VILNIUS UNIVERSITY

NATURE RESEARCH CENTRE
INSTITUTE OF GEOLOGY AND GEOGRAPHY

VIOLETA PUKELYTĖ BALTRŪNIENĖ

THE INFLUENCE OF GEOLOGICAL STRUCTURE ON THE DEVELOPMENT OF GEOMORPHOLOGICAL REGIONS (CASE STUDY OF SOUTH LITHUANIA)

Summary of Doctoral Dissertation
Physical sciences, Physical geography (06 P)

Vilnius, 2014

The dissertation was prepared at the Nature Research Centre, Institute of Geology and Geography in 2009–2012.

Scientific supervisor

Prof. Dr. Hab. Algimantas Česnulevičius (Vilnius University, Physical sciences, Physical geography – 06 P)

The dissertation is defended at the Council of Geographical Research of Vilnius University:

Chairman

Prof. Dr. Arūnas Bukantis (Vilnius University, Physical sciences, Physical geography – 06 P).

Members:

Prof. Dr. Inga Dailidienė (Klaipėda University, Physical sciences, Physical geography – 06 P).

Dr. Virgilija Gregorauskienė (Lithuanian Geological Survey under the Ministry of Environment, Physical sciences, Physical geography – 06 P).

Prof. Dr. Egidijus Rimkus (Vilnius University, Physical sciences, Physical geography – 06 P).

Doc. Dr. Julius Taminskas (Nature Research Centre, Institute of Geology and Geography, Physical sciences, Physical geography – 06 P).

Opponents:

Dr. Albertas Bitinas (Klaipėda University, Physical sciences, Geology – 05 P).

Dr. Darius Jarmalavičius (Nature Research Centre, Institute of Geology and Geography, Physical sciences, Physical geography – 06 P).

The official defence of the dissertation is due to be held at the public meeting of the Physical Science Council at the Nature Research Centre, Institute of Geology and Geography on March 25, 2014, at 15.00
Address: T. Ševčenkos str. 13, LT-03223, Vilnius, Lithuania.

The summary of the dissertation was distributed on February 24, 2014
The dissertation is available in the libraries of Vilnius University and Nature Research Centre, Institute of Geology and Geography.

VILNIAUS UNIVERSITETAS

GAMTOS TYRIMŲ CENTRAS

GEOLOGIJOS IR GEOGRAFIJOS INSTITUTAS

VIOLETA PUKELYTĖ BALTRŪNIENĖ

GEOLOGINĖS STRUKTŪROS ĮTAKA GEOMORFOLOGINIŲ RAJONŲ RAIDAI (PIETŲ LIETUVOS PAVYZDŽIU)

Daktaro disertacijos santrauka

Fiziniai mokslai, fizinė geografija (06 P)

Vilnius, 2014

Disertacija rengta 2009-2012 metais Gamtos tyrimo centro Geologijos ir geografijos institute

Mokslinis vadovas

Prof. habil. dr. Algimantas Česnulevičius (Vilniaus universitetas, fiziniai mokslai, fizinė geografija – 06 P).

Disertacija ginama Vilniaus universiteto Geografijos mokslo krypties taryboje:

Pirmininkas

Prof. dr. Arūnas Bukantis (Vilniaus universitetas, fiziniai mokslai, fizinė geografija – 06 P).

Nariai:

Prof. dr. Inga Dailidienė (Klaipėdos universitetas, fiziniai mokslai, fizinė geografija – 06 P)

Dr. Virgilija Gregorauskienė (Lietuvos geologijos tarnyba prie Aplinkos ministerijos, fiziniai mokslai, fizinė geografija – 06 P)

Prof. dr. Egidijus Rimkus (Vilniaus universitetas, fiziniai mokslai, fizinė geografija – 06 P)

Doc. dr. Julius Taminskas (Gamtos tyrimų centras, Geologijos ir geografijos institutas, fiziniai mokslai, fizinė geografija – 06 P).

Oponentai:

Dr. Albertas Bitinas (Klaipėdos universitetas, fiziniai mokslai, geologija – 05 P)

Dr. Darius Jarmalavičius (Gamtos tyrimų centras, Geologijos ir geografijos institutas, fiziniai mokslai, fizinė geografija – 06 P)

Disertacija bus ginama viešame Geografijos mokslo krypties tarybos posėdyje 2014 m. kovo mėn. 25 d., 15 val. Gamtos tyrimų centro Geologijos ir geografijos instituto salėje. Adresas: T. Ševčenkos 13, LT–03223, Vilnius, Lietuva.

Disertacijos santrauka išsiuntinėta 2014 m. vasario mėn. 24 d.
Disertaciją galima peržiūrėti Vilniaus universiteto ir Gamtos tyrimų centro Geologijos ir geografijos instituto bibliotekose.

INTRODUCTION

In recent decades mach data have been published about the influence of geological structure (geophysical anomalies, tectonic structure and neotectonic activity, palaeo-surface morphology, *etc*.) on the distribution, formation conditions and palaeogeo-graphical development of relief complexes (morainic uplands and plains, terrace plains and river valleys, aeolian massifs, *etc*.). Yet specialised researches dealing with this issue are lacking in Lithuania. Therefore, the question is open as to the consistency and typical-lity of this influence in the continental glaciation territories, research methods of this influence and the character and dimension of geological heredity.

The subject of investigation is related with solution of relevant issues in everyday practices. The information about concrete links of geomorphological complexes with the geological structure contributes to better understanding of the causes of generation of these complexes, development of specific (sand, gravel, till and sediments of variable composition) layers of deposits and geoecological conditions. Data of this kind are very impor-tant for territorial planning, evaluation of geoecological conditions of territories and prediction of the distribution of some valuable minerals, groundwater in particular. Inves-tigations of palaeogeographical evolution of surfaces are important for reconstructions of the evolution of palaeosystems and palaeoenvironments.

Research Object

The geomorphological regions of South Lithuania and their subterranean geological structures (geophysical anomalies, tectonic faults, sub-Quaternary rock surfaces and the basic Pleistocene palaeosurfaces). In comparison with other Lithuanian regions, the South Lithuania region under consideration is best geologically and geomorphologically investigated (Fig. 1).

The Aim of the study

The main objective of the present research was to evaluate the influence of geological structure on the development of earth surface geomorphological complexes (regions) based on the case study of South Lithuania.

Fig. 1. Location scheme of investigated territory

Main Tasks

The following tasks had to be fulfilled:

1. Analysis of previous geomorphological investigations and geomorphological and palaeogeomorphological regionalisation.

2. New palaeogeomorphological regionalisation of sub-Quaternary rock surface and analysis of the main palaeosurfaces of Pleistocene strata.

3. Evaluation of lithomorphogenetic structure and palaeogeographical evolution of geomorphological regions of recent earth surface.

4. Evaluation of the links of deep geological structure with the distribution of geomorphological regions.

5. Evaluation of the links of sub-Quaternary and Pleistocene rock surfaces with the distribution of geomorphological regions.

Methods

The present research is based on methodology of complex investigations. It emphasises the synchronous application of genetic, morphological and lithological criteria for determining the lithomorphogenetic structure of geomorphological regions. The principle of reference objects investigation also was applied allowing detailing of some geomorphological and geological processes (filling of palaeoincisions, formation of aeolian massifs, *etc.).*

The following other methods were applied: palaeogeomorphological regionalisation of sub-Quaternary surfaces, investigation of lithomorphogenetic structure of geomorphological regions, evaluation of the filling material of palaeoincisions, calculation of the relative entropy of till deposits, and correlation analysis for statistical comparison of palaeosurfaces and current surface using *Surfer* and *Excel* computer programs.

Novelty of Research

New regionalization of sub-Quaternary surface was conducted and reliability of differentiation and comparability of Pleistocene palaeosurfaces evaluated using correlation analysis method. A new map (at a scale 1:200 000) of lithomorphogenetic regions was compiled and the palaeogeographical post-glacial development of the distinguished geomorphological regions was evaluated. A conception of geomorphological heredity of relief, i.e. the evolution of geomorphological regions is linked with the geological structure predetermined by tectonic structure and neotectonic activity and sub-Quaternary and Pleistocene palaeosurfaces of rock masses, is suggested. The correlation links between the compared surfaces were determined.

Practical importance

The practical importance is related with distinguishing smaller territorial units – micro-regions – in lithomorphogenetic structure of geomorphological regions based on their distribution, morphology and geological composition. Lithomorphogentic micro-regions serve as the mineral substratum of ecosystems of defined territories which together with other constituents of ecosystems comprise a unique landscape. Geomorphological heredity helps to understand the process of deposition what is important for prediction of the incidence of some valuable minerals and evaluation of local geo-

ecological conditions. Investigations of palaeogeographic evolution of surfaces are essential for reconstruction of the history of palaeosystems and palaeoenvironments. The data of palaeogeographic evolution of surfaces supplemented with the ecogeological data and information about the degree of technogenic impact can be used in territorial planning – development of master plans, regional land management projects and development schemes of specialised activity.

Main Vantage Points

1. The South Lithuanian geomorphological regions are represented by large geomorphological complexes generated by one or a few prevailing geological-geomorphological processes. They are distinguished for specific palaeogeographical evolution, differ in age and scale of post-genetic transformation and have a specific and variable lithomorphogenetic and deep geological structure.

2. The influence of geological structure on the evolution of geomorphological complexes is displayed through the links between areal and linear tectonic movements (endogenic processes) and relief-generating egzogenic processes (exaration and erosion and glacial aquaglacial, aeolian and fluvial accumulation).

