Geological Quarterly, 2001, **45** (4): 365–372

Remote sensing of eskers from Vormsi and Väinameri vicinity, northwestern Estonia

James S. ABER and Volli KALM

Aber J. S. and Kalm V. (2001) — Remote sensing of eskers from Vormsi and Väinameri vicinity, northwestern Estonia. Geol. Quart., **45** (4): 365–372. Warszawa.

We have utilised techniques of remote sensing in combination with ground observations in order to investigate eskers of the Vormsi and Väinameri region of northwestern Estonia. Landsat Thematic Mapper (TM) images were the basis for recognition and regional interpretation of esker systems, and kite aerial photography was employed for detailed, low-height views of selected eskers. A special Landsat TM composite was developed to enhance the display of shallow sea floor features. On this basis, we have extended known, land-based eskers across the sea floor, and we have identified additional probable eskers marked by shallow shoals and tiny islands. The known and suspected eskers of Vormsi and surroundings demonstrate a regular pattern in their distribution, which we suggest represents a subglacial drainage network that was anastomosing in character. The esker network is located along the central pathway of the Väinameri ice lobe, and the overall direction of drainage was toward the Palivere glacial limit. We interpret eskers of the Vormsi-Väinameri vicinity as evidence for substantial meltwater discharge beneath the Väinameri ice lobe, which terminated in a proglacial lake.

James S. Aber, Earth Science, Emporia State University, Emporia, Kansas, 66801-5087 USA, e-mail: aberjame@emporia.edu; Volli Kalm, Institute of Geology, University of Tartu, 51014 Tartu, Estonia, e-mail: vkalm@ut.ee (received: December 7, 2000; accepted: February 2, 2001).

Key words: Estonia, Palivere, Landsat, esker, subglacial meltwater, ice lobe surge.

INTRODUCTION AND GEOLOGICAL BACKGROUND

The island of Vormsi and the adjacent mainland are parts of the West Estonian Lowland, and the island of Hiiumaa lies in the West Estonian Archipelago. The islands are separated from each other and from the mainland by shallow sea floor of the Väinameri (Fig. 1). The region has low topographic relief; land elevations are mostly less than 20 m. The Väinameri sea floor is less than 10 m deep; water depth in parts of Hari Kurk is 10–16 m, and the sea floor descends northward to more than 100 m deep in the central Gulf of Finland. The region is underlain by Upper Ordovician and Lower Silurian limestone bedrock that dips gently to the south. The thickness of Quaternary sediment is generally less than 5 m on the island of Vormsi, 5–10 m on the adjacent mainland, and more than 20 m on Hiiumaa (Raukas and Kajak, 1997, fig. 91). Thicker Quaternary sediments are encountered in buried valleys. The northwestern portion of Vormsi is considered an “alvar”, a region with exposed bedrock at the surface.

Two prominent eskers cross Vormsi from north-west to south-east (Raukas *et al.*, 1971, fig. 51; Ratas, 1977; Kadastik and Kaljuläte, 2000), and a third esker is present on the mainland in the Noarootsi parish (Fig. 1). These previously mapped eskers are identified in this report by local place names Hullo, Norrby and Noarootsi. Lying between these eskers, buried valleys are known beneath Voosi Kurk and Haapsalu Bay, and under the Sviby vicinity of Vormsi. Surficial marine sediment of the Limnea Sea covers much of Vormsi and adjacent, low-lying land areas (Kajak *et al.*, 1999) and dates from around 4000 years ago (Raukas, 1997). As a result of submergence, the eskers are covered by reworked beach gravel, consisting mainly of limestone pebbles, and large erratic boulders are concentrated along raised beach ridges. The region continues to experience slow postglacial rebound and emergence along the coast.

