaks near the lakes (Wharton, quoted in Doran *et al.* 1994), and proglacial transfer during the replacement of glacial ice by lake ice (Pickard & Adamson 1983).

Large boulders rest on the ice cover of Lake Untersee (71°21'S, 13°28'E), a perennially ice-covered freshwater lake in the Otto-von-Gruber-Gebirge (Gruber Mountains), East Antarctica (Figs 1 & 2). They are mostly derived from supraglacial till, and their occurrence is a consequence of glacial ice being replaced by lake ice. The transport of such boulders by lake ice can be best explained by the following mechanism: glacial ice is gradually replaced by lake ice at their interface without melting. When the boulders reach the surface of the proglacial lake, they are then rafted across the lake in response to glacier movement (Clayton-Greene & Hendy 1986, Chinn & Maze 1983). This process is enhanced by the formation during most summers of narrow zones of open water (*c.* 1–3 m wide) along the shore of Lake Untersee. Along these the lake ice cover is 'consumed'.

Only a few boulders could have fallen directly onto the lake from steep valley sides. Large erratics are massive enough to prevent their melting through the ice cover because of insufficient heat transfer. On the other hand it can be seen at some places on Lake Untersee that small boulders melt into the lake ice, forming cryoconite hollows. Such debris will ultimately subside through the ice cover.

To our knowledge, transport velocity and direction of such lake ice-rafted boulders have never been determined. During two summers, we therefore carried out a geodetic survey of some boulders resting on the ice of Lake Untersee. The aim was to obtain information on the persistence of the perennial ice cover.

Site description

Lake Untersee is one of the largest freshwater lakes (11.4 km^2 surface area) on continental Antarctica (Hermichen *et al.* 1985) and characterized by a number of peculiarities (Wand *et al.* 1997), among them a perennial ice cover. The lake has repeatedly attracted scientific interest during recent years (Kaup *et al.* 1988, Richter & Bormann 1995, Wand *et al.* 1994, 1996, 1997). It has no drainage, is up to 169 m deep and the ice cover is up to 4 m thick in summer. The lake lies in a deep cirque-like valley, which is dammed at its northern end by the Anuchin Glacier (Fig. 1). Steep, partly moraine-covered mountain slopes of the Elisseev Anorthosite Massif (Simonov *et al.* 1985) surround the remaining sides of the lake.

Lake Untersee is fed primarily by glacial melt water, supplied mostly by subaquatic melting of Anuchin Glacier, and it loses water only by sublimation at the surface of the lake ice, mainly in summer (Hermichen *et al.* 1985). The loss by evaporation from small zones of open water is negligible. According to own measurements, the ablation amounts to up to 60 cm of lake ice per year. During the winter, the ice cover thickens again by freezing of water from below.

https://doi.org/10.1017/S0954102099000310 Published online by Cambridge University Press