3. The palaeosurfaces of sub-Quaternary and main palaeosurfaces of Pleistocene strata are a result of the interaction between endogenic and egzogenic processes and compose the statistically proved basal complex of recent geomorphological regions (sub-regions).

Data Sources

The data used in the present research were collected through participation in the projects supported by the Lithuanian Science and Studies Foundation “Stone Age in South Lithuania” and “Raigardas” and the scientific research programme supported by the Lithuanian Scientific Council “Ciklas”. The necessary additional data were collected during field expeditions and by analysis of the results of previous investigations, i. e. large-scale maps and cartographic and aerophotogeological decoding reports stocked at the Lithuanian Geological Survey (Ber *et al.*, 1997; А**.** Шляупа *и др*., 1972, 1973, 1974 a, 1979; Битинас *и др.*, 1983; Саткунас *и др*., 1991 a and others), medium-scale Quaternary geological and geomorphological maps (Guobytė, 1998, 2000), and

ecogeological maps of Vilnius, Trakai, Varėna and Šalčininkai districts at a scale 1:50 000 (Taikomųjų…, 1989; Varėnos…, 1992; Lietuvos geologinio…, 1993–1998).

Approbation of the doctoral dissertation

The results were presented at twelve international Symposium: in Finland (2006, 2011), Estonia (2009), Germany (2010), Russia (2005 – Kola; 2012 – Valday), and Lithuania (2007 – Plateliai; 2013 – Trakai).

The research results also were reported in 13 publications 4 of which in issues included in the database of *Thomson Reuters Web of Science* and database with cited references *ISI WOS*, 4 in journals included in the *Thomson Reuters Master Journal List* and five in other refereed periodical, serial and one-off scientific issues.

Extent and Structure

The doctoral dissertation is composed of Introduction, Overview of Previous investigations, Methods, Results (four sections and 11 sub-sections), Conclusions and a List of References (318 entries). The dissertation includes three annexes with the list of author's publications on the dissertation subject, list of geomorphological regionalization and list of boreholes used in the present research. The dissertation is comprised of 154 pages, 48 illustrations and 11 tables.

A c k n o w l e d g e m e n t s

The author is grateful to supervisor Prof. Dr. Hab. Algimantas Česnulevičius and colleagues who devoted their time and energy to the author at different stages of preparation of the following dissertation –

Dr. Hab. Valentinas Baltrūnas, Dr. Bronislavas Karmaza, Doc. Dr. Kęstutis Švedas, Dr. Hab. Saulius Šliaupa, Dr. Miglė Stančikaitė, Dr. Rimantas Petrošius, Dr. Vaidotas Kazakauskas, Dr. Stasys Paškauskas for valuable advices and support.

1. OVERVIEW OF PREVIOUS INVESTIGATIONS

The present dissertation is based on the data of complex geological and geographical investigations. The survey includes the research works carried out in the fields of recent dynamic processes, geomorphological mapping, structural geomorphology, and morphology of relief.

Structural geomorphological investigations. The first investigations aimed at tracing the links between the deep and surface structures of the earth were carried out at the beginning of the 20th century by V. Karoliewicz (1928) though already L. Sawicki (1909) in his works mentioned the possible link between relief and geological-tectonic structures. V. Gudelis was the pioneer of the use of structural geomorphology methods for geological purposes (Gudelis, 1955; Гуделис, 1957, 1960, 1961 a, c, 1981, 1982). The influence of neotectonic movements on the development of landforms was analysed by V. Čepulytė (Чепулите, 1956, 1965, 1967, 1971) and A. Basalykas (Basalykas, 1955 a, b, 1956, 1958 a, b, 1965; Басаликас, 1955, 1957 a, b, 1961). The structural geomorphological investigations have gained special attention with intensifying prospecting for oil. Of extreme importance are A. Šliaupa‘s researches (A. Šliaupa, 1994; А.ШЛяупа, 1968, 1970 a, b, 1972, 1976, 1978, 1979; А. Шляупа, Философов, 1969).

Studies and regionalization of sub-Quaternary rock surface. The first publications about this surface appeared in Lithuania in the 20th century (Friederichsen, 1918; Hess won Wichdorft, 1919; Hundt, 1919; Mortensen, 1926). A. Jentzsch (1900) was one of the first who by means of schematic isohypses depicted the sub-Quaternary surface in 1899. It was later described by A. Tornquist (1910). J. Lewinski and J. Samsonowicz (1918) compiled a scheme of the sub-Quaternary surface of South-Western Lithuania and neighbouring territories. The first map of the Lithuanian sub-Quaternary surface with explanation of its genesis was compiled by J. Dalinkevičius (1930). Later, maps of this palaeosurface were compiled by V. Čepulytė (Čepulytė, 1959; Чепулите, 1956, 1965), P. Vaitiekūnas (1959), A. Ignatavičius (1959), and V. Vonsavičius (Вонсавичюс, 1965, 1972, 1976, Kondratienė, Vonsavičius, 1994). A. Gaigalas, S. Vaitekūnas, A. Klimašauskas and G. Prakapaitė compared their individual map of sub-Quaternary relief with geotectonic data and made a conclusion that the main elements of this surface

in the territory of Lithuania were generated by a long-lasting tectonic development process of South Baltic sedimentary rock mass structure (Гайгалас *и др.*, 1967).

1968–1969, when A. Šliaupa's studies appeared, may be regarded as the beginning of a new research stage of sub-Quaternary rock surface (А. Шляупа, 1968; 1970 a, b). In his later works, A. Šliaupa suggested that the hypsometric position of scarps not always depend on the lithology of sub-Quaternary rock layers whereas the system of palaeoincisions is related with geological and tectonic deep structures (A. Šliaupa, 1996, 1997 a, b *ir kt.*). The issues of palaeochannels of recent rivers were discussed by P. Vaitiekūnas, V. Gudelis, L. Petrulis, A. Čepulytė, A. Ignatavičius and others. The sub-Quaternary surface for compilation of morphological and other thematic geological maps was regionalized by A. Gaigalas and M. Melešytė (Gaigalas *ir kt.*, 1976; Мелешите, 1976 *ir kt.*), V. Vonsavičius (Kondratienė, Vonsavičius, 1994), A. Basalykas (Басаликас, 1980), Č. Kudaba (Kudaba, 1983), and J. Paškevičius (Paškevičius, 1994).

Studies of Pleistocene strata palaeosurface. The first detailed works dealing with Pleistocene surface appeared in around 1958 when methodically systematic geological mapping at a scale 1:200 000 was undertaken. Two palaeosurfaces were most reliably distinguished: roofs (tops) of Dainava formation and Medininkai sub-formation of Žeimena formation. Namely these two palaeosurfaces were productively studied by V. Čepulytė (Čepulytė, 1959, 1968, 1973; Чепулите, 1967, 1968, 1971, 1972 and 1974). These studies bore regional character and were confined to hypsometric mapping of roofs and floors (tops and bottoms) of strata.

The buried Pleistocene palaeochannels within Vilnius territory were described by L. Petrulis (Petrulis, 1958 a, b). An attempt to reconstruct the interglacial palaeochannels in Kaunas was undertaken by V. Kemėšis (Кямешис, 1968). L. Micas (Мицас, 1968, 1974), M. Melešytė (Мелешите, 1976, 1978), Z. Malinauskas (Малинаускас, 1991) and V. Baltrūnas (Baltrūnas, 1995, 2002) were interested in structural, palaeogeographical and palaeogeomorphological aspects of palaeochannels.

Studies of postglacial palaeogeographical evolution. Many scientists investigating into this issue confined to general schematic palaeogeographical characteristics of the region. The obtained results later served as a theoretical and methodological basis for new investigations (Micas, 1963, 1964; Basalykas, 1965; Vaitiekūnas, 1968; Kudaba, 1983; Kabailienė, 1990; Dvareckas, 1993; Gaigalas, 1995 b; Гуделис 1973; Гайгалас,

1979; Кондратене, 1996 and others). Other research works were more targeted, i. e. devoted to investigation of concrete objects and using special methods. The fundamental conclusions of these research works largely contributed to knowledge of palaeogeographical conditions of the time under consideration. Firstly, these were spores-pollen investigations of last glaciation and Holocene sections in South Lithuania and neighbouring regions and correlation of biostratigraphically analysed sections with other regions (Seibutis, 1974; Kunskas, 1977; Kabailienė, 2001; Stančikaitė *et al.*, 1998; Kabailienė, Stančikaitė, 2001 and others). The results of geochemical, lithological, petrographical and textural investigations added to better understanding of palaeogeographical environment (Baltrūnas, 1995, 1997 a, 2001 a, b, 2002; Gaigalas, 2001; Švedas, 2001; Микалаускас, 1985 and others).

Studies of continental aeolian formations. The continental dunes of Vilnia basin were studied by L. Micas (Micas, 1955). A. Basalykas was the first who characterised in detail the dunes of south-eastern Dainava plain A. Basalykas (Basalykas, 1955 c, 1958 a, 1965, 1969; Басаликас, 1987 and others). They also were investigated by (Kristapavičius, 1961 a, b, 1962, 1964; Кристапавичюс, 1960), V. Klimavičienė (Климавичене, 1968), V. Gudelis ir R. Vaitonienė (Gudelis, Vaitonienė, 1974 a, b, 1975; Вайтонене, 1975, 1976), R. Morkūnaitė (Dvareckas, Morkūnaitė, 1996; Morkūnaitė *ir kt.*, 2002; Česnulevičius *ir kt*., 2004). The available literary data show that the aeolian deposits of South Lithuania were rather thoroughly investigated in terms of genetic identification and mapping and dune morphology and classification. Yet the issues of palaeogeography and geochronology of aeolian deposits and the influence of endogenic forces on them remain controversial issues.