Vormsi is situated in the central pathway of an ice lobe of the Palivere phase of the Võrtsjärv (Late Weichselian) Glaciation. This ice lobe followed the Väinameri topographic low toward the south-southeast (Kadastik and Kalm, 1998). The Palivere limit of glaciation is marked by a prominent moraine on the mainland and by a string of small islands across the Väinameri (Fig. 1). A reentrant in the Palivere glacial limit at Kassari Bay marks the junction of the Väinameri ice lobe with another lobe that covered the western portion of Hiiumaa and Saaremaa. As

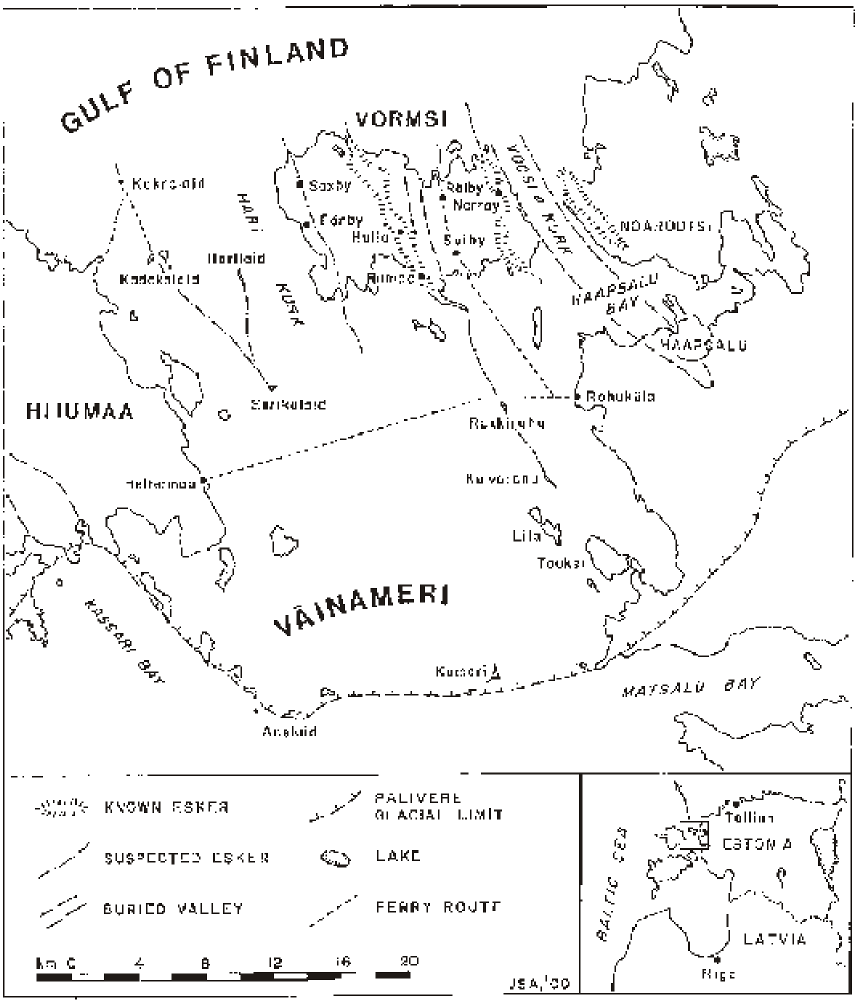

Fig. 1. General locality map for Vormsi, Väinameri, and surrounding area

Positions of suspected eskers based on interpretation of Landsat TM images; other glacial features adapted mainly from Kajak *et al.* (1999)

surficial landforms, the eskers of Vormsi and Noarootsi are considered to be genetically related to the Väinameri ice lobe and Palivere phase of glaciation. However, the age and genesis of buried valleys are uncertain and could relate to previous glaciations. The Palivere stade has been interpreted as a re-advance of the Scandinavian ice sheet, following complete deglaciation of the Estonian territory after the Pandivere stade (Raukas, 1986; Karukäpp and Raukas, 1997). The exact age of the Palivere readvance is uncertain, but was probably in the range of 11 000 to 12 000 years ago (Kadastik and Kalm, 1998).

Remote sensing of Estonia based on satellite imagery has been carried out for various mapping, land-use classification, and environmental investigations. Of special interest for this study is the discussion by Peterson *et al.* (1998) of satellite imagery for the Väinameri region. Given the relatively shallow and clean water of Väinameri, it is possible to view the sea floor in satellite images. Local sea level fluctuates daily in response to changes in wind direction; tides have negligible influence. Short-term changes in sea level of 10–25 cm are common in coastal zones. Such fluctuations can have marked impact on the appearance of the low-relief coastal environment in satellite images.