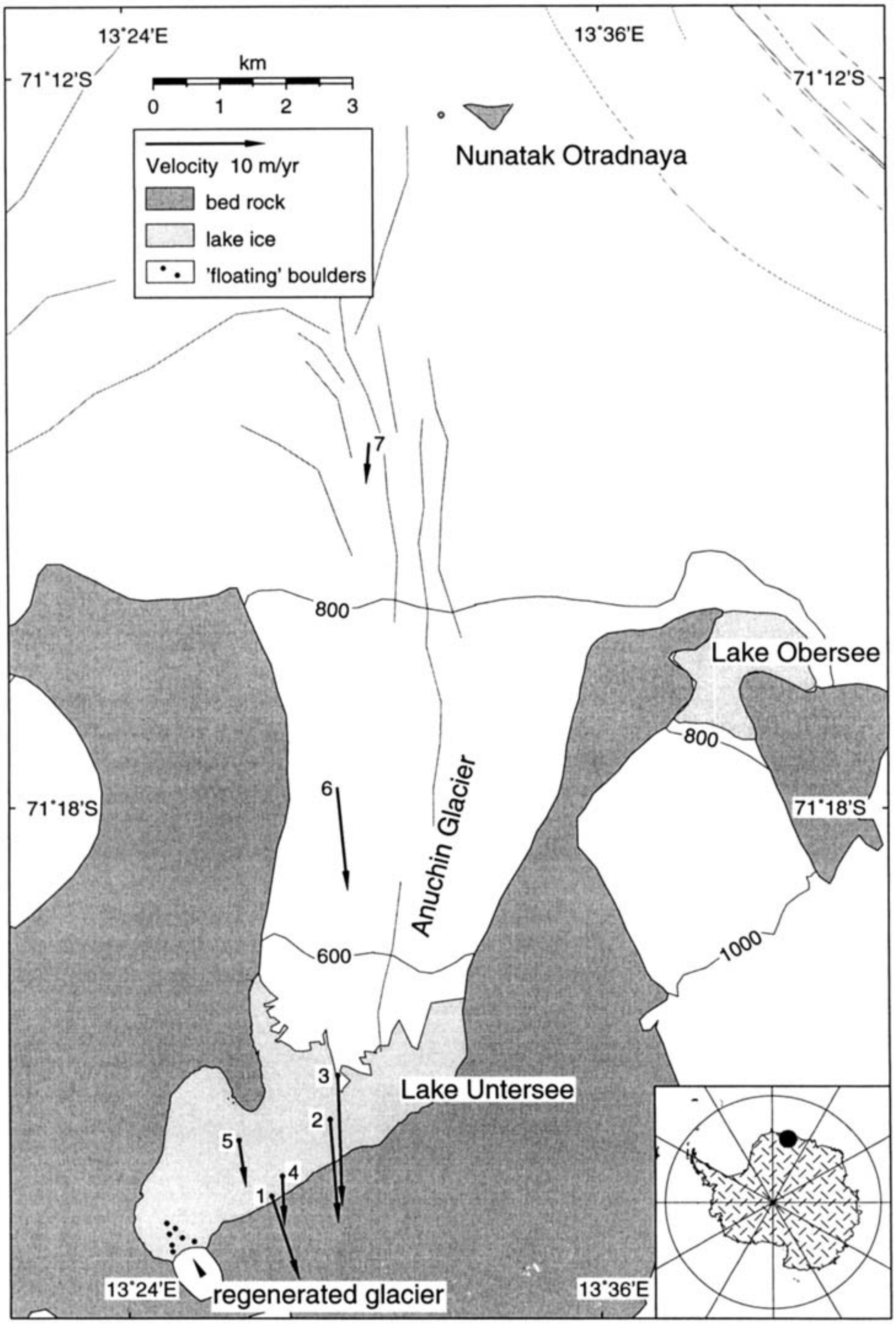

Fig. 1. Direction and velocity (vectors 1–5) of glacial boulders floating on the ice cover of Lake Untersee; the length of the arrows is proportional to the rate of movement of the boulders. Vectors 6 & 7 indicate the ice flow of the Anuchin Glacier, damming Lake Untersee. The dashed lines on the glacier are flow lines visible on aerial photographs. Contours in m above sea level.

The more than one hundred boulders on the lake ice have been delivered by two glaciers which partially border the lake: the damming Anuchin Glacier in the north and a small glacier at the southern shore. The latter, referred to here as 'regenerated' glacier, is fed (regenerated) by ice avalanches falling from a higher-lying glacier, over a steep several hundred metres high rock face (Kosenko & Kolobov 1970). Most of the boulders are located in the southern part of Lake Untersee in front of the regenerated glacier. This glacier creates an approximately 1–2 m high pressure ridge trending parallel to the glacier snout (see Fig. 2). Although none of these boulders has been geodetically surveyed, a general north-west floating direction can be deduced from the boulders' arrangement, which is concentric to the glacier termination.

