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# EVOLUTION OF THE ISLETS IN THE VÄINAMERI, WESTERN ESTONIA

**Abstract.** The islets in Western Estonia have emerged from the sea in the course of the uplift of the Earth's crust and can be treated as field laboratories for landscape-ecological studies. The main goal of the present work was to find out links between the process of the formation of plant communities, soils, and waters on the one hand and the Quaternary history of the islets on the other. As a result, a model of the evolution of the landscapes on small islands is suggested.

The model illustrates gradual development of an islet through temporal transitions from one landscape type to another. We distinguished 21 variants of minor landscape units. They are grouped according to their location on the relief forms and the regimes of substance movement.

Descriptions of chemical characteristics of soil and water, plant coverage, deposits, and landforms are given. Pollen diagrams for several islets are presented. The analyses of multi-dimensional data from 74 sample plots revealed the main factors in the course of the development of the landscape pattern.

Proceeding from the present-day rate of the uplift of the Earth's crust — 2.2 mm per year — the approximate ages of the evolution stages of the islets could be determined as younger than 500 years; ca 1000 years; ca 1600 years; and ca 2300 years. These ages correspond to the phases of the Limnea Sea. A remarkable fact is that islets develop from stage to stage with a step of ca 600 years.

**Key words:** islands, landscape units, development, eastern Baltic.

## Introduction

The natural environment of the West-Estonian islands has been relatively little affected by man. Therefore, researches into natural developments can be successfully conducted here.

The present research was conducted by the Island Research Group of the Tallinn Botanical Garden. The field work was carried out in the years 1984—1988. The research work was, to some extent, coordinated by the 7th project "Ecology and Rational Utilization of Island Ecosystems" of the international programme "Man and Biosphere" (MAB).

We examined the interactions between plant communities, soils, and waters under the conditions of coastal environments. The main goal of the present work is to assess the links between the studied processes and the Quaternary history of the islands concerned: to find out the background for the evolution of small islands as models of developing landscape systems.

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## Study Area

The islets studied in greater detail are located in the Väinameri, the inland sea in the eastern part of the Baltic between the mainland and the major islands of Saaremaa and Hiiumaa (Fig. 1). The area of the Väinameri is 2240 sq km and its mean depth is only 4.9 m, maximal 22 m. The water level depends here on the wind direction; the absolute amplitude of water level is 2.3 m. Waves are low with maximal registered height 2.5 m (Mardiste, 1971). The mean surface salinity (5—6‰) is lower than that in the northern part of the Baltic Sea (6.5—7‰).

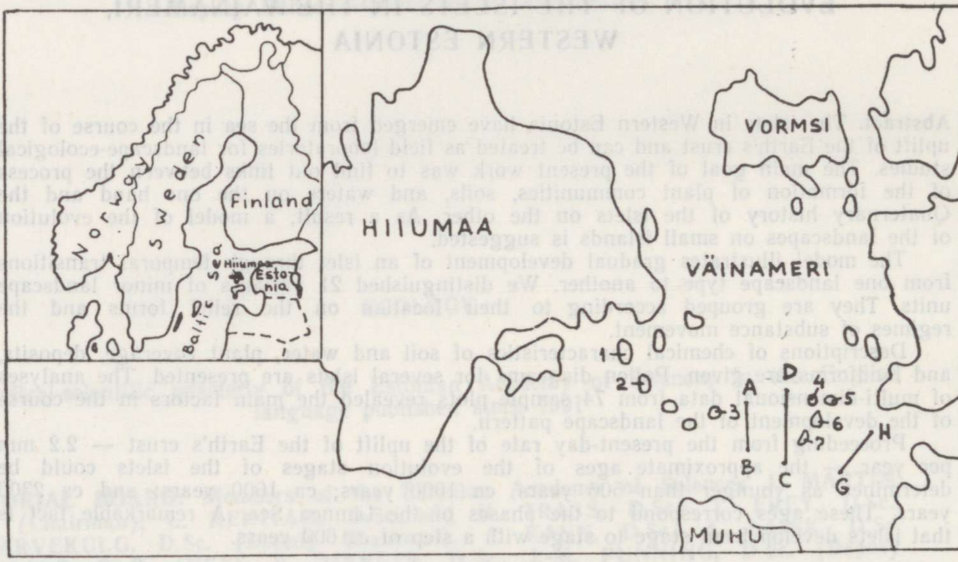


Fig. 1. Location of the study area. *1* — Saarnaki, *2* — Hanikatsi, *3* — Kõverlaid, *4* — Valgerahu, *5* — Tondirahu, *6* — Kumari, *7* — Sipelgarahu. A—B, C—D, and G—H are echo sounding profiles.

Geological conditions are determined by the carbonate rocks of Middle and Upper Ordovician as well as Lower and Upper Silurian deposits; their outcroppings can be observed all over the considered region. The Quaternary coverage is represented by a thin layer of till and also marine and coastal deposits.

During the post-glacial period, the origin and development of the islets were closely connected with the Baltic Sea. The islets emerged gradually from water as a result of the uplift of the Earth's crust (Валлнер and Желнин, 1975) and a gradual regression of the sea. In Estonia, all the sediments of the Baltic Sea that were formed during the Subboreal and Subatlantic periods are included in the Limnea Sea stage. They are represented by five regressive phases (Lim I—V) (Hyvärinen et al., 1988).

In the central part of the Väinameri, there lies a crescent consisting of 18 islets, seven of which (see Table 1) have been studied more profoundly. The examined islets are located on the most distinct forms of the marginal esker ridges and the end moraines of the Palivere stage of the last glaciation that extend above sea surface. On the echo sounding profiles, the considered ridges can be observed on the flat sea-bottom (Fig. 2).

The plant communities of the islets are extremely varied in their development stage and structure. Vegetation units occur here in the forms of coastal, dry, and wet meadows, wooded meadows, juniper shrubberies, and forests.

Over centuries human impact on the islets has appeared mostly in the form of grass mowing and cattle grazing. During the last decades the economic significance of the islets has decreased considerably, but they have been still of interest as objects of cultural heritage and scientific research.

*Table 1*

**List of the studied islets**

| Name | Area, ha | Max height, m a.s.l. |
|---|---|---|
| Saarnaki | 136.1 | 9 |
| Hanikatsi | 82.7 | 6 |
| Kõverlaid | 20.1 | 4 |
| Kumari | 18.9 | 6 |
| Sipelgarahu | 1.6 | 2 |
| Tondirahu | 1.1 | 3 |
| Valgerahu | 0.1 | 0.5 |

