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Geomorphic interpretation of landsat imagery for Western Estonia

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Abstract. The geomorphology of western Estonia is a mosaic of glacial and coastal landforms of late Pleistocene and Holocene age. We have utilized Landsat thematic mapper (TM) imagery to identify, classify, and interpret different landscape elements within this region. Image processing methods include false-color composites, normalized difference vegetation index (NDVI), tasseled-cap transformation, and isocluster unsupervised classification. The geobotanical approach was employed for interpretation of geomorphic features. The most effective false-color composite proved to be TM bands 3, 4, and 5 color coded as blue, green, and red respectively. Conspicuous geomorphic elements are peat bogs, moraines, eskers, and sand dunes. The synoptic quality of Landsat imagery allows for visual interpretation of regional landscape patterns related to ice lobes during deglaciation and to gradual emergence of coastal lands during postglacial times. Landsat imagery in combination with existing ground-based observations and maps provides for improved interpretation of regional geomorphology in western Estonia.

Key words: Estonia, glacial and coastal landforms, landsat imagery

Introduction

Estonia is situated at the eastern end of the Baltic Sea in a region that was subjected to multiple glaciations of the Fennoscandian ice sheet during the Pleistocene. Ice streams advanced from the north and northwest, repeatedly crossing the Baltic depression and ascending onto higher land to the south and east. Glacial erosion and deformation modified the Paleozoic bedrock substratum, and glacial deposition built up constructional landforms, particularly in the southern portion of Estonia. During each major glaciation, substantial crustal depression and rebound took place. Glacial lakes or interglacial seas occupied the Baltic depression and innudated the coastal lowland areas of Estonia. Following the last deglaciation, northwestern portions of Estonia have emerged, as the land raised relatively to the sea, and peat bogs have spread over sizeable portions of the country.

The goal of our research is to utilize Landsat thematic mapper (TM) imagery to identify, classify, and interpret different landscape elements within the lowland terrain of western Estonia. Both glacial and coastal geomorphic processes were important in shaping the modern landscape. The region has furthermore been subjected to a long history of human land use and modification. The land cover consists mainly of agricultural fields, forest, and peat bogs, which are the dominant features visible in Landsat TM images.

Geomorphic setting

Estonia has an area of more than 45,000 km^2, of which about one tenth is comprised of some 1500 islands and islets mainly in the west. Estonia's geomorphology acquired its present appearance under the influence of geological, glacial, biological, and anthropogenic factors, the relative importance of which has changed with time. The territory lies in a critical transition zone in the continental pattern of glacial geomorphology (Aber 1992). To the north and west, the Baltic zone of ice-sheet outflow was subjected to strong erosion during repeated Quaternary glaciations. This zone, which includes much of Finland and Sweden, is characterized by crystalline basement rocks that have been stripped of most soft sediment and soil cover. The outer geomorphic zone of glaciation to the south and east, in contrast, was a region of predominant glacial deposition and deformation of soft Paleozoic, Mesozoic, and Cenozoic sedimentary bedrock. This region is covered by a thick blanket of sediment that built up during repeated ice advances.

Estonia reflects this transition. The thickness of the Quaternary cover in the northwestern part of the territory is generally less than several meters, but in the southern part is up to 100-200 m thick (Raukas and Kajak 1997). The underlying bedrock is composed mainly of well-consolidated Ordovician and Silurian carbonate sedimentary strata in central and northern Estonia and poorly consolidated Devonian sandstone in southern Estonia. Owing to slight monoclinal dip of strata (10-15°S) and distinct lithological heterogeneity, the topography is cuesta-like, which exerted a great influence on ice movement and glacial erosion patterns.