The largest boulders have diameters of about 5–6 m. Some of them perch on lake ice pedestals, approximately 0.2–0.4 m high, and are surrounded by a shallow 'moat' (see Fig. 3). These dry 'moats', mostly between 0.1 and 0.3 m deep, are caused by a combination of heat radiation and wind ablation processes (Richter 1986, Pickard & Adamson 1983).

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Fig. 2. Lake Untersee with numerous boulders resting on its ice cover. The small regenerated glacier at the southern shore causes a pressure ridge in the lake ice. Snow-scooter in foreground for scale.

Methods and instruments

For the survey, five large (up to 6 m in diameter) boulders, which obviously originated from Anuchin Glacier, were selected (Fig. 3). They were widely dispersed across the surface of Lake Untersee. The boulder velocities were calculated from the difference in positions from two independent geodetic surveys during the summers 1994–95 and 1995–96 (period between both surveys: *c.* 11 months). The first survey was carried out with an electro-optical RECOTA tachymeter (Carl Zeiss Jena) and the second by GPS (global positioning system) using Trimble GPS receivers and two-frequency antennas (see Fig. 3). The mean error of the position determination with the tachymeter was approximately 20 mm. Based on an observation time of between 20 and 30 minutes and a base line length of < 5 km, the accuracy of the GPS method amounted to 10–20 mm. As a mean observation date, the calendar day of the observation was regarded as sufficient. An annual movement of 10 m corresponds to a daily increment of approximately 28 mm. The possible error caused by using the calendar day is less than 14 mm. Identical benchmarks were used for both the GPS and the tachymeter measurements.

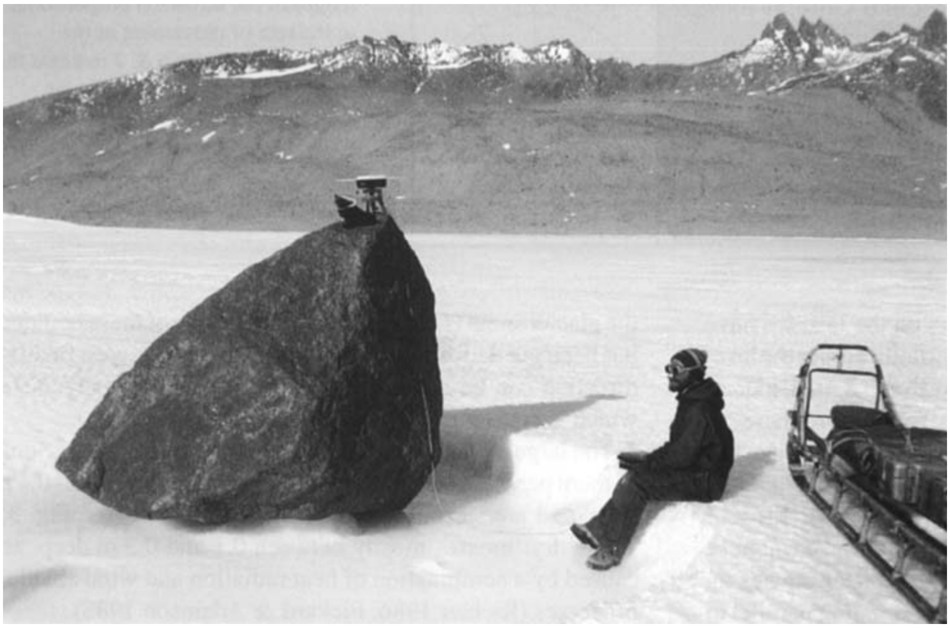

Fig. 3. Large boulder on the ice of Lake Untersee. The antenna of the GPS equipment, used for position determination, is placed on the top of the boulder.

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Results and discussion

The results of the survey of the movement of the five boulders on the lake ice and of two beacons installed on Anuchin Glacier are presented in Table I and Fig. 1. The movement of the boulders is surprisingly high, varying between 3.9 and 11.1 m year^{-1}.