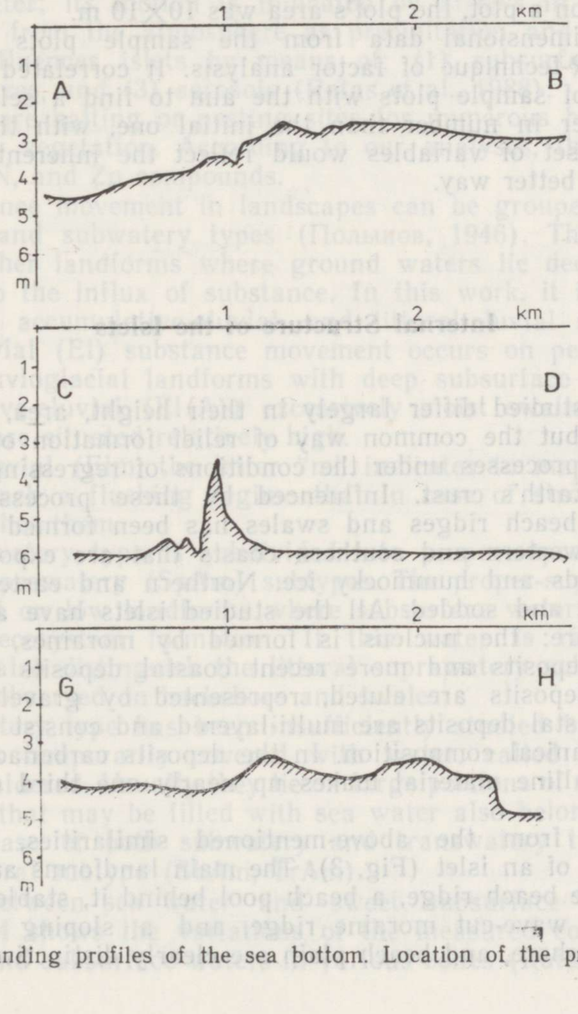


Fig. 2. Echo sounding profiles of the sea bottom. Location of the profiles see Fig. 1.

## Methods

The complex profile method has been used to compile the landscape and geochemical characterizations of the islets. The complex profiles cross the landforms of the islets presenting different landscape units of the islets. The present work is based on eight complex profiles with a total length of 1940 m. To characterize the variations of the landscape pattern, data from 74 sample plots, where Quaternary deposits, soils, waters, and vegetation were studied, have been used.

During five years the islets were examined repeatedly; in case of some islets (Saarnaki, Kumari) up to four times per fieldwork season. This enabled to study both spatial and temporal variations on the profiles.

Samples of different soil horizons were taken for laboratory analyses. The concentrations of $N—NO_3$, Cl, B, and Na were determined in water extract and those of P, Ca, Mg, Mn, and Zn in hydrochloric acid extract. Sea-level was measured relative to fixed marks on the profiles, the level of the subsurface waters was measured in soil pits relative to the ground level. We use the term "subsurface water" here because on small islets it is almost impossible to distinguish between ground- and soil-waters. Samples of water were also taken for laboratory analyses.

Geobotanical data were obtained on 3×3 m plots. In case some trees were growing on a plot, the plot's area was 10×10 m.

The multidimensional data from the sample plots were treated by means of *R*-technique of factor analysis. It correlated the variables on the basis of sample plots with the aim to find a selection of new variables, fewer in number than the initial one, with the assumption that the new set of variables would reflect the inherent character of processes in a better way.

## Internal Structure of the Islets

The islets studied differ largely in their height, area, and diversity of landforms, but the common way of relief formation of the islets is active coastal processes under the conditions of regressing sea and the uplift of the Earth's crust. Influenced by these processes, a typical alternation of beach ridges and swales has been formed on the islets, especially on western and southern coasts that are exposed to strong prevailing winds and hummocky ice. Northern and eastern coasts are mostly sloping and sodded. All the studied islets have a similar geological structure: the nucleus is formed by moraines, covered with fluvioglacial deposits and more recent coastal deposits on them. The fluvioglacial deposits are eluted, represented by gravel and shingle sediments. Coastal deposits are multi-layered and consist of material of different mechanical composition. In the deposits carbonaceous material prevails, crystalline material makes up nearly one third of the deposit composition.

Proceeding from the above-mentioned similarities, we drafted a general profile of an islet (Fig. 3). The main landforms are represented on it: an active beach ridge, a beach pool behind it, stable beach ridges and swales, a wave-cut moraine ridge, and a sloping beach, where foreshore, backshore, and beach plain are clearly distinctive.

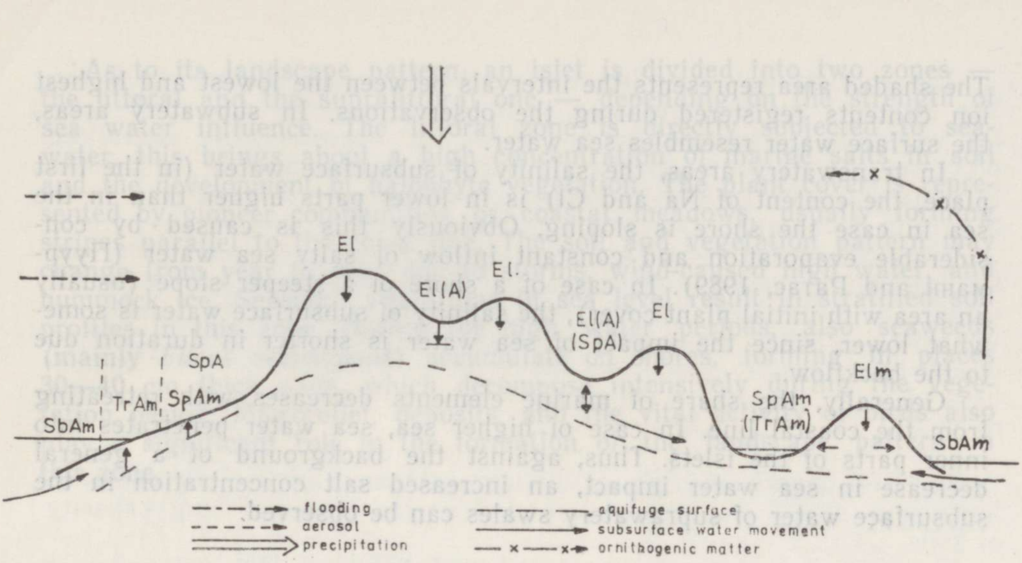


Fig. 3. Generalized profile of an islet and ways of substance movement.

The main bearer of substance movement, assembling an islet in one system, is water; its motion is indicated by arrows in Fig. 3. Water comes mainly from the atmosphere as precipitation and from the sea. Sea water influences islets by means of: (1) subsurface water, (2) floods and waves, and (3) aerosols (Ratas et al., 1988).

The islets are halting or nesting sites for numerous birds, who may totally destroy vegetation. According to our analyses, the birds enrich soils with P, N, and Zn compounds.

The substance movement in landscapes can be grouped into eluvial, suprawatery, and subwatery types (Полынов, 1946). The eluvial type occurs on higher landforms where ground waters lie deep and do not contribute into the influx of substance. In this work, it is divided into proper-eluvial, accumulative-eluvial, and littoral-eluvial subtypes.

Proper-eluvial (El) substance movement occurs on percolated beach ridges and fluvioglacial landforms with deep subsurface water.

Accumulative-eluvial (El(A)) excessively moist swales with a local aquifuge bed are situated relatively high.

Littoral eluvial (Elm, the letter "m" indicates to marine influence) places have such a flushing regime that in case of strong undulation sea water reaches them.

The suprawatery type is subdivided into proper-suprawatery (SpA) and littoral-suprawatery (SpAm) subtypes. The proper-suprawatery subtype is formed on low landforms where subsurface waters lie near and take part in ecosystem formation. If this water is rich in marine elements, we also distinguish the littoral suprawatery subtype (SpAm), which can be observed on backshore and swales.