Geomorphological regionalization. The first attempts to regionalize the Lithuanian surface occurred at the beginning of the 20th century and were rather sketchy (Wołłosowich, 1920; Mortensen, 1926; Vireliūnas, 1926; Šinkūnas, 1931, 1935; Baronienė, 1937; Tarvydas, 1937; Klimas, 1938).

A more thorough regionalization was undertaken after the war along with intensive geomorphological investigations. Surface regionalization was based on newly obtained data (Čepulytė, 1953, 1956 a, b, 1957; 1958; Tarvydas, 1955). Of special importance were the complex work performed in 1958 “Physical geography of the Lithuanian SSR“, V. I, which consistently generalised the available material about the Lithuania‘s nature

(Lietuvos..., 1958) and physical geographical regionalization conducted in 1965 (Basalykas, 1965). He distinguished 6 landscape provinces, 22 regions and 250 sub-regions.

In the seventies of the 20th century, a new conception – landscape – of regionalization method was developed (Basalykas, 1977, 1981, 1984, 1986; Басаликас, 1976). Based on Č. Kudaba's glaciomorphological investigations of the surface, P. Kavaliauskas compiled a scheme of regionalization of Lithuanian landscapes. He distinguished 18 landscape provinces, 45 regions and 108 sub-regions. On the orographic-belt basis, the provinces were incorporated into 8 landscape tracts (Galvydytė, Kavaliauskas, 2003; Каваляускас, 1986). The Lithuanian Quaternary geological map (1:200 000) compiled in 1998 and the Lithuanian geomorphological map (1:200 000) compiled in 2000 allowed their compiler R. Guobytė distinguishing 6 geomorphological provinces, 24 regions, 13 sub-regions, and 467 micro-regions (Guobytė, 2001 a, b). In 2004, R. Guobytė and A. Česnulevičius conducted lithomorphogenetic regionalization of Lithuania within the state research programme "Lithosphere". The last published works were performed by R. Guobytė, P. Kavaliauskas and A. Česnulevičius. R. Guobytė and P. Kavaliauskas distinguished 15 geomorphological provinces, 37 regions, and 33 sub-regions (Visuotinė..., 2007). The geomorphological regionalization scheme made by A. Česnulevičius includes 7 provinces and 30 regions (Česnulevičius, 2010).

Generalising it can be pointed out that attempts of regionalization of Lithuania's surface were interesting and useful. Yet the taxonomic units or regionalization still are ill-defined and ambiguity and there remains the problem of application of different criteria. Also it is obvious that too little attention has been devoted to lithomorphogenetic structure of geomorphological regions, use of boring data, and complex application of genetic, morphological and lithological criteria.

2. METHODS

South Lithuania was chosen for the present study as a territory marked by high diversity of relief age, genesis and composition (Fig. 1). The surface of the studied territory is composed of the Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau, South Lithuanian Upland, South-eastern (Dainava) Plain, Middle Nemunas Plateau, and the southern part of Lower Nemunas Plain.

In comparison with other Lithuanian regions, South Lithuania has been better geologically-geomorphologically investigated. In this territory, large scale geological mapping (1:50 000) and aerophoto geological decoding have been performed by V. Baltrūnas, A. Bitinas, A. Jusienė, A. Juškevičiūtė, R. Guobytė, B. Karmaza, D. Karmazienė, J. Satkūnas, A. Šliaupa, A. Veršickienė and others (Ber *et al.*, 1997; Guobytė, 1998, 2000; Шляупа *и др*., 1972, 1973, 1974, 1979; Битинас *и др*., 1983; Саткунас *и др*., 1991 a and other). The obtained results, boring data in particular, were very important for investigation of the influence of geological structure on the evolution of surface relief complexes and geomorphological heredity phenomenon in South Lithuania.

For stratigraphic classification and identification of the Quaternary deposits, the Lithuanian Quaternary stratigraphic scheme compiled by the Lithuanian Geological Survey was used (Satkūnas *ir kt.,* 2007). The stratigraphic classification of surface geomorphological complexes was performed based on the scheme of the last deglaciation stages and phases which has been used for many years already (Gaigalas, 2001).

Regionalization of sub-Quaternary surface. Regionalization of the Lithuanian sub-Quaternary surface was performed based on the age, genesis and morphology of relief. This historical genetic principle of regionalization has been in use for a rather long time and is of high theoretical and practical value for compilation of palaeomorphological schemes and maps of buried relief. The palaeogeomorphological regionalization of sub-Quaternary rock surface undertaken in the present dissertation included the following steps:

1. Analysis of sub-Quaternary surfaces of Lithuania and neighbouring regions. V. Vonsavičius's (Вонсавичюс, 1972, 1976) and A. Šliaupa's (A. Šliaupa, 2004 b) maps supplemented with the data of large-scale geological mapping (Guobytė, 1998, 2000;

A. Шляупа *и др*., 1972, 1973, 1974 a, 1979; Битинас *и др*., 1983; Саткунас *и др*., 1991 a) were used and preliminary palaeogeomorphological regions distinguished based on the absolute altitude and character of erosion-exaration features of palaeorelief.

2. Comparative analysis of variable age geological complexes and tectonic structure (incidence of faults) of sub-Quaternary surface was performed using geological, structural-formation and tectonic maps of East Baltic region (Baltic countries) (Геологическая..., 1980; Тектоническая..., 1980; Структурно..., 1982).

3. Analysis of the lower part of Quaternary strata was performed determining the age and genesis of deposits bedded on top of palaeowatersheds of sub-Quaternary surface and genetically and stratigraphically identifying and typifying the strata filling the palaeoincisions. The age and origin of the deposits overlying the palaeosurface also show the age and origin of the palaeosurface itself.

4. Formulation of generalised lithomorphogenetic and stratigraphic characteristics of the distinguished palaeogeomorphological regions.

5. Compilation of the palaeogeomorphological regionalization scheme based on the legend.

Evaluation of the texture of the filling material of palaeoincisions. Analysis of the material filling the palaeoincisions of sub-Quaternary surface allowed compilation of generalised circle diagrams of dominant sections for most of palaeogeomorphological regions using the method widely applied in Denmark (Geological..., 1993). The outer ring of the diagram indicates the composition of Quaternary deposits from –200 m to 0 m (sea level) abs.a. and the inner ring from 0 (sea level) to +200 m abs.a. The different colours stand for different origin of deposits.

Evaluation of palaeosurfaces of Pleistocene strata. Two problems had to be solved during the investigation of Pleistocene palaeosurfaces: evaluation of reliability of surface classification and comparability of palaeosurfaces.

The South Lithuanian Quaternary deposits were identified and characterised by genesis and age using the data of grain size, mineral (in the fractions of 0.25–0.1 and 0.1–0.05 mm), petrographic (in the fractions of 30–10, 10–5 and 5–2 mm) and geochemical (in the fraction <1 mm) analyses of glacial sediments and of other investigations. The identification of the two chosen palaeosurfaces (Dainava and Žeimena formations) was rather complicated, in cases of stratified till cover in particular, since the absolute majo-

rity of the sections of Quaternary strata have unidentified interglacial layers. The multi-layer structure of tills was preliminary identified microscopically according to the archival curves of boring diagraphy.

An attempt was made to determine the relative entropy of grain size composition, as an indicator of multi-component mixture, of tills. The method of relative entropy has been used in geosciences since long ago (Baltrūnas, 1995). Entropy ***H***, as a function of state, is expressed as:

$$H = -\Sigma pi \log pi ,$$

where p_i – portion of ***i*** component in the system and $\Sigma p_i = 1$. The used relative entropy shows the ratio between the entropy and the maximal entropy of the studied system:

$$S = H_r / H_m$$

The latter expression is convenient for comparison and graphic depiction of different systems (tills).

For detailed analysis, the areas with the complete and stratigraphically most reliably identified sections of Pleistocene strata in the Trakai District (south-west of Vilnius) (Baltrūnas *et al.*, 2008) and areas in Daugai and Varėna environs (Baltrūnas, Pukelytė, 2008) were chosen.

For analysis and comparison of palaeosurfaces, 256 boreholes through the entire Quaternary strata with reliable stratigraphic classification of their sections were used following the Quaternary stratigraphic scheme compiled by the Lithuanian Geological Survey (Satkūnas *ir kt*., 2007). As the values of absolute altitude of compared palaeo-surfaces in the boreholes are marked by stochastic links (non-deterministic links between random values) binary correlation coefficients (***r***) were calculated for statistical determination of correlation links between two compared palaeosurfaces.

$$r_{xy} = \frac{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)\times\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2 \times \sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2}}$$

,where **–1 ≤ *r* ≤ +1;** (x_i, y_i) **, (i=1, …, N**) – binary measurement; ***N*** – number of binary measurement (x_i, y_i) ; $\bar{x}$ – mean of stochastic quantity ***X***; $\bar{y}$ – mean of stochastic quantity ***Y*.**

The significance of correlation coefficients was determined using B. Smirnov‘s formula:

$$|r_\alpha| = t_{\alpha, f} / (t_{\alpha, f}^2 + N - 2)^{1/2},$$

where N – number of samples, α – significance level, $t_{\alpha, f}$ – critical value of Student‘s distribution with $f = N - 2$ degrees of freedom.