METHODS OF INVESTIGATION

We have utilised techniques of remote sensing in combination with ground observations and reference to existing maps and previous geological studies. Our primary method involves Landsat Thematic Mapper (TM) imagery. Four Landsat TM datasets were acquired from the spring and summer of 1986 and 1988 (Table 1). These scenes were processed using *Idrisi32* software; standard image enhancement and analysis techniques were employed (Jensen, 1996). Based on previous experience in similar settings, the geobotanical approach was used for interpretation of images (Aber and Ruszczyńska-Szenajch, 1997). With this approach, vegetation cover and water bodies are assumed to indi-

Table 1

Landsat Thematic Mapper (TM) datasets selected for analysis in this study

Scene identification number	Scene date	Path/row
LT5188019008620910	1986/07/28	188/19
LT5188019008617710	1986/06/26	188/19
LT4189019008813410	1988/05/13	189/19
LT5189019008618410	1986/07/03	189/19

Scenes from path/row 188/19 include the mainland of western Estonia; scenes from path/row 189/19 are centered on the Baltic islands of westernmost Estonia; all datasets contain less than 10% cloud cover; Landsat TM datasets acquired from the EROS Data Center, U.S. Geological Survey

cate variations in soil types and landforms, which in turn reflect underlying sediment and bedrock conditions.

Two types of composite images were found to be most useful for interpretation of geomorphic features. For display of land vegetation and general depiction of water bodies, we utilised a false-colour composite based on TM bands 3, 4 and 5 colour coded as blue, green and red (Fig. 2). Band 3 (red light) is strongly absorbed by photosynthetically active vegetation, whereas band 4 (near infrared) is strongly reflected. Band 5 (mid infrared) is sensitive to moisture content in leaves and soil. This composite enhances the appearance of different kinds of land vegetation and cleared or bare land surfaces, and water bodies appear quite dark regardless of water depth or turbidity.

To view the shallow sea floor, we developed a special composite in which, land and sea areas were first separated, then processed differently, and finally recombined. The land-water separation was accomplished with the TM band 7/2 ratio. Band 7 (mid infrared) is totally absorbed by all types of surface water, whereas band 2 (green) is weakly reflected from water; both bands are reflected from other materials. With the 7/2 ratio, lowest values represent water, and higher values are land areas of all kinds. A supervised classification was carried out to create a land-water mask. Specular reflections (sun glitter) from the sea in the northwestern corner of the scene were manually removed. This mask was then multiplied with TM band 2; the result is an image in which, land is blank and the sea (and small lakes) are depicted in various tones that represent differences in water depth and/or turbidity. The band 2 water-only image then was combined with bands 3 and 5 to create a false-colour composite in which, both land areas and the sea are enhanced (Fig. 3).

To acquire ground truth, we employed kite aerial photography to capture low-height images of the landscape and shallow sea floor. Kite aerial photography (KAP) involves the use of large kites to lift a light-weight camera rig 50–150 m above the ground (Aber *et al.*, 1999; Aber and Gałązka, 2000). Camera position (pan and tilt) and shutter release are operated by radio control from the ground. KAP provides a means to acquire large-scale, high-resolution images in which dm-sized objects are depicted. Details of vegetation, soils, sediment, bedrock, drainage and water bodies are clearly evident in kite aerial photographs. Photographs can be taken in any orientation — vertical, low- and high-oblique, and in any direction relative to the Sun. This provides for a greater variety of perspectives and lighting onditions compared to conventional airphotos. KAP was carried out at four sites on the island of Vormsi — Norrby, Saxby, Förby, and Rumpo (Fig. 1). We employed *Kodak Ektachrome* 35-mm, colour-visible, diapositive film (ISO 200) for general depiction of land cover and penetration of the shallow sea.

REMOTE SENSING RESULTS

The eskers of Vormsi are shown in Landsat TM images by distinctive patterns of land use and by their prominent peninsulas (Fig. 4). As the highest and best-drained landforms, the eskers are largely cleared for agricultural fields and are sites for roads and villages (Fig. 5). This land use contrasts with forest cover in lower, poorly drained zones between eskers. The eskers at Hullo and Norrby are both marked by peninsulas which, serve to further define their trends. The mainland esker in Noarootsi displays similar land-use patterns, and it forms a peninsula to the north-west.