The subwatery type has been insufficiently studied by the authors, instead places temporarily covered with water, called "transwatery", have been considered. Usually they lie on large portions of sloping shores; young swales that may be filled with sea water also belong to this subdivision. In case of both subwatery and transwatery types, we deal with their littoral subtype (SbAm, TrAm).

The line between sea water and sweet subsurface water is not distinct. Fig. 4 shows the variations of the measured contents of ions in sea water and subsurface waters in various zones (Ratas et al., 1988).

The shaded area represents the intervals between the lowest and highest ion contents registered during the observations. In subwatery areas, the surface water resembles sea water.

In transwatery areas, the salinity of subsurface water (in the first place, the content of Na and Cl) is in lower parts higher than in the sea in case the shore is sloping. Obviously this is caused by considerable evaporation and constant inflow of salty sea water (Пуурманн and Ратас, 1989). In case of a shore of a steeper slope (usually an area with initial plant cover), the salinity of subsurface water is somewhat lower, since the impact of sea water is shorter in duration due to the backflow.

Generally, the share of marine elements decreases with retreating from the coastal line. In case of higher sea, sea water penetrates into inner parts of the islets. Thus, against the background of a general decrease in sea water impact, an increased salt concentration in the subsurface water of suprawatery swales can be observed.

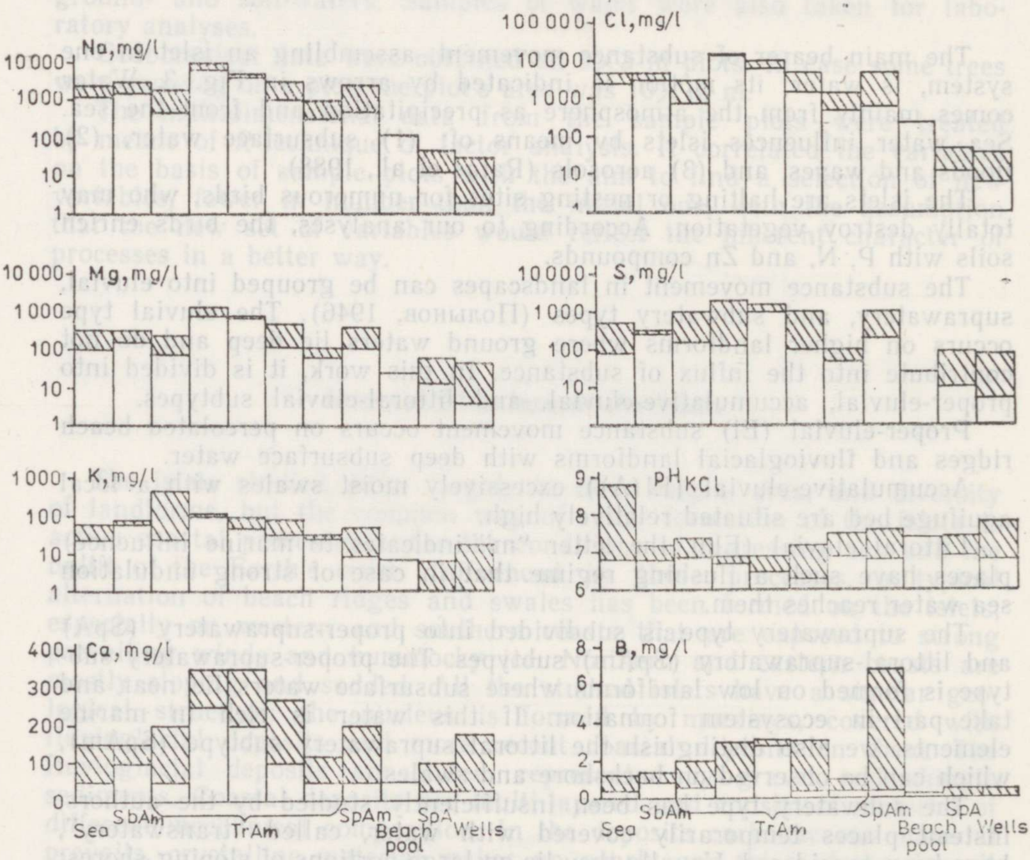


Fig. 4. Variations (min to max shaded area) of the contents of Na, Cl, Mg, S, K, Ca, and *B* and pH in sea- and subsurface water under different conditions of substance movement. TrAm type includes the following variants of landscape units: *4* and *6* on sands (low), *6* on till, *6* on sands (more elevated), and *8* (rarely flooded), see Table 2.

As to its landscape pattern, an islet is divided into two zones — the littoral and the supralittoral one — depending on the strength of sea water influence. The littoral zone is directly subjected to sea-water, this brings about a high concentration of marine salts in soil and the development of halophyte vegetation. The plant cover is represented by pioneer communities or coastal meadows, usually forming stripes parallel to the coast line. The soil and vegetation pattern may change from year to year due to storms, wind-caused high water, and hummock ice. Seasonal alterations in sea level result in stratified soil profiles in this zone. During the high water periods, also seaweeds (mainly *Fucus vesiculosus*) accumulate on shores, forming in places 30—40 cm thick pads, which decompose intensively during the vegetation period. Microrelief, deposits, and the vital activity of birds also play a significant role in the formation of the landscape pattern in this zone.

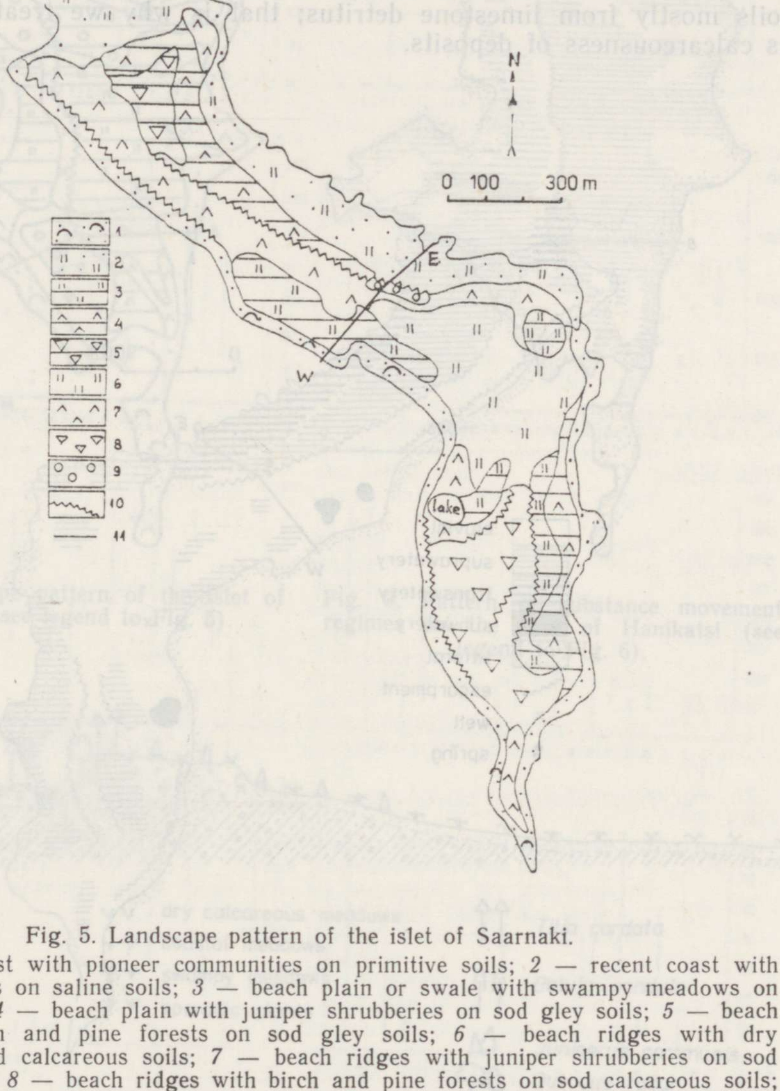


Fig. 5. Landscape pattern of the islet of Saarnaki.