The statistically significant correlation coefficients were identified by comparison with the critical value α of the calculated coefficient. For evaluation of statistical significance, a ternary α value was used: $\alpha = 0.05$, $\alpha = 0.01$ and $\alpha = 0.001$. In all cases, the correlation coefficients of all compared surfaces are statistically significant and reflect the actual interdependence.

Using the *Surfer* program and *“Cringing”* interpolation method, the data of geological mapping of boreholes, embracing the whole Quaternary strata, were generalised and hypsometric models of palaeosurface relief were compiled.

Investigation of lithomorphogenetic structure of geomorphological regions. Relatively homogeneous areas (micro-regions) were distinguished in the studied territory paying special attention to relief morphology, genesis, geological structure and texture, lithological composition, and groundwater level. Lithomorphogenetic micro-regions incorporating one or a few genetically comparable lithological complexes represent structural parts of higher rank territorial units – geomorphological regions. Investigation of lithomorphogenetic structure of geomorphological regions had to reveal the character of non-homogeneity of these regions and serve as a structural basis for their distinguishing.

The mapping of lithomorphogenetic regions on middle and large scale was realised in the following sequence:

1 – The map is compiled on the basis of Quaternary geological and geomorphological map.

2 – Lithomorphogenetic (geological-geomorphological) micro-regions are distinguished joining the areas of dominant genesis and lithological composition marked by uniform geomorphology, comparable absolute altitude and other features (aeolian, periglacial and other).

3 – The genesis and age of deposits is colour-coded, relief is marked using brown, and lithological composition using black conventional signs.

4 – The thickness of the surface layer and groundwater depth are shown in generalised formulae for areas and micro-regions and the dominant absolute altitude is indicated in numbers.

5 – The written text (tables) gives the titles and abbreviations for micro-regions and briefly describes the lithological, geological-geomorphological and other characteristics.

The material about micro-regions was collected from geological and geomorphological maps of various scales, sections of prospecting boreholes and test pits and from the data obtained during map sketching of quarries and outcrops.

Investigation of palaeogeographical evolution. The investigation of palaeogeographical evolution of South Lithuania in late glacial and Holocene was carried out for palaeogeographical reconstruction of the formation of geomorphological regions and their lithomorphogenetic structure. The palaeogeographical maps at a scale 1:200 000 were compiled based on Quaternary geological and geomorphological maps (M1:200 000) (Guobytė, 1998, 2000; А. Шляупа *и др*., 1972, 1973, 1974 a, 1979; Битинас *и др*., 1983; Саткунас *и др*., 1991 a). They palaeogeographical maps were compiled using original methods and legend which has been published in print (Baltrūnas, 1997 a; Baltrūnas *et al.*, 2007, 2010; Švedas *ir kt.*, 2004). The maps in the present dissertation are given in the form of simple schemes. The schemes are made for all stages of palaeogeographical evolution: Žiogeliai phase of Late Nemunas, Baltija stage and its South Lithuanian phase, and Early Holocene (Boreal) (Švedas *ir kt*., 2004).

Investigation of continental aeolian formations. Aeolian formations represent an important part in the lithomorphogenetic structure of South Lithuanian geomorphological regions. They are widespread in the studied territory and very dynamic, i. e. they respond to such important environmental factors as genetic-lithological foundation, climate conditions and wind intensity, deep structures and neotectonic movements.

Eleven smaller study areas were chosen in the South Lithuanian dune terrains. They are Rūdninkai, Barčiai, Varėna, Palkabalis, Lynežeris, Marcinkonys, Musteika, Katra, Randamonys, Dubas and Latežeris aeolian reference areas. The morphometric indices of 966 big dunes (absolute altitude of dune top and bottom, relative altitude and crest length, crest lee-ward azimuth, number of dune offshoots, spatial position of dunes and other) were calculated using topographic maps at a scale 1:25 000 (Table 1). The parameters were statistically generalised and analysed for correlation: correlation between pairs and

Spearman's and Kendall's rank correlation coefficients for the entire aeolian stretch (966 dunes) and for separate aeolian areas. Gravimetric, magnetometric, tectonic, structural and other maps were used for determining the link between the incidence of aeolian forms and geological-tectonical deep structures (Baltrūnas *ir kt.*, 1998).

DUNE PARAMETERS	AEOLIAN AREAS AND NUMBER OF MEASURED DUNES										
	RŪD-NINKŲ (70)	BARČIŲ (107)	VARĖNOS (90)	PALKA-BALIO (165)	LYN-EŽERIO (55)	MARCIN-KONIŲ (55)	MUS-TEIKOS (36)	KATROS (44)	RANDA-MONIŲ (107)	DUBO (66)	LAT-EŽERIO (167)
ABSOLUTE ALTITUDE OF THE BOTTOM (m)	155-128 / 146	175-135 / 152	150-120 / 140	150-100 / 134	150-100 / 130	145-130 / 138	140-128 / 135	135-130 / 132	140-118 / 129	145-120 / 133	138-103 / 124
ABSOLUTE ALTITUDE OF THE TOP (m)	168-133 / 151	180-139 / 157	158-123 / 145	160-110 / 139	160-105 / 135	150-133 / 143	153-132 / 140	141-131 / 135	150-123 / 134	151-122 / 136	145-105 / 129
RELATIVE ALTITUDE (m)	18-1 / 4,6	15-1 / 4,8	13-1 / 4,3	20-2 / 5,3	20-1 / 5,6	12-2 / 5,0	13-1 / 4,9	6-1 / 2,5	10-2 / 4,6	8-1,5 / 3,6	18-1 / 4,6
LENGTH OF THE MAIN CREST (m)	1525-125 / 551	1125-200 / 407	1100-150 / 393	1750-150 / 382	3000-125 / 431	1250-200 / 516	1600-160 / 482	1000-100 / 329	1250-150 / 450	1875-125 / 458	1500-125 / 430

Table 1. Generalised characteristics of the big dunes in South Lithuanian aeolian areas (maximal, minimal and average values) (Pukelytė, 2001)

3. RESULTS

3.1. SUB-QUATERNARY ROCK SURFACE AND ITS PALAEOGEOMORPHOLOGICAL REGIONALIZATION

The absolute altitude of the South Lithuanian sub-Quaternary surface ranges from +100 to +80 m above sea level in its north-eastern part and from 0 to –20 below sea level in the western part (A. Šliaupa, 2004). The bottoms of palaeoincisions are plunged to a depth from –160 to –140 m in the western part. Their average depth is –70 ÷ –120 m below sea level (Fig. 2, 3 a, b). In South Lithuania this palaeosurface is composed of rocks of various geological systems. Chalk (chalk, chalk marl, marl) is the most widespread deposit in the studied territory. The south-western part of the territory is predominated by deposits of Palaeogene system (sand, aleurite, clay, marl, opoka) and the south-eastern part by sandy deposits of Neogene system (Lietuvos geologija, 1994; Lietuvos Žemės gelmių..., 2004). The north-eastern edge of the territory the sub-Quaternary surface is somewhere composed of Devonian, Permian and Triassic deposits which in other parts of the region occur in the slopes and bottoms of palaeoincisions.

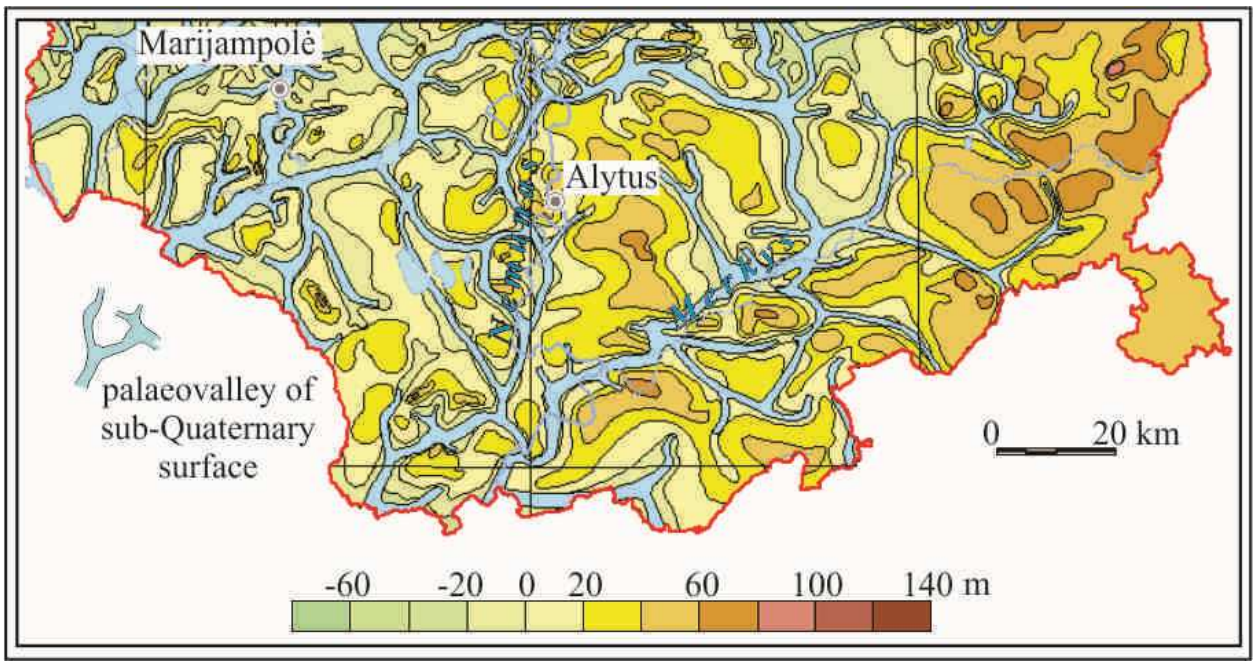

Fig. 2. Map of South Lithuanian sub-Quaternary surface and palaeovalley. *Compiled by A. Šliaupa* (A. Šliaupa, 2004 a)