The special Landsat TM composite contains considerable information about the Väinameri region (Fig. 3). Comparison of the composite with bathymetric charts indicates the image depicts subtle variations in water depth. The appearance of the sea floor is enhanced by light gray colour of underlying limestone bedrock and gravel deposits derived from the limestone. The sea floor is revealed in such detail that dredged ferry channels are clearly visible at Heltermaa and Sviby harbours. On this basis, it is evident that Vormsi eskers continue onto the sea floor as shallow linear shoals and tiny islands (Fig. 1). The Hullo esker can be traced to the south-east to Rukkirahu and Kuivarahu, a distance of nearly 12 km. The existence of a shallow (esker) bar just north of Rukkirahu was confirmed in 1999, when the ferry channel between Rohuküla and Heltermaa was dredged to accommodate larger ships. On this basis, the total length of the Hullo-Kuivarahu esker is about 25 km.

The Norrby esker appears to extend offshore approximately 5 km toward the north-west as a shallow linear bar. The south-eastern end of this esker branches in two ridges marked by peninsulas which diverge by roughly 40°. The eastern branch

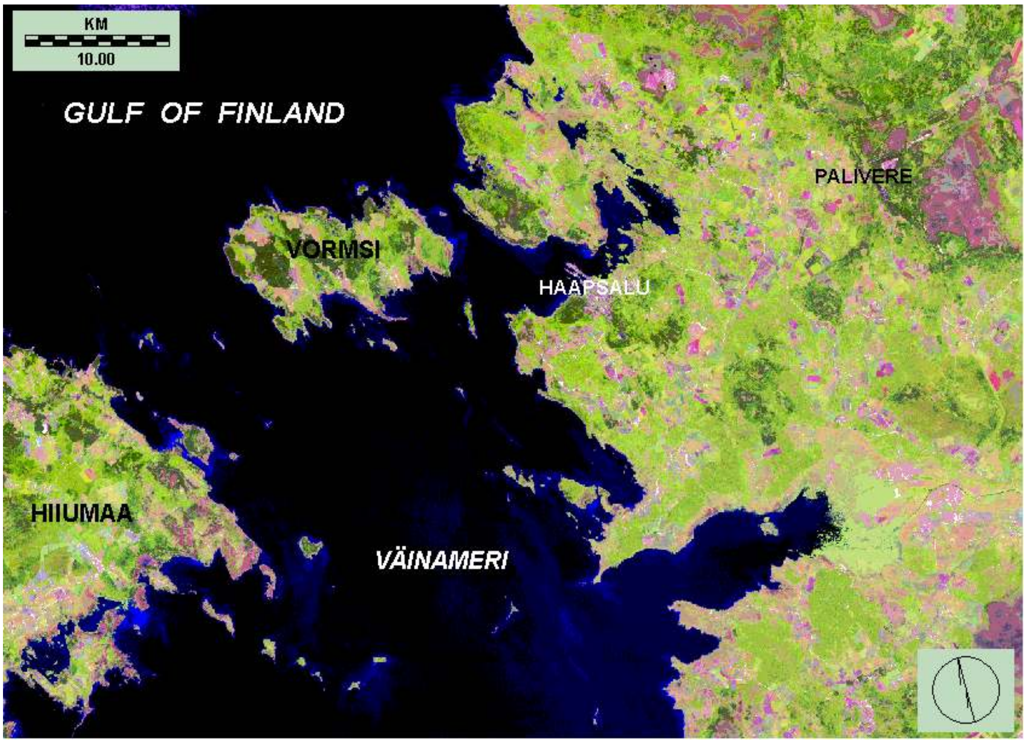

Fig. 2. Landsat TM composite made of bands 3, 4 and 5, colour coded as blue, green and red, 28 July 1986; dark blue and black — water bodies, dark green — spruce forest, reddish-green — pine forest, yellowish-green — deciduous forest, pink and purple — agricultural fields, white — cultural structures (roads and villages)