*1* — recent coast with pioneer communities on primitive soils; *2* — recent coast with coastal meadows on saline soils; *3* — beach plain or swale with swampy meadows on sod gley soils; *4* — beach plain with juniper shrubberies on sod gley soils; *5* — beach plain with birch and pine forests on sod gley soils; *6* — beach ridges with dry meadows on sod calcareous soils; *7* — beach ridges with juniper shrubberies on sod calcareous soils; *8* — beach ridges with birch and pine forests on sod calcareous soils; *9* — beach ridges with groves of broad-leaved trees on sod calcareous soils; *10* — escarpment; *11* — profile.

The supralittoral zone lies out of direct impact of the sea water. The structure of the landscape in this zone depends above all upon the variation of landforms and diversity of deposits. The prevailing processes in soil formation are sodding and swamping. The plant cover is represented by meadows and *Juniperus* shrubberies with the penetration of *Pinus* and more rarely, deciduous trees as well.

The goal of the factor analyses of empirical data was to find out the leading processes in the formation of the landscape pattern of the islets. The following characteristics of sample plots were used as variables: elevation above sea level; distance from the coast line; depth of subsurface water; number of plant species; coverage of trees; humusness of soils; content of physical clay; pH of soils; and concentration of $NO_3$, P, Ca, Mg, Cl, B, Mn, and Zn ions.

The results of the analysis are the following.

The first factor had high correlations with most of the ions and with humusness and it could be interpreted as the ions-absorbing capacity of soils.

The second factor was connected with Ca and Mg that come to soils mostly from limestone detritus; that is why we treat this factor as calcareousness of deposits.

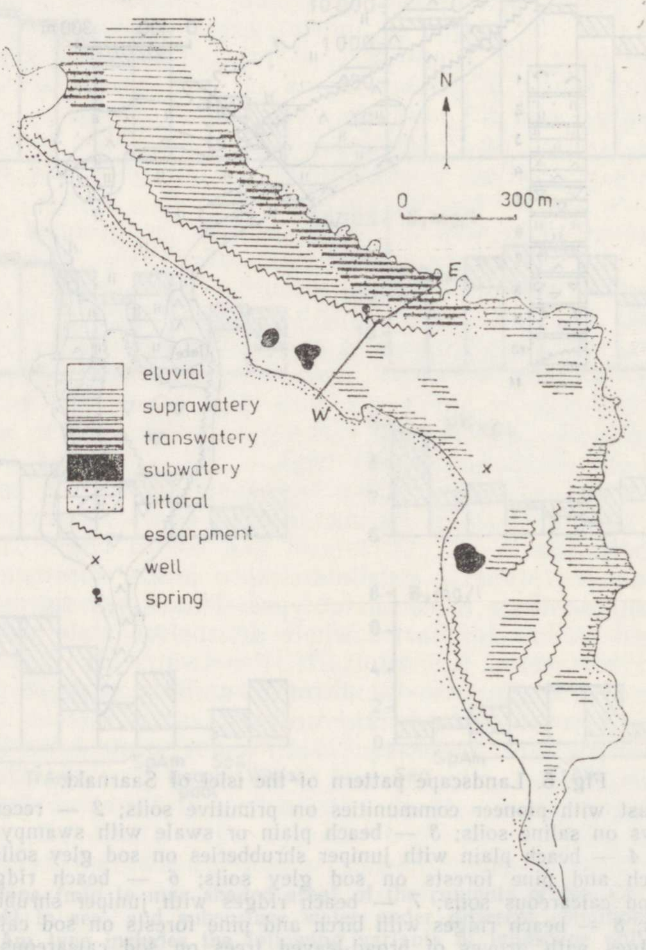


Fig. 6. Pattern of substance movement regimes on the islet of Saarnaki.

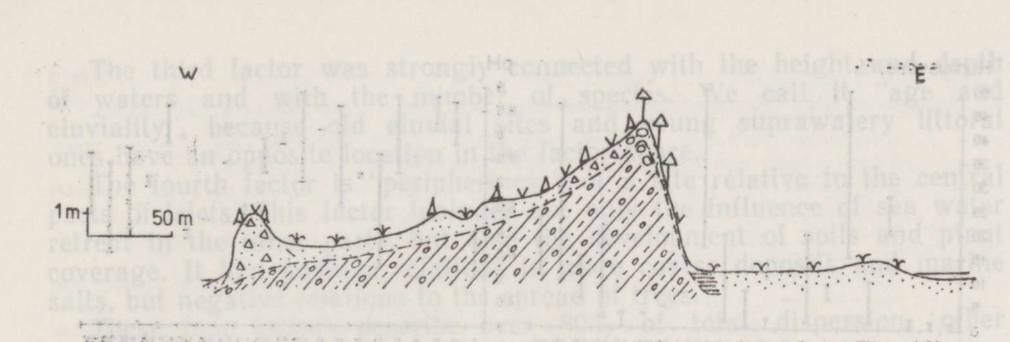


Fig. 7. The complex profile of the islet of Saarnaki (see legend to Fig. 10).

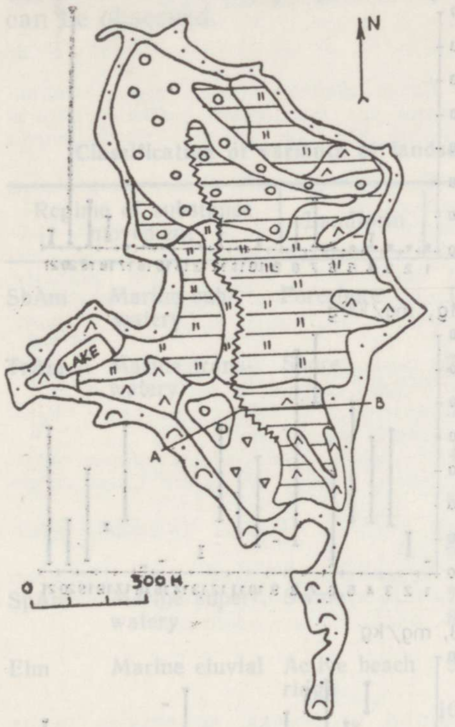


Fig. 8. Landscape pattern of the islet of Hanikatsi (see legend to Fig. 5).