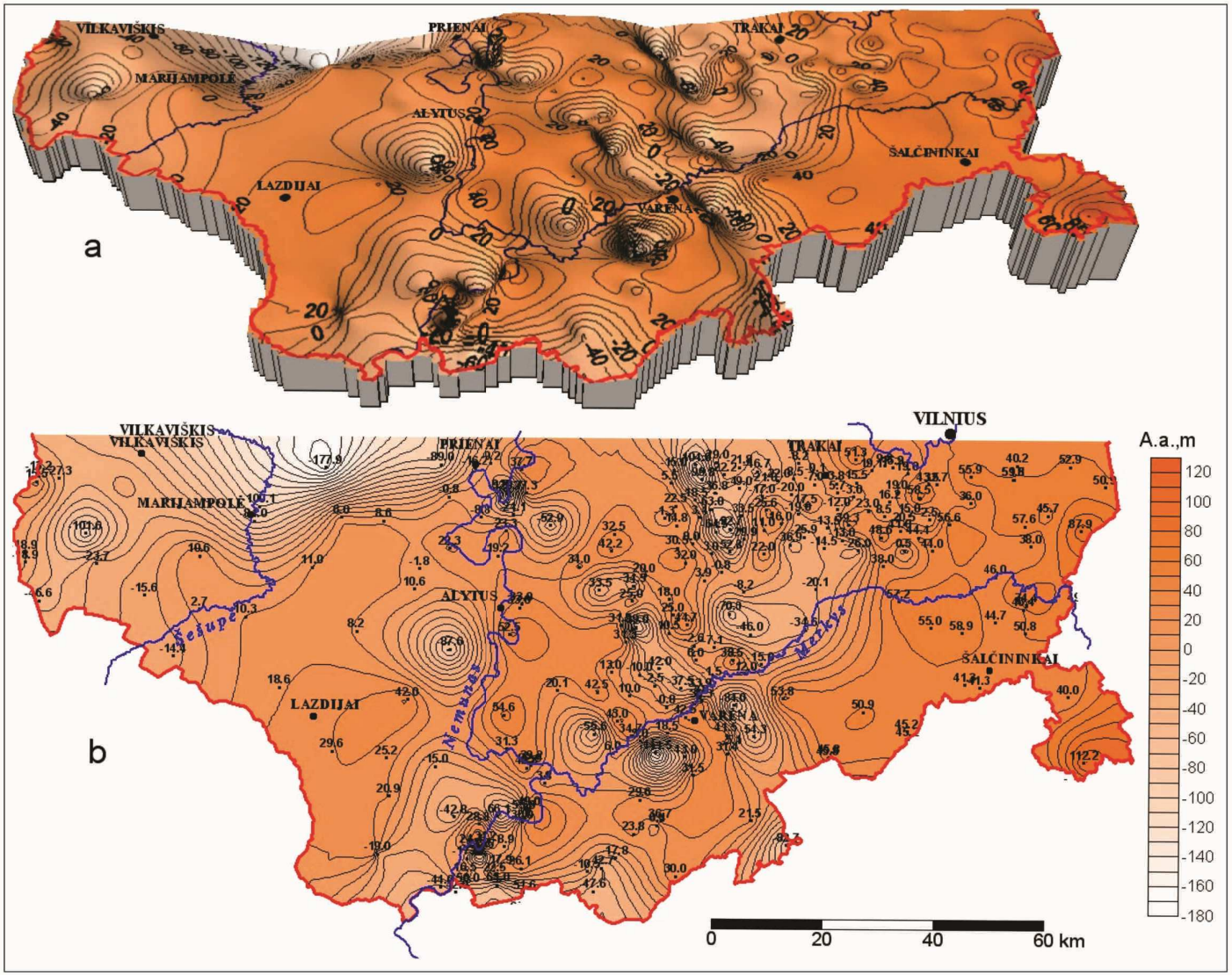

Fig. 3. Palaeorelief of sub-Quaternary surface in South Lithuania by data of 256 boreholes: a – model 3 D; b – planar model

Palaeoincisions are unevenly distributed in the South Lithuanian sub-Quaternary surface. In the eastern part, they are shallow and rare whereas in the western part they are deep and comprise a dense network. In the eastern and central parts, the stretch of palaeoincisions almost coincides with the chain of recent Merkys and Middle Nemunas valleys. In the western part, palaeoincisions are oriented NE–SW what has been predetermined by the evolution of hydrographic network in the first half of Quaternary.

The steps, slopes and palaeoincisions of sub-Quaternary surface are of different genesis and age (Bitinas, 1999 a, b). The formation of palaeoincisions and their steps largely has been predetermined by neotectonic structures. The distribution of palaeochannels once coincided with the network of sub-Quaternary palaeoincisions. Later, these palaeochannels were transformed by exaration processes and glacier melt water flows (Satkūnas, 2000). During the Quaternary, new elements of this network occurred and some sectors of palaeoincisions deepened. The average depth of sub-Quaternary surface incisions reaches 30–80 m (A. Šliaupa, 2004). The depths of their bottoms presumably have been related with World Ocean fluctuations (Baltrūnas, 1997 b). Three types of palaeoincisions are distinguished according to the glacial and aquaglacial filling deposits. Palaeoincisions where:

1. The filling is composed of aqueoglacial interstratified deposits each of which account for 25–75 %. Glacial deposits (tills) concentrate in the upper, middle and lower parts of palaeoincisions.

2. The filling is predominated by glacial deposits. They may be of similar of different age and indicate the time of filling the palaeoincisions.

3. The filling is predominated by fluvial (glaciofluvial, glaciolacustrine, alluvial and limnic) deposits. The greater part is represented by deposits from melt water flows (sand, gravely sand, gravel) or periglacial basins (clay, aleurite, very fine sand).

The conducted research work allowed compiling Lithuanian palaeogeomorphological scheme at a scale 1:500 000 in which, based on lithomorphological characteristics, palaeogeomorphological regions were distinguished. The scheme was made based on the following principles (Baltrūnas, Pukelytė, 1998):

1. Principle of actualism according to which the geological and geomorphological conditions of the present surface are the key for reconstruction of the past surface and its features.

2. Methodological principle according to which the origin, composition and properties of sub-Quaternary deposits may serve as a premise for determining geomorphological characteristics.

3. Dynamic principle which states that large negative forms of this palaeorelief usually comprise open erosion and erosion-exaration systems.

4. Principle of evolution which states that the present surface of sub-Quaternary deposits is a result of surface smoothening by denudation and accumulation processes in Palaeogene and Neogene and erosion, exaration and neotectonic processes in the Quaternary.

5. Palaeogeographical principle stating that the surface of sub-Quaternary deposits and its macro forms were generated and developed by local geological structure and tectonic conditions, during the neotectonic time in particular.

Nine palaeogeomorphological regions were distinguished in the territory of Lithuania four of which are more or less within the studied South Lithuanian territory (Fig. 1). Their description is given below (Fig. 4).

The Great Lithuanian Lowland (II a and II b) – sandy and clayey, carbonaceous, with deep valleys, eriosional-exarational lowland with prevailing Middle Pleistocene Žemaitija undulating terraced watersheds, which in the western part are disintegrated by valleys of cuesta type.

The East Aukštaičiai Plateau (VII b) – sandy and clayey (only sandy in the south-eastern part), carbonaceous denudation plateau with shallow valleys predominated by Middle Pleistocene Dainava undulating and slightly hilly watershed.

The Šventoji Slope (VIII) – sandy, clayey, somewhere carbonaceous, erosional-exarational slope declining in SW direction, with deep valleys and prevailing Middle Pleistocene Dainava undulating and slightly hilly, terraced watershed disintegrated by palaeovalleys of cuesta type.

The South Lithuanian Plain (IX) – sandy, clayey and carbonaceous, erosional-exarational plain with deep valleys and prevailing Middle Pleistocene Žemaitija (in the western part) and Dainava (in the eastern part) undulating and slightly hilly, terraced watershed in the eastern part disintegrated by palaeoincisions of cuesta type.