In the territory of Estonia, glacial ice streams with different speeds and energies alternated regularly with ice-divide areas (Raukas and Karukäpp, 1993). Western Estonia, including Baltic islands, experienced strong

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movement of the Riga ice lobe, which flowed toward the south-southeast (Punkari 1996). Central and southeastern Estonia, however, were interlobate regions that separated the Riga lobe from other major and minor ice lobes farther east. Many directions of ice movement resulted from expansion and contraction of these lobes and local sublobes in different phases. Estonia is, thus, situated in a position that was subjected to a complicated interplay of glacial erosion, deformation, and deposition many times during the Quaternary.

During late- and post-glacial time (last 12,500 years), a considerable area of Estonia was flooded by waters of large proglacial lakes and the Baltic Sea. Land began to emerge from the water as a result of gradual glacio-isostatic uplift. This is manifested in coastal expansion along with evidence for old strand lines inland from the present coast. Northwestern Estonia has uplifted at least 100 m relative to present sea level; whereas southern Estonia has raised up only several meters (Raukas 1997a). The result is tilting of landscape features, up to the northwest.

As glacial landforms of western Estonia emerged from the sea, they were exposed to wave erosion and beach sedimentation, which modified their exterior materials and forms. In general, glacial landforms of the western coastal region were reduced in height and smoothed during coastal emergence; whereas, beach and dune forms were built up. These various geomorphic processes have led to a complex mosaic of landforms and surficial deposits related to glaciation and coastal migration.

Image processing methods

Four Landsat thematic mapper (TM) datasets were selected from the 1980s (Table 1; Fig. 1). The datasets are nearly cloud free and represent spring and summer seasons. Landsat TM data have nominal resolution of 30 m in the