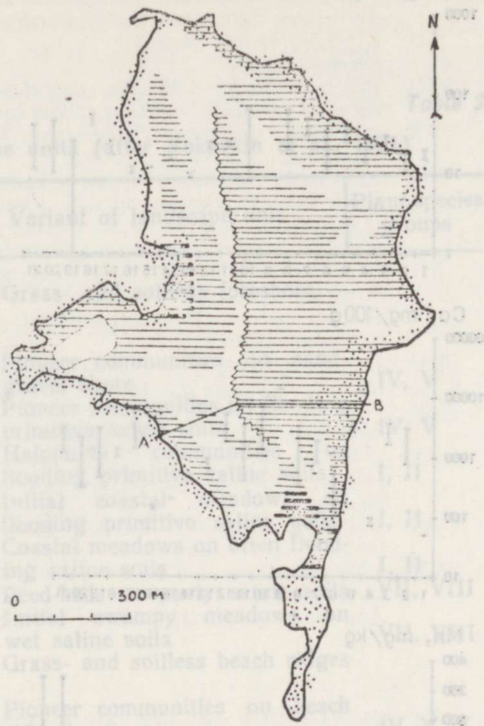


Fig. 9. Pattern of substance movement regimes on the islet of Hanikatsi (see legend to Fig. 6).

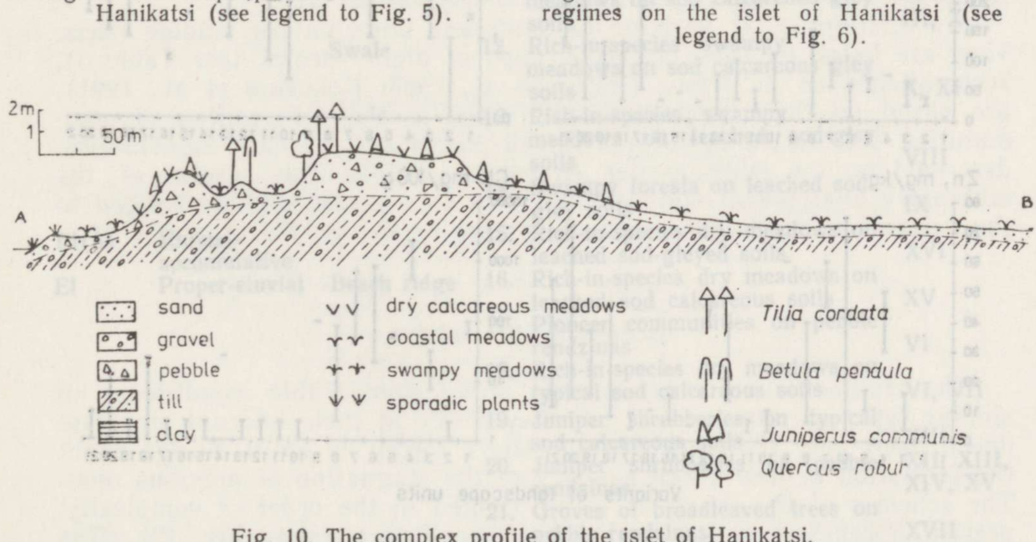


Fig. 10. The complex profile of the islet of Hanikatsi.

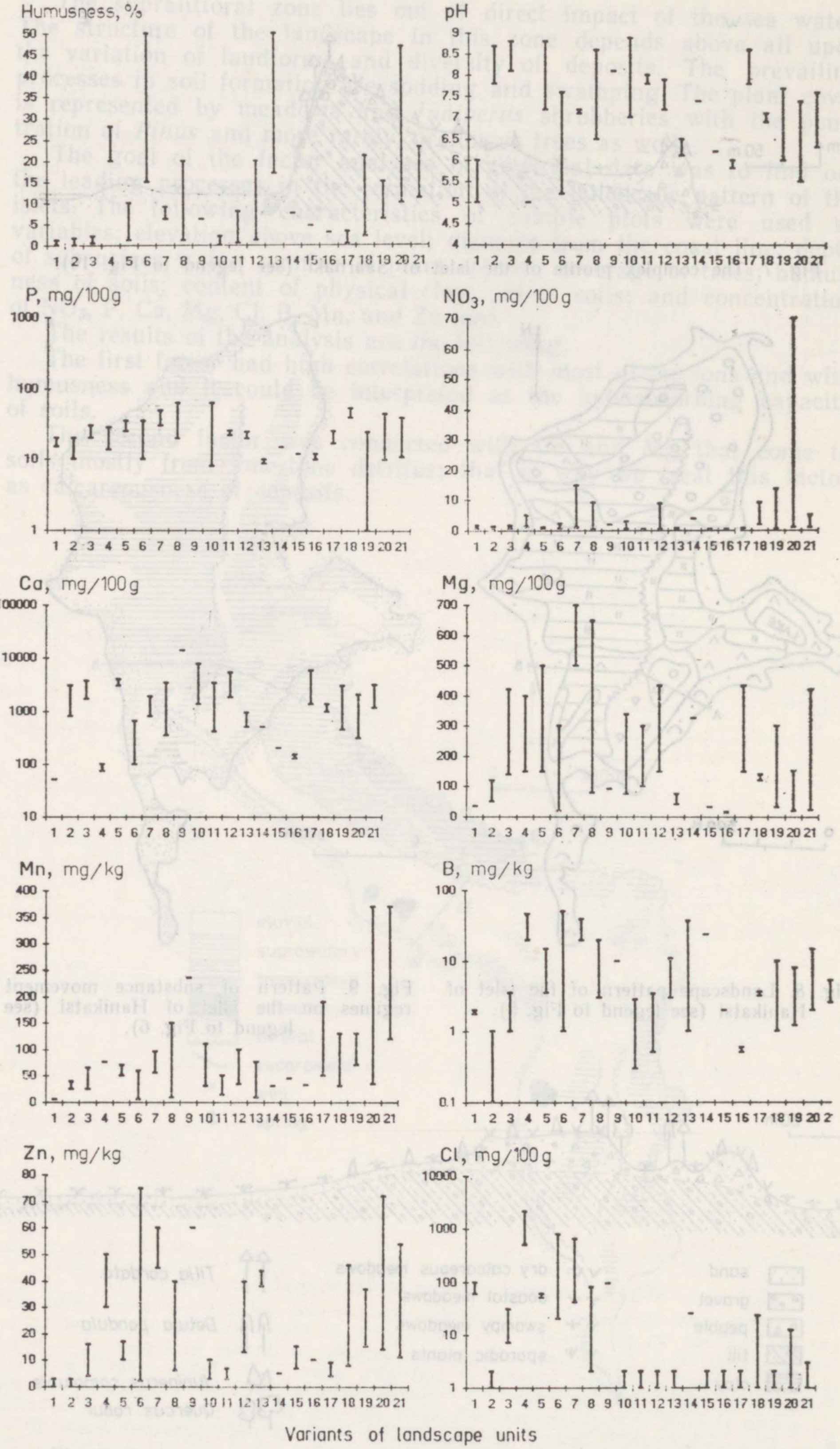


Fig. 11. Variations of measured values of humusness, pH, and contents of P, N—$NO_3$, Ca, Mg, Mn, B, Zn, and Cl in the variants of the landscape units.

The third factor was strongly connected with the height and depth of waters and with the number of species. We call it "age and eluviality", because old eluvial sites and young suprawatery littoral ones have an opposite location in the factor space.