It is interesting to note that the rafting of the surveyed boulders is generally directed towards the south or SSE. This corresponds to the flow direction of the damming Anuchin Glacier (see Fig. 1) and reflects the main direction of the glacier's lateral pressure. The permanent pressure on the adjoining lake ice deforms the ice cover into pressure ridges near the glaciolacustrine margin. These ridges, 1–1.5 m high, run mostly parallel to the glacial margin, have steep (at the glacier margin) or shallow flanks, and exhibit longitudinal and transverse cracks (cf. Pickard & Adamson 1983). A small, up to 2.5 m high, pressure ridge follows most of the south-eastern shore of Lake Untersee.

The residence time (t) of a boulder on the lake ice can be calculated from our measurements using the simple relationship: distance travelled divided by velocity ($t = d/v$). For instance, assuming an average transportation rate of 1 m year^{-1} and a 'floating' distance of 2 km, the residence time would ideally amount to 2000 years. Of the surveyed boulders, No. 4 was one of the 'slowest' boulders and had moreover a relatively long travelled distance (*c.* 2300 m). With a velocity of 4.1 ma^{-1} the resulting residence time amounts to approximately 500 years. This means that Lake Untersee must have been permanently covered by ice for at least that long. The floating boulders disappear into the lake when they reach the edge of the seasonal ice-free zone at the far shore, or when the lake becomes completely free of ice during a climatic optimum. Taking into account that the velocity of a boulder is not constant over its whole lifetime on lake but varies more likely with position, the calculated residence time is only a rough estimate.

The question arises, why despite the large ablation rate, the surface of Lake Untersee is not covered with debris of smaller boulders. This may be due to an average subsidence rate exceeding the ablation rate. Rock subsidence experiments conducted by Chinn (1993) on Lake Vanda (McMurdo Dry Valleys), an Antarctic lake with a comparable ablation rate, demonstrated that rocks from 0.1 m to 0.5 m in diameter and sand moved through the ice and ultimately dropped into the lake (cf. also Squyres *et al.* 1991). The finer the sediment, the faster was its downward movement. Ice covers that are thinner than about 4.5 m do not accumulate abundant sediment because they are rather permeable during part of the year (Andersen *et al.* 1993).

Table I. Results of the geodetic survey.

Number in Fig. 1	Object	Direction (°) of movement	Velocity (ma^{-1})
1	boulder	162	7.4
2	boulder	176	8.8
3	boulder	178	11.1
4	boulder	178	4.1
5	boulder with centre mark	172	3.9
6	beacon on traverse	175	8.8
7	beacon on traverse	184	3.3

In conclusion, measuring the velocity of boulders floating on the ice surface of perennially frozen lakes is a means of evaluating the minimum age of the permanent ice cover. For such a purpose, a modern GPS measuring system is suitable. The study of long-term variations and their relationship to climatic variations (glacier movement) could be a field of future research. The few available data do not allow the derivation of a flow and deformation model. The data are, however, useful to estimate the magnitude of the local ice dynamics (glacial and lake ice). To survey the movement of the lake ice cover in detail, a network of stakes would be more appropriate.

Acknowledgements

We are indebted to M. Schwab, D. Schachtschneider, V.A. Samarkin, and G. Müller for assistance in the field during the austral summer of 1994–95. Thanks is also due to H.-J. Paech (BGR, Hannover) for the invitation to participate in the GeoMaud Expedition 1995–96. The paper benefited from reviews by C.S.M. Doake, C. Hjort, and helpful comments by M.R.A. Thomson. Paul Overduin kindly improved the English. This paper is contribution No. 1390 of the Alfred Wegener Institute for Polar and Marine Research.

Note

For geographic names used see Sievers (1993) and US Board for Geographical Names (1995).

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https://doi.org/10.1017/S0954102099000310 Published online by Cambridge University Press