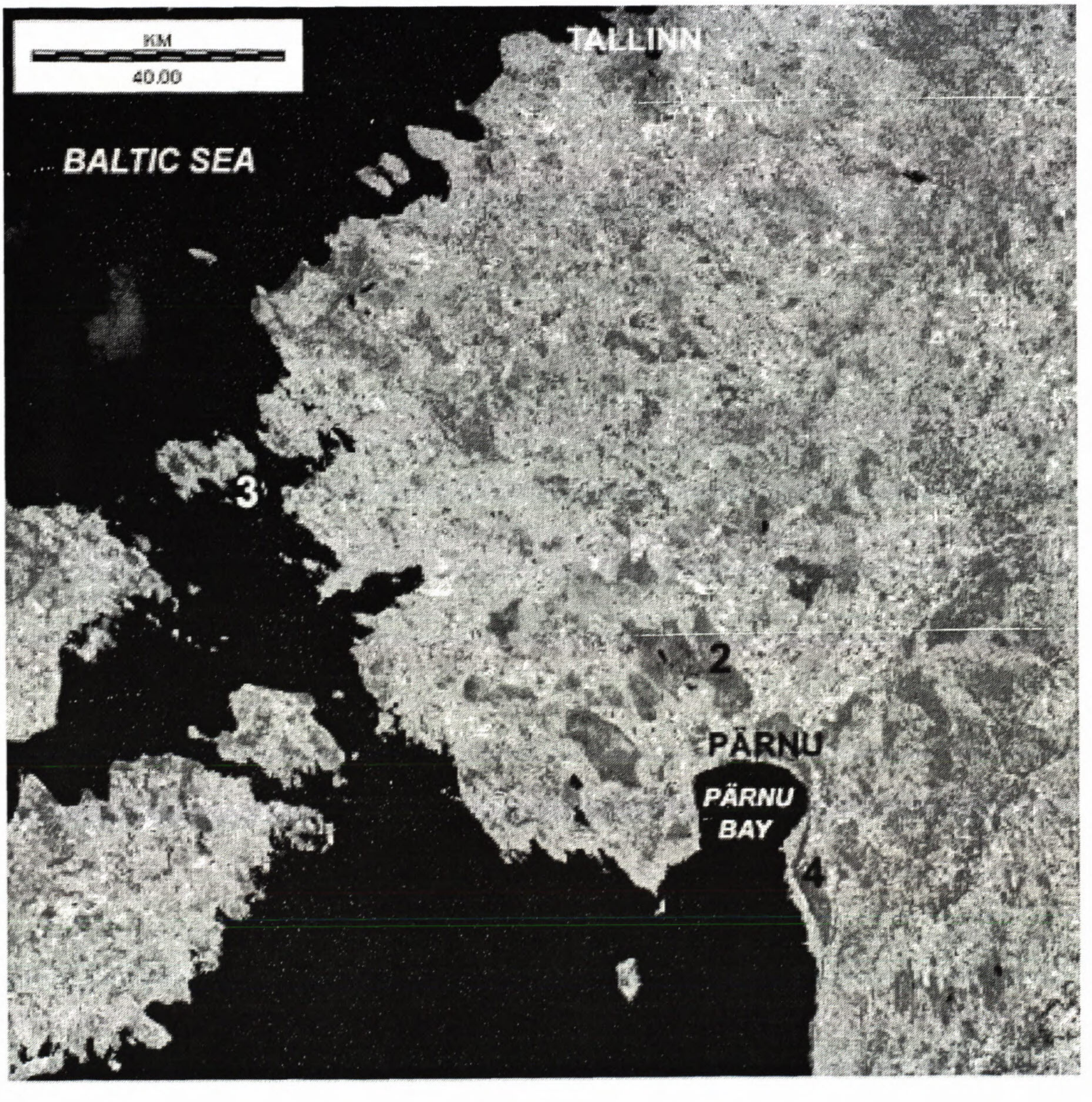

Table 1. Landsat TM datasets selected for analysis in this study. Scenes from path/row 188/19 include the mainland of western Estonia. Scenes from path/row 189/19 are centered on the Baltic islands of westernmost Estonia. All datasets contain less than 10% cloud cover. Landsat TM datasets acquired from the EROS Data Center, U.S. Geological Survey.

Scene ID 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

visible (1, 2, 3), near-infrared (4), and mid-infrared (5, 7) bands, which were used in this investigation. The thermal-infrared (6) band was not utilized. Image processing was carried out using *Idrisi32* software following standard procedures for Landsat TM image enhancement and classification (Jensen 1996). The most useful techniques were false-color composites, normalized difference vegetation index (NDVI), tasseled-cap transformation, and isocluster unsupervised classification (Lewicki 2000). The most effective false-color composite proved to be TM bands 3, 4, and 5 color coded as blue, green, and red respectively. This composite was used as the basis for isocluster classification.

On the basis of previous experience in similar settings, the *geobotanical approach* was employed for interpretation of geomorphology (Aber and Ruszczynska-Szenajch 1997). Vegetation integrates many geomorphic variables, such as sediment and soil, land slope and aspect, and drainage. Thus, vegetation patterns, both natural and cultural, often reflect geomorphic conditions. With the geobotanical approach, vegetation, agriculture, and water bodies are primary clues for interpreting landscape elements.

In western Estonia, agricultural fields are found mainly in low-relief terrain underlain by loamy or sandy sediments. Steeper, hummocky lands are mostly forest covered. Till is the basis for spruce forest; sandy and peaty soils support pine forest. Peat bogs and mires in western Estonia are of the minerotropic type (Ilomets 1997), which developed from infilling of former lakes or marine embayments.

Various composite and classified images were examined visually and further classified to isolate selected types of vegetation, land use, and water bodies for geomorphic interpretation. The identities of Quaternary sediments and landforms were verified by reference to existing maps of Quaternary deposits (Kajak et al. 1999) and peat (Orru et al. 1993).

Geomorphic features

Peat bogs – Peat bogs are the most conspicuous features on Landsat TM images of western Estonia (Fig. 2). Peat bogs have a low level of vegetation activity combined with high moisture content that tend to depress reflection in band 4, the near-infrared. This results in low NDVI values and a relatively dark appearance in composite images. Peat bogs are further identified by their large size and irregular, rounded shapes in the landscape.