The fourth factor is "peripheriness" of a site relative to the central parts of islets. This factor includes not only the influence of sea water retreat in the inner parts, but also the development of soils and plant coverage. It had positive relations to more coarse deposits and marine salts, but negative relations to the spread of trees.

These four factors describe over 80% of total dispersion; other factors were insignificant. In these leading factors, a strong connection between the landscape pattern and peculiarities of substance movement can be observed.

*Table 2*

**Classification of variants of landscape units (after Kokovkin et al., 1991)**

| Regime of substance movement | | Landform | Variant of landscape unit | Plant species groups |
|---|---|---|---|---|
| SbAm | Marine sub-watery | Foreshore | 1. Grass- and soilless foreshore | |
| TrAm | Marine trans-watery | Shore | 2. Pioneer communities on sand-gravel shore | IV, V |
| | | | 3. Pioneer communities on flooding primitive saline soils | IV, V |
| | | | 4. Halophyte communities on flooding primitive saline soils | I, II |
| | | | 5. Initial coastal meadows on flooding primitive saline soils | I, II |
| | | | 6. Coastal meadows on often flooding saline soils | I, II |
| SpAm | Marine super-watery | Swale | 7. Reed-beds on peaty saline soils | VII, VIII |
| | | | 8. Initial swampy meadows on wet saline soils | VII, VIII |
| Elm | Marine eluvial | Active beach ridge | 9. Grass- and soilless beach ridges | |
| | | | 10. Pioneer communities on beach ridges | IV, V, X |
| SpA | Suprawatery | Beachplain | 11. Rich-in-species swampy meadows on sod calcareous gley soils | III, X |
| | | Swale | 12. Rich-in-species swampy meadows on sod calcareous gley soils | X, XI |
| | | | 13. Rich-in-species swampy meadows on leached sod-gley soils | VIII |
| | | | 14. Swampy forests on leached sod-gley soils | IX |
| El(A) | Eluvial-accumulative | | 15. Rich-in-species dry meadows on leached sod-gleyed soils | XVI |
| El | Proper-eluvial | Beach ridge | 16. Rich-in-species dry meadows on leached sod calcareous soils | XV |
| | | | 17. Pioneer communities on pebble rendzinas | VI |
| | | | 18. Rich-in-species dry meadows on typical sod calcareous soils | VI, VII |
| | | | 19. Juniper shrubberies on typical sod calcareous soils | XII |
| | | | 20. Juniper shrubberies on pebble rendzinas | XII, XIII, XIV, XV |
| | | | 21. Groves of broadleaved trees on pebble rendzinas | XVII |

*Table 3*

**Groups of plant species, distinguished on the islets (after Ratas et al., 1988)**

| | |
|---|---|
| I | (*Salicornia europaea — Suaeda maritima*): *Salicornia europaea, Sagina maritima, Suaeda maritima, Atriplex littoralis, Spergularia salina* |
| II | (*Glaux maritima — Juncus gerardii*): *Glaux maritima, Juncus gerardii, Agrostis stolonifera, Plantago maritima, Triglochin maritimum* |
| III | (*Elytrigia repens — Poa subcoerulea*): *Deschampsia caespitosa, Poa subcoerulea, Elytrigia repens* |
| IV | (*Crambe maritima*): *Crambe maritima, Erysimum hieraciifolium, Asperugo procumbens, Cirsium arvense* var. *arvense, Artemisia absinthium* |
| V | (*Atriplex hastata — Galeopsis bifida*): *Galeopsis bifida, Tripleurospermum inodorum, Atriplex hastata, Atriplex littoralis, Fumaria officinalis* |
| VI | (*Tanacetum vulgare — Anthriscus sylvestris*): *Urtica dioica, Carduus crispus, Valeriana officinalis, Tanacetum vulgare, Rubus caesius, Linaria vulgaris, Anthriscus sylvestris, Solidago virgaurea* |
| VII | (*Arrhenatherum elatius*): *Festuca arundinacea, Arrhenatherum elatius, Phragmites australis* |
| VIII | (*Carex disticha — Molina caerulea*): *Carex disticha, Carex nigra, Galium palustre, Molinia caerulea, Plantago major* var. *maritimum, Lythrum salicaria* |
| IX | (*Cnidium dubium — Filipendula ulmaria*): *Cnidium dubium, Calliergonella cuspidata, Filipendula ulmaria* |
| X | (*Scorzonera humilis — Inula salicina*): *Scorzonera humilis, Equisetum pratense, Inula salicina, Galium boreale, Ranunculus acris* |
| XI | (*Lysimachia vulgaris — Scutellaria galericulata*): *Scutellaria galericulata, Lysimachia vulgaris, Veronica scutellata, Alisma plantago-aquatica* |
| XII | (*Helictotrichon pratense — Pimpinella saxifraga*): *Helictotrichon pratense, Asperula tinctoria, Silene nutans, Plantago lanceolata, Achillea millefolium, Galium verum, Poa angustifolia, Pimpinella saxifraga, Filipendula vulgaris, Fragaria viridis* |
| XIII | (*Helianthemum nummularium — Phelum bertholonii*): *Helianthemum nummularium, Dianthus deltoides, Phleum bertholonii, Climacium dendroides* |
| XIV | (*Trifolium montanum — Alchemilla glaucescens*): *Trifolium montanum, Veronica chamaedrys, Veronica spicata, Alchemilla glaucescens* |
| XV | (*Thymus serpyllum — Cladina arbuscula*): *Cladina arbuscula, Cladonia rangiformis, Peltigera canina, Abietinella abietina, Thymus serpyllum, Carex caryophyllea* |
| XVI | (*Agrostis vinealis*): *Luzula campestris, Agrostis vinealis, Cerastium holosteoides, Rumex acetosella* |
| XVII | (*Anthoxanthum odoratum — Geranium sanguineum*): *Primula veris, Geranium sanguineum, Veronica teucrium, Hypericum perforatum, Polygala amarella, Anemone sylvestris, Dactylis glomerata, Anthoxanthum odoratum* |

As an example of the above-mentioned processes, schematic maps and profiles of the islets of Saarnaki and Hanikatsi are presented (Figs. 5—10).

We distinguish 21 variants of landscape units on the studied islets. They are listed in Table 2. The groups of plant species (see Table 3), accomplished by A. Mäses (Ratas et al., 1988; Kokovkin et al., 1991), are based on the criterion of differences in the composition of communities, therefore they mostly do not correspond to plant associations, described on the islets earlier (Rebassoo, 1975). The results of the laboratory analyses of soil samples from the sample plots, arranged to the variants of landscape units, are presented in Fig. 11.

## Genesis of the Islets

The studied islets have formed under comparable conditions on similar types of parent rock, but they differ in their internal structure due to their age. The growth of the islets, forced by uplift, brings about the formation of new beach ridges and the stagnation of previous ones. The schemes of the reliefs of islets, ranged in the order of complexity, present a relief evolution model of a hypothetical islet (Fig. 12). This model shows that different islets, distributed in space, have (or had) their analogues in time, thus the real islets correspond to the evolution stages of a hypothetical islet.