Analysis of the filling material of palaeoincisions in the Lithuanian sub-Quaternary surface allowed making generalised circular diagrams of dominant sections for most of

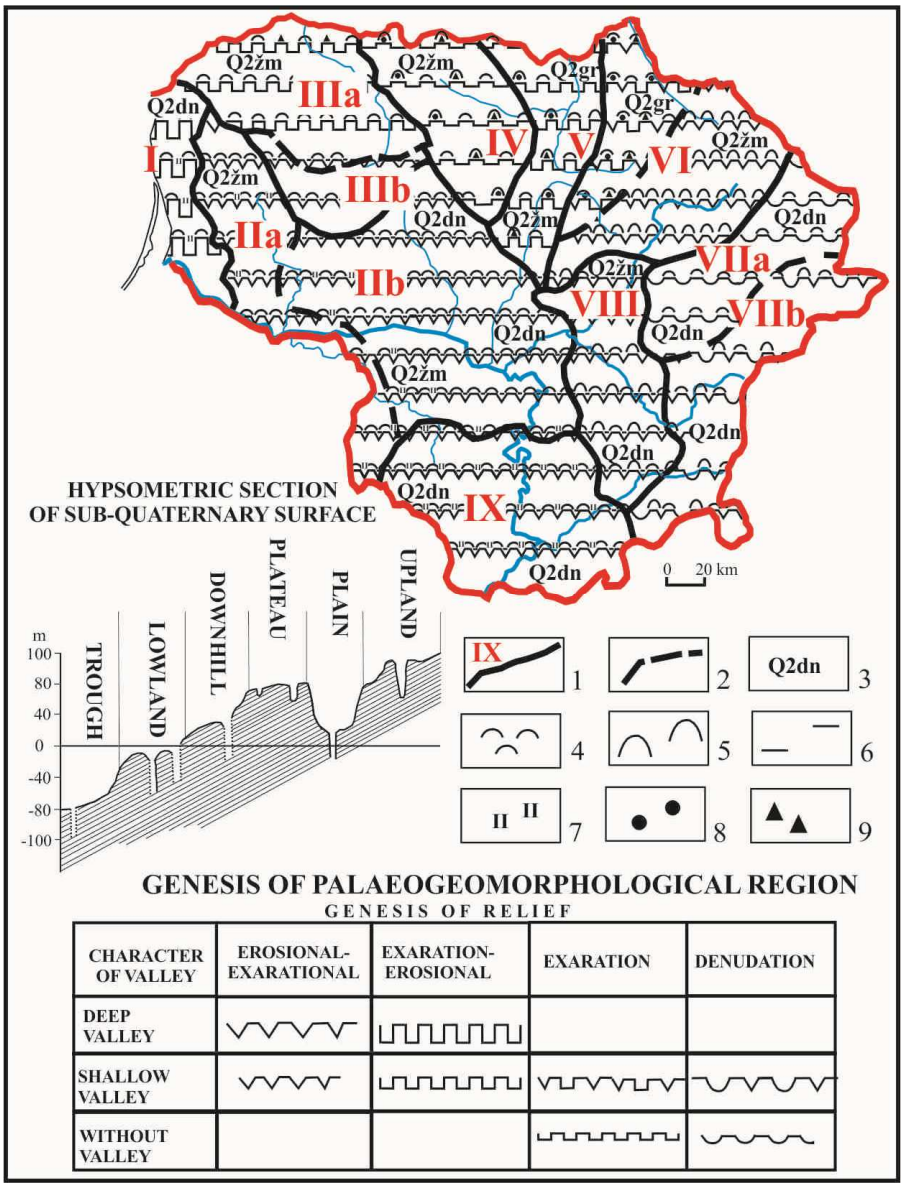

Fig. 4. Palaeogeomorphological regionalization scheme of Lithuanian sub-Quaternary surface (Baltrūnas, Pukelytė, 1998)

Palaeogeomorphological regions of Lithuania (indices show the age of palaeo-watersheds): I – Coastal Depression; II – the Great Lithuanian Lowland; III – the Middle Žemaičiai Slope; IV – the North Žemaičiai Plateau; V – the Middle Lithuanian Plain; VI – the North Aukštaičiai Upland; VII – the East Aukštaičiai Plateau; VIII – the Šventoji Slope; IX – the South Lithuanian Plain

palaeogeomorphological regions (Fig. 5). Some regions stand out for – uniform specific glacial, aqueoglacial and of other origin filling material of palaeoincisions. The filling materials of palaeoincisions in the northern (II a) and southern (II b) parts of the Great Lithuanian Lowland are different. The information of this kind generalises the genetic, lithological and stratigraphic diversity of filling material of palaeoincisions and shows different palaeogeographical evolution of palaeogeomorphological regions and some

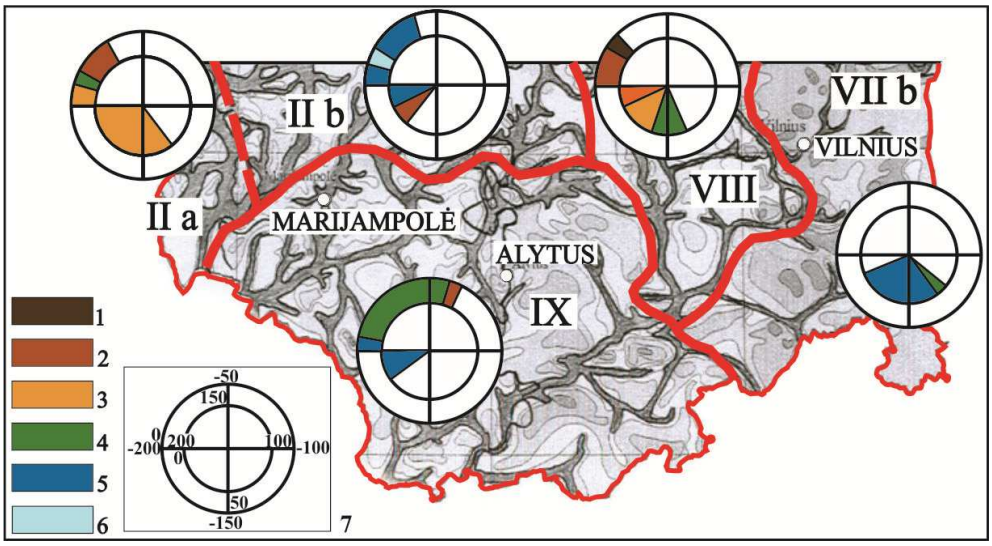

Fig. 5. Generalised circular diagrams of dominant filling material in palaeoincisions of palaeogeomorphological regions

II a and II b – the Great Lithuanian Lowland; VII b – the East Aukštaičiai Plateau; VIII – the Šventoji Slope; IX – the South Lithuanian Plain. 1 – Dzūkija till; 2 – Dainava till; 3 – Žeimena tills; 4 – glaciofluvial deposits; 5 – glaciolacustrine deposits; 6 – alluvial-limnic deposits; 7 – outline of circular diagram

palaeoincisions within them (Fig. 5). Comparison of the given scheme of palaeo-geographical regions with A. Šliaupa's scheme of the terraces in the sub-Quaternary rock surface shows some discrepancy between the boundaries (A. Šliaupa, 1997 a, b). This can be explained by use of data of different character. Some discrepancies are different character. Some discrepancies are natural and can be explained by use of morphological (lithomorphogenetic) criterion for characteristics of palaeorelief sculpture. In the future, the material about the terraces of palaeorelief and data of consistent analysis of palaeoincisions will serve as a basis for more detailed regionalisation of sub-Quaternary surface of Lithuania and neighbouring territories.

The conducted palaeogeomorphological regionalisation of sub-Quaternary surface leads to the following **conclusions**:

1. The distinguished palaeogeomorphological regions are of different absolute altitudes, have terraced structure and differ in the texture, structure and age of deposits.

2. The origin, composition and age of watershed deposits covering the palaeogeomorphological regions and the data obtained about the scale of some Quaternary egzogenic (exaration, erosion, *etc*.) processes showed that Middle Pleistocene

morphosculptural watersheds are dominant.

3. The absolute altitude of palaeoincisions of sub-Quaternary surface and the filling material showed that the hydrographic network was strongly modified by neotectonic, exaration and erosion processes whereas later, in the times of Quaternary glaciations and deglaciations, it was partly regenerated.

4. The congruence of some boundaries of palaeogeomorphological regions with geological and tectonic structures shows the influence of endogenic factors on the development of this surface.

3.2. SPECIFIC FEATURES OF QUATERNARY STRATA

The Quaternary strata of South Lithuania is rather variable. In some river valleys Quaternary deposits are absent altogether or form layers hardly 10–15 m in thickness (at Alytus, down-stream from Birštonas). The thickest Quaternary rock mass is concentrated in the palaeoincisions of sub-Quaternary surface or in the present uplands, in the congruent areas in particular (b. 305 (Prielaukis); b. 475 (Vaikantonys); b. 568 (Komorūnai)). The parameters of Quaternary strata (thickness, stratification) not always imply direct links with the deep structures.

In the small-scale maps of Quaternary surface, compiled by interpolation method, the properties of Quaternary surface are generalised. According to these maps, South Lithuania is predominated by Quaternary rock mass 30–200 m or, most commonly, 100–160 m in thickness (Aleksa, 2007). Only in the environs of Vištytis Lake and Varėna Town, in the Dzūkai and Medininkai Uplands and in some other local areas, the thickness of Quaternary strata exceeds 200 m. The Lithuanian Geological Survey has evaluated the volume of Quaternary deposits and compiled the distribution maps of percentages of glacial and glaciofluvial deposits (Putys *ir kt.*, 2010). In these maps, the boundary between the morainic hills of Dzūkai Upland and glaciolacustrine Middle Nemunas Plateau is especially vividly displayed. Meanwhile, the South-East Lithuanian region of glaciofluvial plains, Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau are ill-defined.

For evaluation of the influence of Pleistocene strata on South Lithuanian geomorphological regions, two well identified marker palaeosurfaces were analysed (Satkūnas *ir*

kt., 2007). One of them is the surface of the top (roof) of Middle Pleistocene Dainava formation (till) which served as a geological foundation for the longest Butėnai (*Holsteinian*) interglacial landscape. The other is the surface of the top of Middle Pleistocene Medininkai sub-formation (till) of Žeimena formation which served as a geological foundation for the Merkinė (*Eemian*) interglacial landscape. At present, the Medininkai till represents the surfaces of Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau.