Peat bogs are divided into two general types--fens and raised bogs--based on position of peat in the landscape and types of plant species (Orru 1997). Fens develop in lowlands with nutrient-rich soil and near-surface ground water. Fens support numerous sedges (*Carex*), reeds, horsetails, and several species of trees (*Betula, Picea, Pinus*). With growth through time, fens may evolve into raised bogs, in which elevated peat accumulation is fed solely by precipitation. Peat mosses, namely *Sphagnum*, predominate along with some horsetail and pine. Fens and raised bogs are clearly distinguished in Landsat images on the basis of differences in vegetation cover (Fig. 2).

In the Pärnu region, fens and raised bogs are situated in elongated, shallow depressions that trend toward Pärnu Bay (Fig. 2). Several of the bogs are located behind a major end moraine that marks the Pandivere stage of deglaciation (Karukäpp and Raukas 1997; Kajak et al. 1999). This leads us to suppose that bog depressions were eroded as shallow troughs by movement of the ice lobe and/or by subglacial melt-water flowing toward Pärnu Bay.

Moraines – Moraines cannot be separated from other types of landforms. Moraines can, however, be recognized as linear borders between areas of quite different land use (Fig. 2). In general, hummocky topography of moraines is characterized by spruce forest with numerous peat bogs situated on the upglacier side. The proximal ice-free vicinity is covered by intensive agricultural land use based on low-relief, sandy and loamy soils of outwash fans and plains.

Among moraines, those of the Pandivere stage of deglaciation are especially prominent in the area northeast of Pärnu (Fig. 2). A moraine of this stage is also visible northwest of Pärnu. These moraines represent the lateral margins of the Pandivere ice lobe. However, the Pandivere ice margin lacks an end moraine in the immediate vicinity of Pärnu. This is the zone toward which peat bogs converge from the north. We speculate that strong melt-water flow at the ice margin either washed away or prevented deposition of an end moraine in this zone.

Eskers and drumlins – Eskers and drumlins are relatively rare in the lowlands of western Estonia according to the map of Quaternary deposits (Kajak et al. 1999). An exception to this situation is the island of Vormsi and adjacent vicinity (Fig. 3). Two mapped eskers cross Vormsi from northwest to southeast, and a third esker has a similar orientation on the adjacent mainland. These eskers are identified on the Landsat imagery by their distinctive shapes, marked by peninsulas, as well as differentiated land-use patterns.

Nearby small islands – Harilaid, Eerikulaid, Hobulaid, Rukkirahu, and Kuivarahu – display similar shapes and positions, which we suspect may be eskers (Fig. 3). Rukkirahu and Kuivarahu could be extensions of the western esker on Vormsi; imagery indicates a shallow linear connection between these islands on the seafloor. Hobulaid might be an extension of the eastern Vormsi esker. Hari-