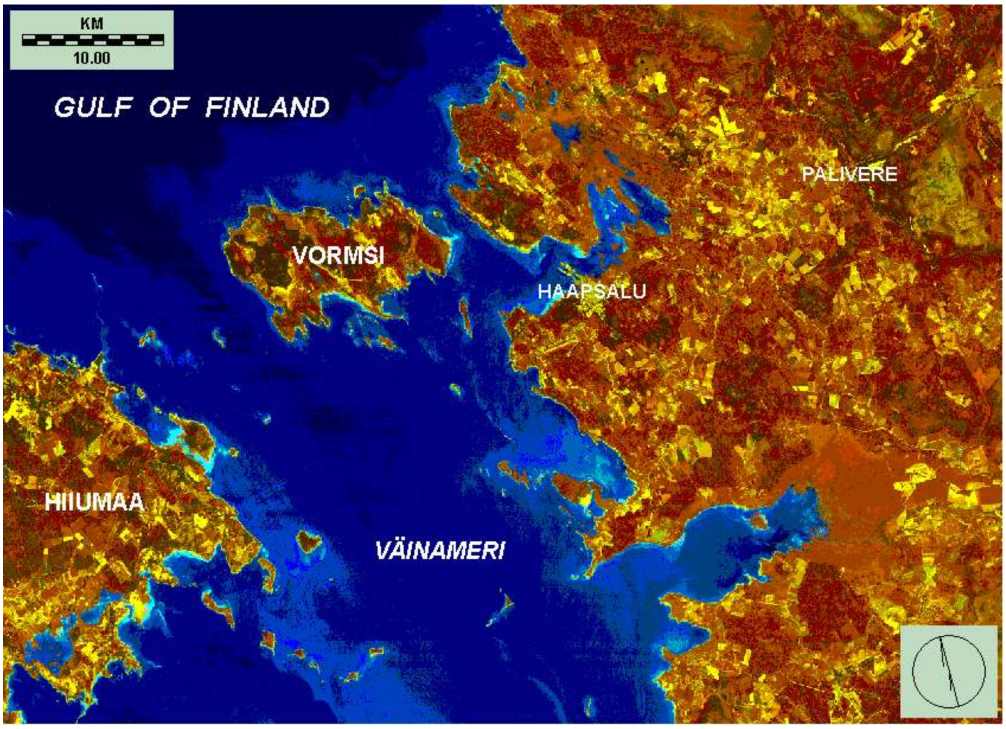

Fig. 3. Landsat TM special composite made of band 2 water-only image combined with bands 3 and 5, colour coded as blue, green and red, 26 June 1986; black — deep water (> 10 m), medium blue — intermediate water depth, light blue and cyan — shallow water (< 3 m), narrow yellow strips — coastlines

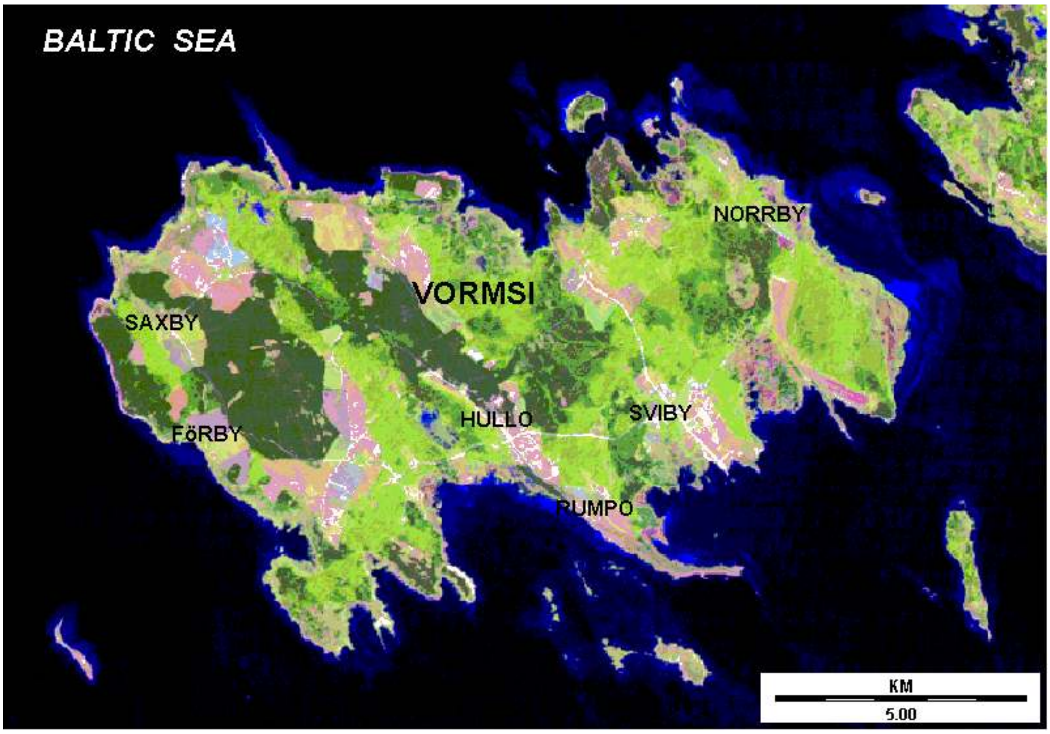

Fig. 4. Enlargement of Vormsi, Landsat TM composite made of bands 3, 4 and 5, colour coded as blue, green and red, 28 July 1986; colour depiction see Figure 2; eskers are marked by agricultural fields, road and villages, and peninsulas