The complex of **Dainava formation** is composed of tills of Dainava glaciation. Their texture and composition imply advances of at least two glacial stages (Baltrūnas, 1995; Satkūnas *ir kt.*, 2007). The macroscopically homogeneous Dainava tills are characterised by a rhythmic multilayer structure which is vividly exhibited by borehole logging data and granulometric analysis. The rhythmic alternation of layers is partly proved by the changes of relative entropy of grain size composition of vertical section. The relative entropy indicating the degree of sorting of material served as a basis for distinguishing four rather homogeneous zones in the vertical till section. An abrupt increase of the relative entropy value shows the beginning of the new sedimentation cycle (glaciation). Even distant zones are in good correlation with each other (Baltrūnas *et al.*, 2008).

Generalised data of 256 geological mapping boreholes through the Quaternary strata and hypsometric models made using *Surfer* program show that the absolute altitude of the watersheds of the top palaeosurface of Dainava formation (till) consistently decrease from east to west: in the Medininkai Upland from +123 ÷ +100 m above sea level and in the Prienai-Marijampolė-Kybartai sector (in the north-western edge of the region) from –20 ÷ –40 m to –136 m below sea level. The greatest relative decrease of the altitude amounts to 260 m or, apart of many anomalous palaeoincisions (palaeo-depressions), to about 100–160 m (Fig. 6 a, b). The variations of the altitudes of palaeosurfaces determined in the Druskininkai, Birštonas, Varėna-Daugai and Elektrėnai-Vilnius areas allow assuming that similar si-tuation is characteristic of the whole South Lithuania. Interpolation of palaeosurfaces yielded large, closed negative forms of relief which in the glacigenic accumulative-erosional surface should be different, i. e. they should comprise complex valley systems.

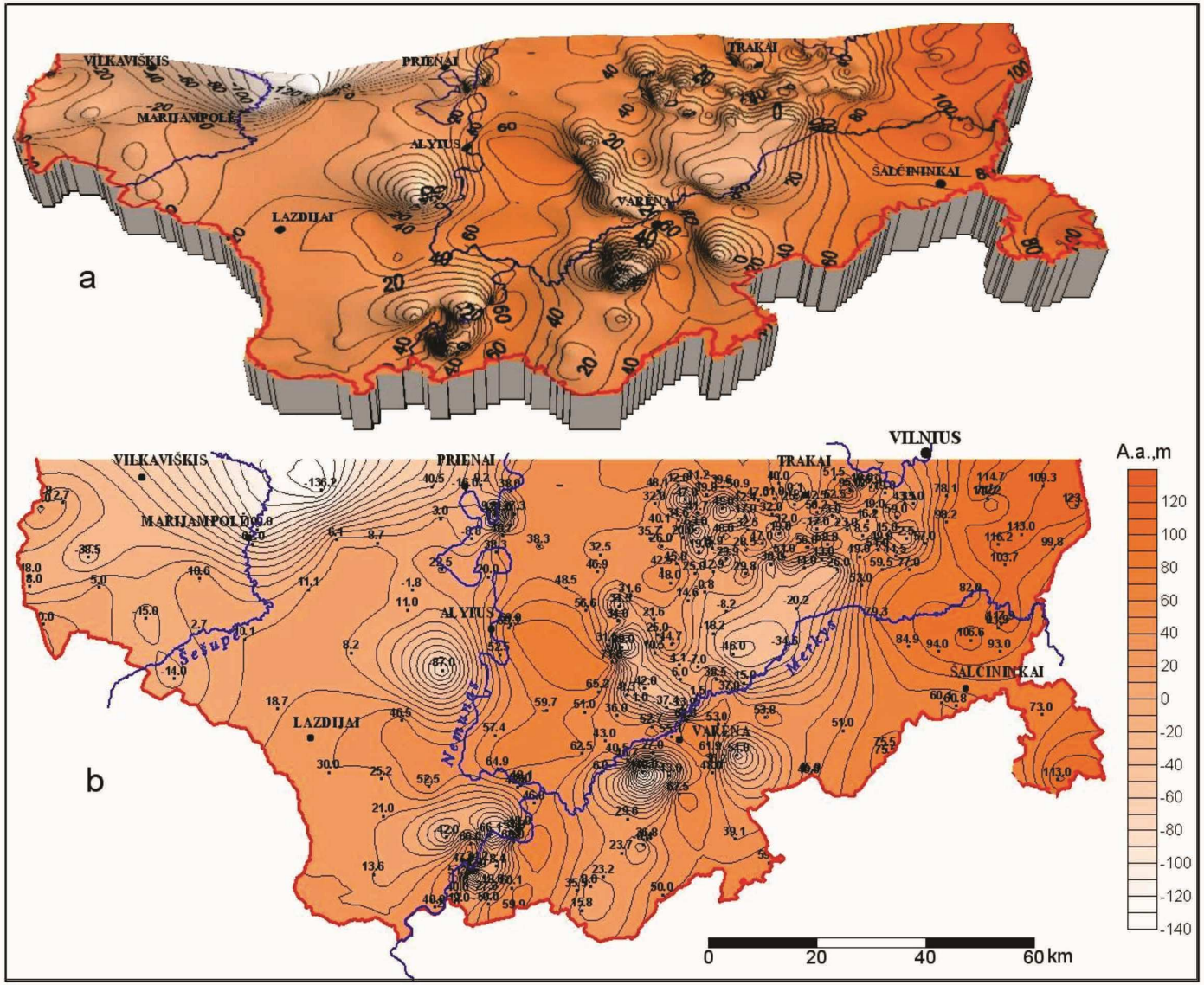

Fig. 6. Palaeorelief of the top of Dainava till in South Lithuania:
a – model 3 D, b – planar model

The complex of **Žeimena formation** is composed of Žemaitija and Medininkai sub-formations tills. Their structure and composition also imply advances of two glaciers. The tills of these sub-formations are homogeneous and macroscopically almost identical. The Medininkai till contains more dolomite and is less rich in Mesozoic clastic material (Baltrūnas, 1995; Гайгалас, 1979).

The top of the Medininkai till is well-identified when covered by the interglacial weathering crust, described in the outcrops of Middle Nemunas and its tributaries, and in some boreholes. Problems of identification occur when sandy loam of the last glaciation (Nemunas) directly overlies the brown dolomite-bearing Medininkai loam. This may be interpreted as manifestation of the multilayered structure of Medininkai till complex. In this case, identification of palaeosurface is facilitated by analytical investigations and comparison of grain size composition entropy variations.

The top of Medininkai till (sub-formation) is of two types: buried under the deposits of the last glaciation and exposed in the surface of Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau.

The borehole data show that the absolute altitude of the top palaeosurface of Žeimena formation (Medininkai till) decreases from east to west. In the Medininkai (Ašmena) Upland, it varies from +290 ÷ +260 m above sea level in hill tops to +220 ÷ +180 m in troughs and in the western edge decreases to +10 ÷ –10 m below sea level (Fig. 7 a, b). In palaeoincisions (palaeodepressions), the top of this till goes down to –66 ÷ –53 m below sea level. The maximal relative lowering amounts to 300–350 m whereas the dominant lowering reaches 160–180 m.

Elimination of the values for Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau shows that in the remaining part of South Lithuania the variations of the absolute and relative altitudes are considerably less conspicuous: from +120 m to 0 m (dominant 0 ÷ +30 m) in the western part and +50 ÷ +100 m in the eastern part. The local elevation of the top of Medininkai till at Vištytis-Gražiškiai Upland (up to +80 m) stands out as also the elevation at the northern part of Dzūkai Upland (up to +80 ÷ +100 m) which in the south-eastern direction is gradually elevating up to +130 ÷ +160 m before the Eišiškės (Lyda) Plateau (Fig. 7 a, b).