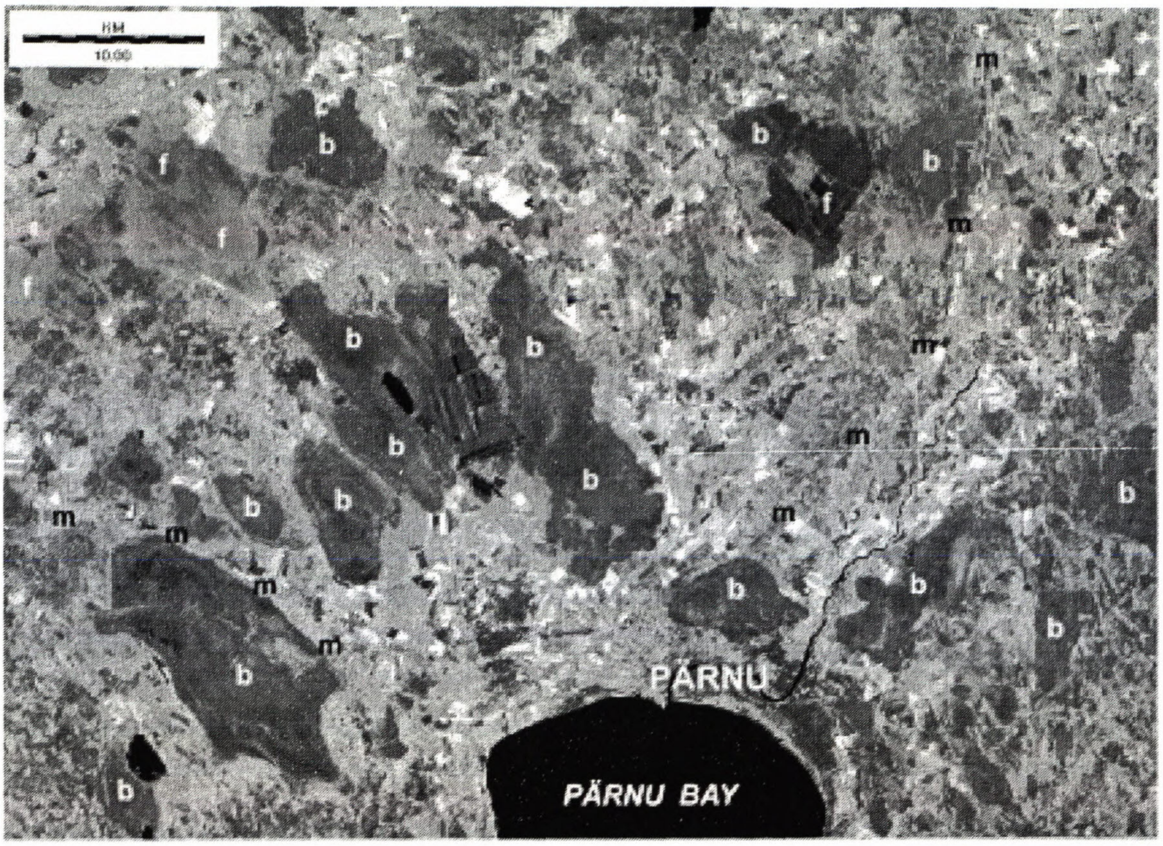

Fig. 2. Landsat TM scene of the Pärnu region, 28 July, 1986, band 4 (near-infrared). Dark gray zones depict large peat bogs: f = fen, b = raised bog. Lateral moraines of the Pandivere glacial stage are indicated by "m" northeast and northwest of Pärnu.