continues offshore to a tiny island. Total length of this esker is about 12 km. The Noarootsi esker is aligned to the south-east with mainland peninsulas at Haapsalu, but the sea floor in between does not reveal a topographic connection. The trends of these several eskers display sinuous or zig-zag patterns, as displayed by the peninsula at Rumpo (Fig. 6). Directions of individual esker segments differ by as much as 90°. The range of downstream directions varies from about 110 to 200° with an overall trend of roughly 150°. Normal to their average trends, the Hullo, Norrby and Noarootsi eskers are spaced 4 to 6 km apart.

We have identified additional trends that we believe may represent eskers (Figs. 1, 3 and 4). The first possible esker is located on western Vormsi in vicinity of Saxby and Förby. Land clearings and roads follow a linear trend of higher ground, and small peninsulas extend to the north-west and south-east. The southeastern peninsula appears to continue some 4 km as a shallow shoal on the sea floor; total length of this supposed esker is approximately 14 km. Another likely esker runs through Rälby and Sviby. Ratas (1977) and Kadastik and Kaljuläte (2000) noted discontinuous esker sediments at these villages, and the esker appears to extend offshore to the north a short distance. Total length of this esker is about 8 km. Suspected eskers at Förby and Rälby are spaced 3–4 km apart from the larger eskers at Hullo and Norrby.

To the west of Vormsi, a probable esker is represented by the island Harilaid in the middle of Hari Kurk. The island is a narrow strip of land barely above sea level. Harilaid trends toward the south-east, and this trend may extend *via* shallow shoals to the island of Eerikulaid. Total length of this probable esker is about 8 km. The final presumed esker is a shallow shoal system marked by the tiny island of Kakralaid. The shoal extends northward from Kakralaid about 1 km and reaches southward to a peninsula of Hiiumaa; total length of this supposed esker is 6 km. From Kakralaid, another linear shoal extends south-eastward to Kadakalaid and hence to Eerikulaid, a distance of roughly 15 km. The angle between the two branches of the Kakralaid esker is about 40°. Spacing between these suspected eskers is roughly 4–6 km, which is comparable to spacing of eskers to the east. The suspected eskers of Väinameri and Hari Kurk are just beginning to emerge above sea level as a result of continuing postglacial rebound.

INTERPRETATION OF ESKERS

The known and suspected eskers of Vormsi and surroundings demonstrate a regular pattern in their distribution. Eskers are oriented toward the south and south-east with somewhat sinuous or zig-zag paths. They are spaced 3–6 km apart, and some display branching patterns. Given this arrangement of eskers, we suggest they represent the preserved portions of a subglacial drainage network that was anastomosing in character. The angular divergence of esker segments could reflect deep fissuring in the ice body. The esker network is located along the central pathway of the Väinameri ice lobe, and the overall direction of drainage was toward the Palivere glacial limit (Fig. 1). The main region of eskers — Hari Kurk, Vormsi

Fig. 5. Kite aerial photograph at Rumpo, Vormsi

View toward north-west; the village and agricultural fields are located on the esker crest, and the road follows the esker to the village of Hullo in the distance

Fig. 6. Kite aerial photograph of esker peninsula at Rumpo, Vormsi

View toward south-east; notice distinctive bend of the peninsula in the distance; the road follows the esker crest, and raised beach ridges are visible to right of road and Noarootsi — is situated some 20–30 km upstream from the glacial limit, although the Kuivarahu esker extends to within 10 km of the glacial limit. The northern ends of eskers — Kakralaid and offshore northern Vormsi — reach some 34 km upstream from the glacial limit. On this basis, the esker network appears to occupy a distinct zone relative to the position of the Väinameri ice lobe at the time of the Palivere phase of glaciation.