This model clearly reflects gradual alterations, but not the qualitative changes in the course of the development of islet landscapes (i.e. irreversible changes in soils, water characteristics, plant coverage, etc.). Replacing the landforms on the scheme by substance movement regimes, localized on them, we obtain a model that reflects the alterations of landscape units in a better way (Fig. 13). The rows of this scheme reflect the horizontal structure of a stage, while the columns show the gradual development of the background on which the landscape pattern is shaped. Here also the reason of the homogeneity of the central parts of islets, i.e. the spread of eluvial conditions can be seen.

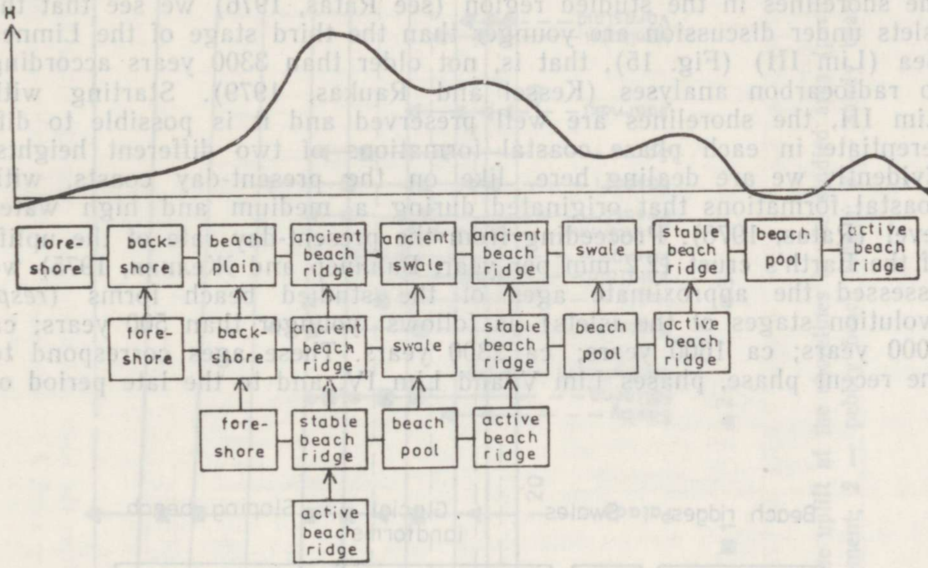


Fig. 12. Evolution of landforms on an islet.

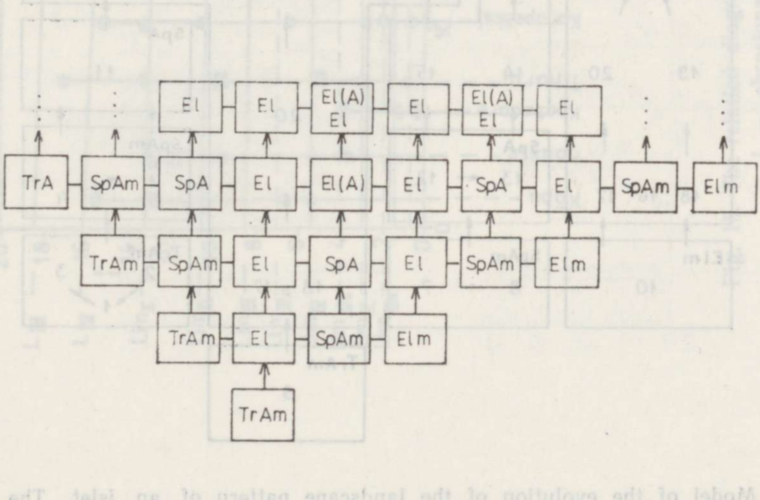


Fig. 13. Evolution of the pattern of substance movement regimes on an islet.

The above-described models could probably be applied to a wide range of small islands in a regressive sea. The model becomes more concrete when the variants of landscape units are added (Table 2). Every landscape unit could be looked upon as a long-term state in the process of the evolution of landscapes. In the evolution of the islets under discussion, four relatively specific genetic series can be distinguished: wave-cut glacial ridges, sloping shores, beach ridges, and swales. The resulting model (Fig. 14) associates these genetic series, substance movement regimes (environed with a line), and long-term states (*resp.* numbers of landscape unit variants) of the studied islands. The arrows show possible transitions from state to state. Obviously, despite the initial states in the evolution of the islets, the landscape units are assimilating with one another in the longer run, thus stabilizing in the eluvial environment.

The studied beach forms converge to elevations of 0.5—1 m, 2 m, 3.5 m, and 5 m a.s.l. Adding these results to the relation diagram of the shorelines in the studied region (see Ratas, 1976) we see that the islets under discussion are younger than the third stage of the Limnea Sea (Lim III) (Fig. 15), that is, not older than 3300 years according to radiocarbon analyses (Kessel and Raukas, 1979). Starting with Lim III, the shorelines are well preserved and it is possible to differentiate in each phase coastal formations of two different heights. Evidently we are dealing here, like on the present-day coasts, with coastal formations that originated during a medium and high water level (Ratas, 1976). Proceeding from the present-day rate of the uplift of the Earth's crust (2.2 mm per year, Валлнер and Желнин, 1975) we assessed the approximate ages of the studied beach forms (*resp.* evolution stages of the islets) as follows: younger than 500 years; ca 1000 years; ca 1600 years; ca 2300 years. These ages correspond to the recent phase, phases Lim V and Lim IV, and to the late period of

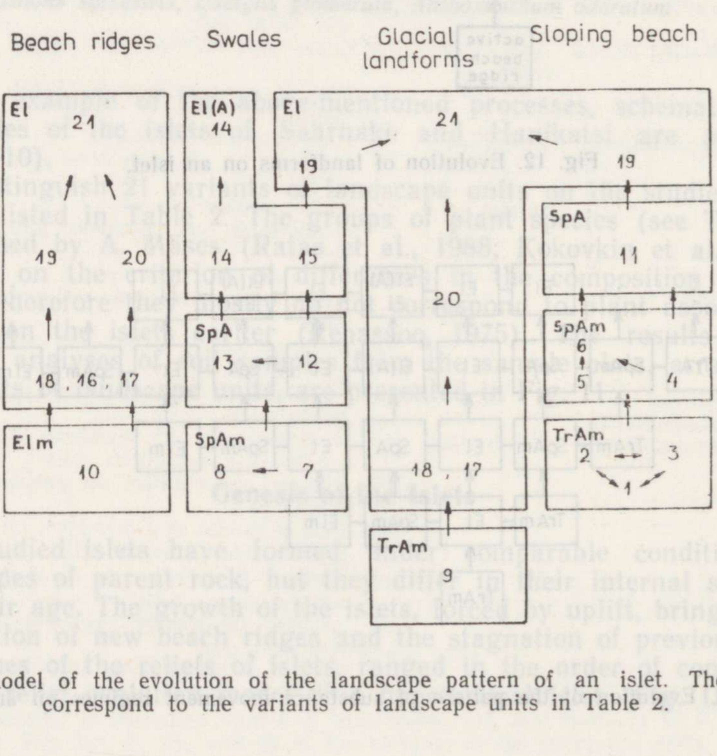


Fig. 14. Model of the evolution of the landscape pattern of an islet. The numbers correspond to the variants of landscape units in Table 2.