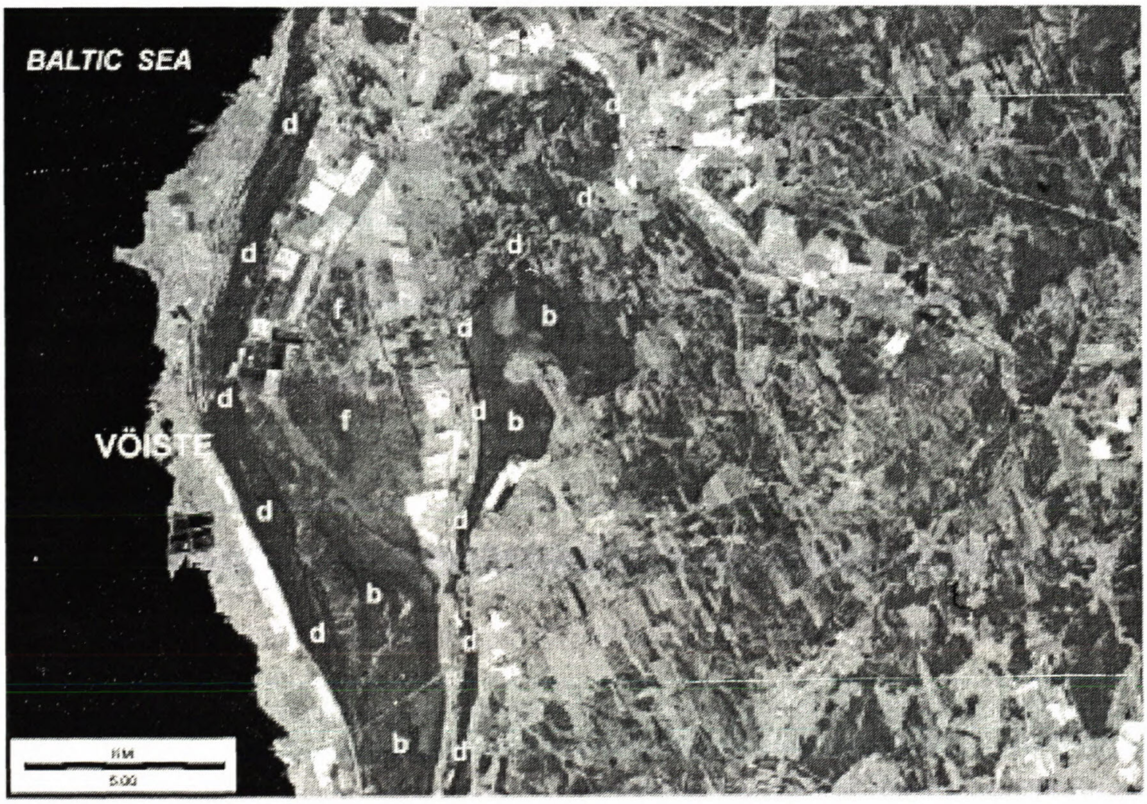

Fig. 3. Landsat TM scene of the island of Vormsi and adjacent mainland, 28 July, 1986, band 4 (near-infrared). The positions of three known eskers are indicated by "e." The eskers form distinctive peninsulas on the northern and southern coasts of the island. Suspected eskers are represented by the small islands of Harilaid, Eerikulaid, Hobulaid, Rukkirahu, and Kuivarahu.