It is assumed the Palivere phase took place after the region had been completely deglaciated at least for a brief interval (Raukas, 1986; Karukäpp and Raukas, 1997; Kadastik and Kalm, 1998). In such a situation, it is most likely that ice readvanced into a proglacial lake environment within the western Estonian region. Such late glacial readvances were quite common along all the southern margin of the Baltic basin. These readvances moved upslope and were often accompanied by large discharges of subglacial meltwater, which created numerous tunnel valleys and eskers (Piotrowski, 1997). Many large glaciotectonic structures were also created in the soft substratum of Germany, Denmark and Poland (Aber and Ruszczyńska-Szenajch, 1997). The late-glacial readvances of the southern Baltic are interpreted by many as results of ice lobe surging in which subglacial meltwater and proglacial lakes played key roles (Piotrowski, 1994; Aber and Ruszczyńska-Szenajch, 1997).

We interpret eskers of the Vormsi vicinity as evidence for substantial meltwater discharge beneath the Väinameri ice lobe. The esker system represents a zone beneath the ice lobe in which subglacial meltwater flow became channelised into an anastomosing network. Meltwater flowing in subglacial channels subsequently lost its ability to transport sediment downstream, hence deposition of the eskers. The lack of eskers in the upstream (northward) direction suggests that meltwater was either erosive or not channelised under thicker ice in the Gulf of Finland. The disappearance of eskers southward (upslope) may indicate that distinct channels dispersed into fan or sheet flow beneath thin, partly floating ice. The existence of a proglacial lake at the Palivere glacial margin is demonstrated by water-lain sediment in the upper portion of the Palivere diamicton on the western Estonian islands. This diamicton, which is up to 25 m thick, is interpreted as subaquatic outwash and glaciolacustrine deposits (Kadastik and Kalm, 1998). It is overlain by more than 10 m of varved clay from the Baltic Ice Lake.

The hydraulic character of the bedrock may influence the mode of channel development by subglacial streams (Piotrowski, 1999). In regions of resistant bedrock, so-called “Röthlisberger channels” (Röthlisberger, 1972) melted upward into the ice are favoured in contrast to “Nye channels” (Nye, 1973) incised into soft substratum. In cases where sediment is deposited and preserved in the former, eskers are formed; the latter lead to tunnel valleys. The ability of the substratum to transmit ground water away from the base of the ice is also a key factor. Subglacial water tends to accumulate in situations where aquifer transmissivity is less than meltwater supply. The Upper Ordovician limestone of Vormsi and eastern Hiiumaa generally has low specific capacity (< 0.5 l/s per metre) and is classified as a fissured aquifer with limited ground-water potential (Perens *et al.*, 1998). The hydraulic character of this bedrock combined with relatively thin Quaternary sediments means that subglacial meltwater could not be removed readily *via* ground-water flow. There is no significant change in substratum bedrock or sediment conditions that could explain the upslope disappearance of eskers to the south.

We suggest bedrock conditions in the Vormsi and Väinameri vicinity favoured trapping of subglacial meltwater, melting of a braided channel network into the base of the ice, and floating of the ice lobe toward its margin, which terminated in a proglacial lake during the Palivere phase of glaciation. The scarcity of glaciotectonic structures (Rattas and Kalm, 1999), in contrast to the southern Baltic, can be accounted for by three conditions:

— relatively well-consolidated Ordovician and Silurian limestone of the region;

— general lack of thick unconsolidated Quaternary sediments;

— decoupling of the ice lobe from the substratum by subglacial meltwater.

CONCLUSIONS

On the basis of Landsat TM imagery, the land-based eskers of Vormsi can be extended across the shallow sea floor to the north and south. Additional eskers are recognised, as marked by tiny islands and shallow shoals of the Hari Kurk and Väinameri sea floor. These eskers in combination define an anastomosing network of subglacial channels related to the Väinameri ice lobe of the Palivere phase of glaciation. The regional context suggests that when the Väinameri ice lobe readvanced, a large volume of subglacial meltwater was released. The esker network marks a zone, some 10 to 34 km behind the ice margin, in which channelised subglacial meltwater flow lost its ability to transport sediment. In the upstream direction, meltwater flow was either erosive or not channelised; toward the ice lobe margin meltwater discharge dispersed into fan or sheet flow beneath partly or fully floating thin ice that terminated in a proglacial lake. The lack of glaciotectonic structures, in contrast to the southern Baltic, is due in large part to the well-consolidated nature of the substratum, absence of thick Quaternary sediments, and decoupling of the ice lobe from its substratum.