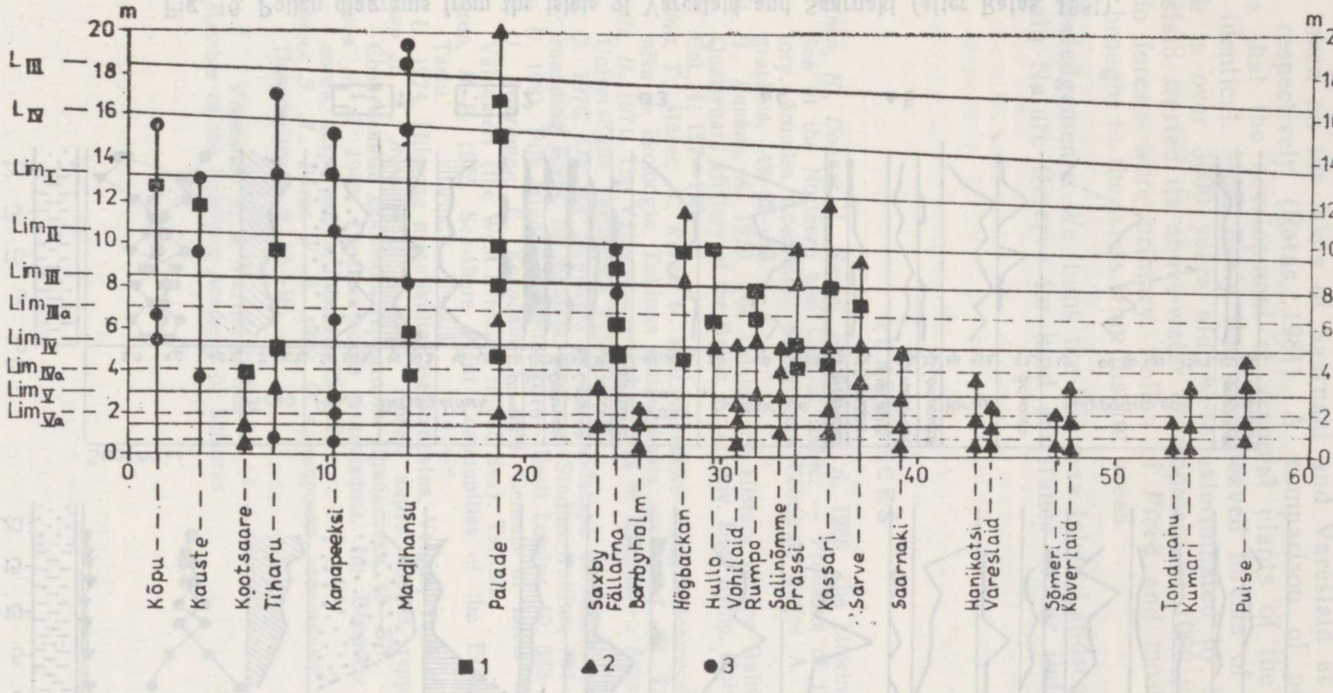


Fig. 15. The relation diagram of the uplift at the shorelines in the studied area (partly after Ratas, 1976). *1* — abrasional escarpment; *2* — pebbly beach ridges; *3* — sandy beach ridges.

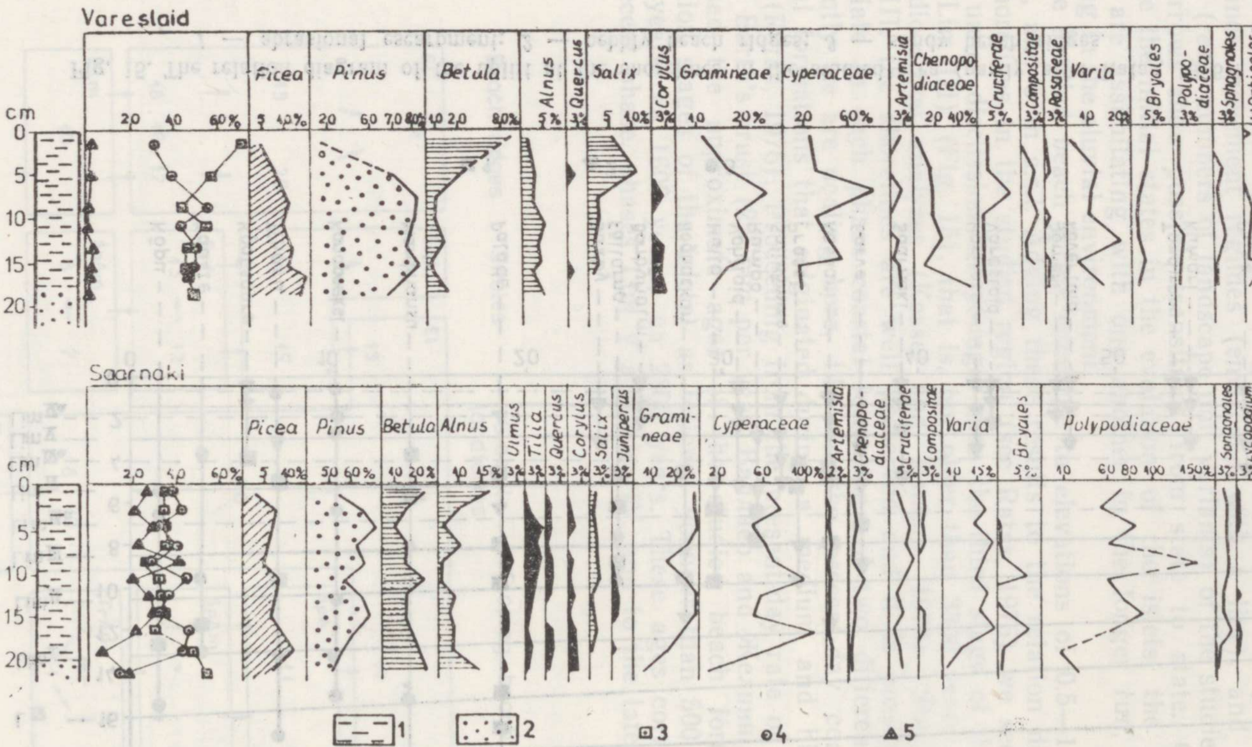


Fig. 16. Pollen diagrams from the islets of Vareslaid and Saarnaki (after Ratas, 1981).
*1* — raw humus; *2* — sand; *3* — tree pollen; *4* — herb pollen; *5* — spores.

Lim III (Sepp, 1974). A remarkable fact is that islets develop from stage to stage with a step of ca 600 years.

The pollen diagrams for islets were made by U. Ratas. Unfortunately, the changeful conditions close to the sea level do not favour the accumulation of pollen in the laminated way, so the lower parts of the diagrams (Fig. 16) should be treated as less representative. The cores were taken on the islets of Saarnaki and Vareslaid at 2.6 and 1.1 m a.s.l., respectively (Ratas, 1981). A comparison of pollen diagrams shows that the development of arboreal plants of the islets has not been identical. Most likely the broad-leaved forests of Saarnaki Islet, which is over 3000 years old, were exterminated by human activity. Vareslaid started its above-water development ca 1000 years later, here *Betula* forests were primary. Pollen of *Picea* and most of *Pinus* has been brought to the islets from distant areas.

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