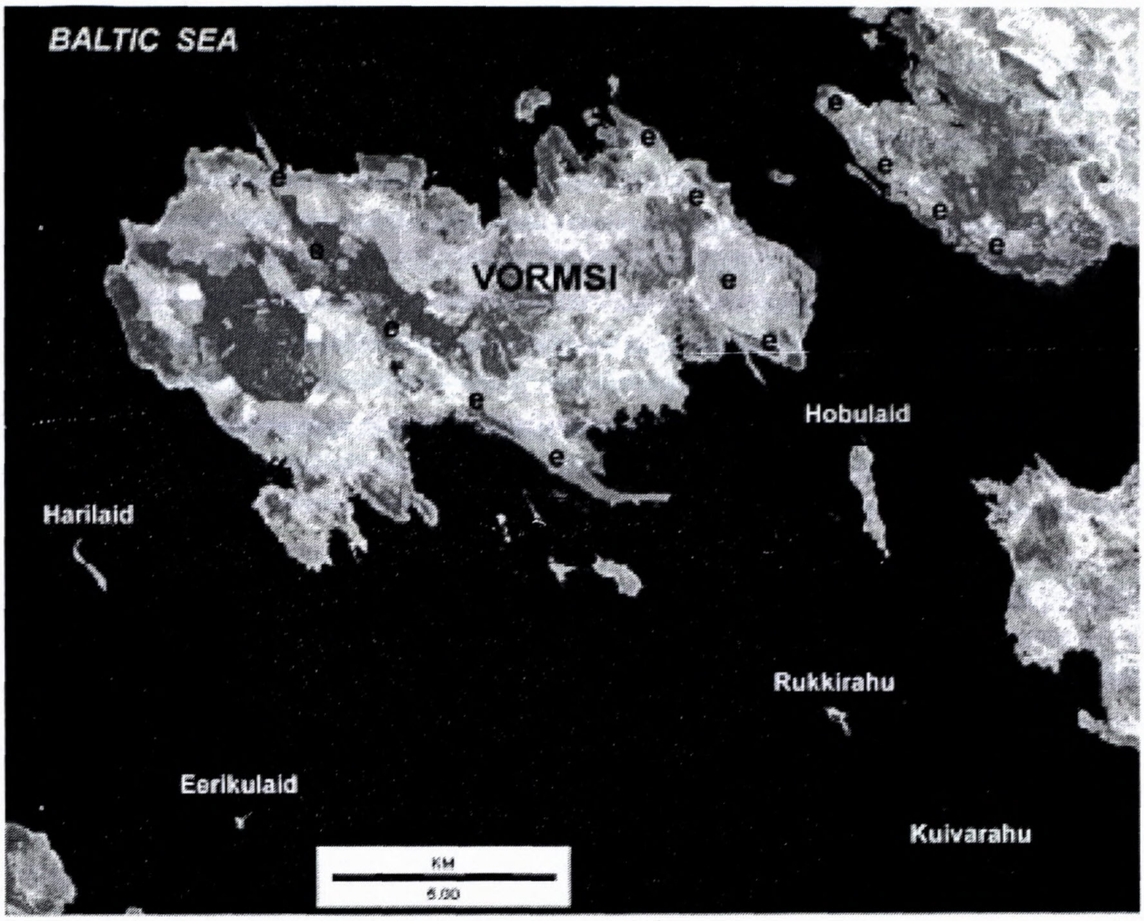

Fig. 4. Landsat TM scene of the southernmost Baltic coast of mainland Estonia, 28 July, 1986, band 4 (near-infrared). Two sets of sand dunes (d) are marked. Peat bogs are located behind each dune complex.

laid appears to be another esker west of Vormsi, and Eerikulaid may be an extension of this esker. All the known and suspected eskers follow a NW-SE trend that parallels local ice movement of the Palivere stage of deglaciation (Karukäpp and Raukas 1997). The eskers are interpreted by us as deposits of subglacial streams draining through an ice-lobe depresssion toward the Palivere glacial limit, which is situated a few km to the south of the Vormsi vicinity.

The eskers of Vormsi, nearby islands, and adjacent mainland are covered by coastal sediments of the Limnea Sea (Kajak et al. 1999), which developed about 4000 years ago (Raukas 1997a). The present land regions have emerged since the Limnea Sea regressed from the region. During the emergence, the eskers were subjected to wave erosion and beach development. Eventually the eskers of Vormsi and the mainland were uplifted above the shore zone. The uplift process continues today with the emergence of small islands west and south of Vormsi.

Sand dunes – Sand dunes form conspicuous linear or arcuate trends parallel to the coast in many parts of western Estonia (Fig. 4). Sand dunes are typically developed on top of former beach ridges. In several locations, multiple generations of dune ridges may be identified inland from the present coast. Sand dune ridges are characterized by pine forests, and peat bogs are commonly developed in former lagoons behind dune ridges.

The impressive dune ridges at Võiste developed during transgression of the Litorina Sea, about 7000 years ago (Raukus 1997a, 1997b). The main dune complex parallels the modern coast and is about one km in width (Fig. 4). Raised bogs and fens are located behind the dune complex. Another narrow dune ridge is clearly evident inland from the main ridge. It also has a peat bog situated behind it. Only the southern portion of this second dune ridge is depicted on the map of Quaternary deposits (Kajak et al. 1999). Landsat imagery reveals that the second dune ridge extends farther to the north, where it defines a large curved embayment in the former coast.

Conclusions

Landsat TM imagery has proven effective for identifying various glacial and coastal landforms in the lowlands of western Estonia. The false-color composite based on TM bands 3, 4, and 5 was most useful for general interpretation and classification based on the geobotanical approach to recognizing landscape elements. Among the most conspicuous geomorphic features are peat bogs, moraines, eskers, and sand dunes. The synoptic quality of Landsat imagery allows for visual interpretation of regional landscape patterns related to ice lobes during deglaciation and to gradual uplift of coastal lands during

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postglacial times. Landsat imagery in combination with existing ground-based observations and maps provides for improved interpretation of regional geomorphology in western Estonia.

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