Acknowledgements. The authors wish to thank U. Peterson for fruitful discussions concerning applications of satellite imagery in Estonia. M. Rattas, T. Hang and E. Kadastik supplied much useful information and help. Kite aerial photography on Vormsi was carried out with the assistance of S. W. Aber. This investigation was supported primarily by a grant from the U.S. National Research Council. Additional support was provided by the Kansas NASA EPSCoR project for remote sensing of rural resources, by Emporia State University, Kansas, and by the University of Tartu, Estonia.

REFERENCES

ABER J. S. and GAŁĄZKA D. (2000) — Potential of kite aerial photography for Quaternary investigations in Poland. Geol. Quart., **44** (1): 33–38.

ABER J. S. and RUSZCZYŃSKA-SZENAJCH H. (1997) — Glaciotectonic origin of Elbląg Upland, northern Poland, and glacial dynamics in the southern Baltic region. Sed. Geol., **111**: 119–134.

ABER J. S., SOBIESKI R., DISTLER D. A. and NOWAK M. C. (1999) — Kite aerial photography for environmental site investigations in Kansas. Kansas Acad. Sc., Trans., **102** (1–2): 57–67.

JENSEN J. R. (1996) — Introductory digital image processing: a remote sensing perspective. Prentice Hall, Ser. Geogr. Inf. Sc.

KADASTIK E. and KALJULÄTE K. (2000) — Map of the Quaternary deposits of Vormsi Island in scale 1:50 000. Geol. Surv. Estonia.

KADASTIK E. and KALM V. (1998) — Lithostratigraphy of Late Weichselian tills on the West Estonian Islands. Geol. Soc. Finland, Bull., **70** (1–2): 5–17.

KAJAK K., RAUKAS A., KARUKÄPP R. and RATTAS M. (1999) — Quaternary deposits of Estonia, map scale 1:400 000. Geol. Surv. Estonia.

KARUKÄPP R. and RAUKAS A. (1997) — Deglaciation history. In: Geology and mineral resources of Estonia (eds. A. Raukas and A. Teedumäe): 263–267. Estonian Acad. Publ. Tallinn.

NYE J. F. (1973) — Water at the bed of a glacier. Symposium on the Hydrology of Glaciers, **95**: 189–194. IAHS Publ.

PERENS R., VINGISAAR P. and PARM T. (1998) — Hydrogeological map of Estonia in scale 1:400 000. Geol. Surv. Estonia.

PETERSON U., AUNAP R. and EILART J. (1998) — Eestimaa nähtuna kosmosest. Koolibri. Tallinn.

PIOTROWSKI J. (1994) — Tunnel-valley formation in northwestern Germany — geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley. Sed. Geol., **89**: 107–141.

PIOTROWSKI J. (1997) — Subglacial hydrology in northwestern Germany during the last glaciation: groundwater flow, tunnel valleys and hydrological cycles. Quatern. Sc. Rev., **16**: 169–185.

PIOTROWSKI J. (1999) — Channelized subglacial drainage under soft-bedded ice sheets: evidence from small N-channels in central European Lowland. Geol. Quart., **43** (2): 153–162.

RATAS U. (1977) — Vormsi Loodusest. Valgus. Tallinn.

RATTAS M. and KALM V. (1999) — Classification and areal distribution of glaciotectonic features in Estonia. Geol. Quart., **43** (2): 177–182.

RAUKAS A. (1986) — Deglaciation of the Gulf of Finland and adjoining areas. Geol. Soc. Finland, Bull., **58**: 21–33.

RAUKAS A. (1997) — Evolution of the Baltic Sea. In: Geology and mineral resources of Estonia (eds. A. Raukas and A. Teedumäe): 268–274. Estonian Acad. Publ. Tallinn.

RAUKAS A. and KAJAK K. (1997) — Quaternary cover. In: Geology and mineral resources of Estonia (eds. A. Raukas and A. Teedumäe): 125–136. Estonian Acad. Publ. Tallinn.

RAUKAS A., RÄHNI E. and MIIDEL A. (1971) — Marginal glacial formations in North Estonia (in Russian with English summary). Estonian Acad. Sc., Inst. Geol. Tallinn.

RÖTHLISBERGER H. (1972) — Water pressure in intra- and subglacial channels. J. Glaciol., **11**: 177–203.