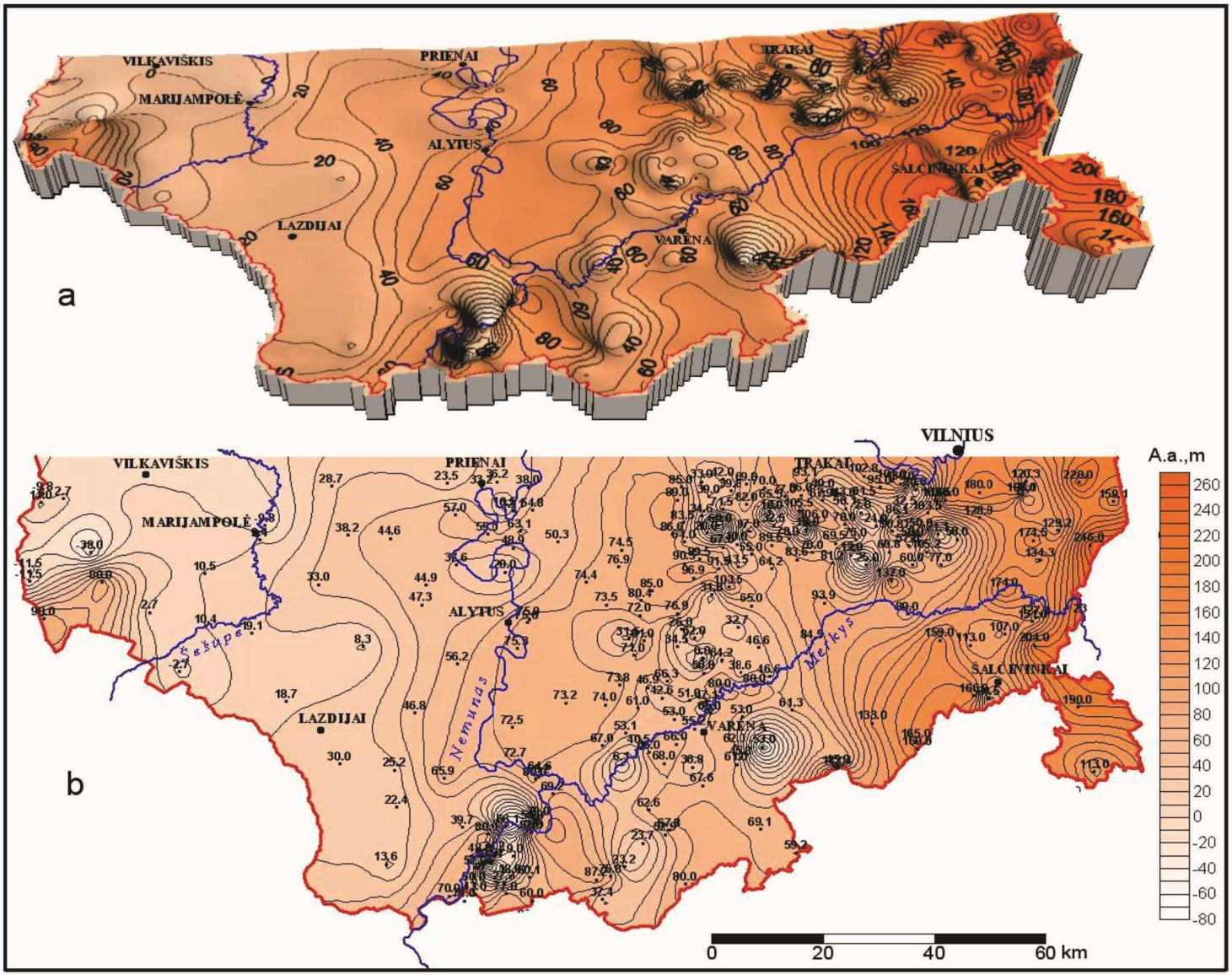

Fig. 7. Palaeorelief of the top of Žeimena formation (Medininkai till) in South Lithuania: a – model 3 D, b – planar model

Investigation of the Pleistocene palaeosurfaces leads to the following **conclusions**:

1. Two palaeosurfaces are most reliably identified in the South Lithuanian Pleistocene surface: top of Dainava formation (till) and top of Žeimena formation (Medininkai till) which served as the geological foundation for interglacial Butėnai (*Holsteinian*) and Merkinė (*Eemian*) landscapes.

2. The top of Dainava formation (till) is characterised by a marked downward inclination in the western direction and frequent and marked variations of relative altitudes what implies that the sub-Quaternary surface had a strongly broken pattern.

3. The top of the thick Žeimena formation is subsiding in the western direction. Yet the variations of the relative altitudes are less conspicuous, in the territory of the last glaciation in particular. This once strongly broken palaeosurface has been smoothed considerably. The rock mass of this formation has smoothed the underlying palaeosurface.

3.3. SPECIFIC FEATURES OF SOUTH LITHUANIAN SURFACE

In its origin and composition, the South Lithuanian surface is rather variable because it is related with geomorphological and geological processes taking place during glacials, interglacials and post-glacial (Švedas *ir kt.*, 2004; Baltrūnas *ir kt*., 2007). The different composition, texture and distribution of deposits covering the territory are responsible for different groundwater levels, water yield of small streams, types of forest fauna and flora, and occurrence of some valuable minerals (flintstone, chalk, clay, boulders) in its various parts. The oldest deposits were affected by subsequent post-sedimentation processes: cryogenesis, solifluction, thermokarst, erosion, deflation, bogging, *etc.* The result of all these processes is recorded in the compiled Quaternary geological and geomorphological maps (Guobytė *ir kt*., 1998, 2008 and others). They vividly demonstrate vast areas of South Lithuania occupied by deposits generated by one of these processes. They are Rūdninkai, Varėna, Marcinkonys and Ratnyčia-Randamonys massifs of aeolian deposits stretching in the South-Eastern (Dainava) sandy Plain wedging between the morainic hill terrains of different age (Basalykas, 1965) (Fig. 8.)

The morphological and morphographic correlation analysis of this stretch of continental dunes (the chosen 966 dunes) showed some distinct correlation links (*CL*). The positive strong *CL* between the relative coordinates of dunes shows consistent dune

formation and advance from south-west to north-east. The absolute altitudes of the tops and bottoms of the dunes also are in strong correlation with their coordinates. This proves the known regional pattern – elevation of the absolute altitude of aeolian deposits in NE direction. The *CL* also is positive between the relative altitudes of dunes and the length and branchedness of the crests. A negative correlation link was determined between the azimuth of vertical dune crest direction and the absolute altitudes and coordinates of dunes. This implies the variation of some azimuth values (reflecting the dominant direction of generating winds): from frequent south-eastern to frequent north-eastern in different sectors of the dune stretch (Baltrūnas *et al.*, 1998; Baltrūnas, Pukelytė, 2001).

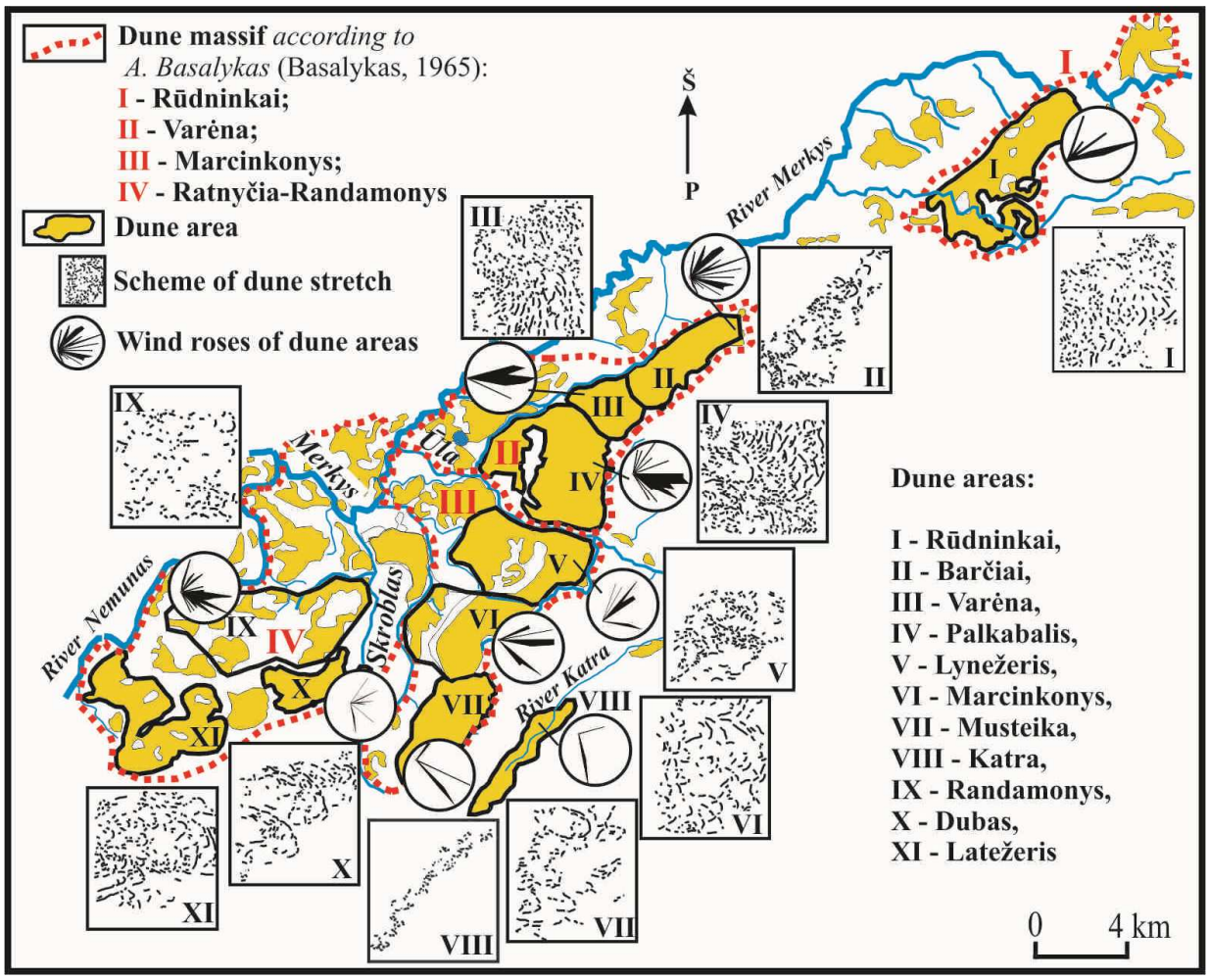

Fig. 8. Aeolian stretch of South Lithuania, its massifs and reference areas

The positive *CL* between the relative altitudes of dunes and crest length shows intensive aeolian processes. The long-lasting aeolian processes were identified based on positive correlation links between branching of dunes and their coordinates. The *CL* of

lee-ward azimuth of dune crest with branching of dunes, more seldom with the altitudes of dune top (Palkabalis area) and bottom (Randamonys area), is weak but positive (Rūdninkai, Palkabalis, Marcinkonys, Musteika areas).

Based on the differences of *CL* matrixes, a few groups of aeolian areas in some way related with time can be distinguished. The relatively short-lasting aeolian processes generated Rūdninkai, Barčiai, Palkabalis, Lynežeris and Randamonys areas. The longer-lasting aeolian processes generated Varėna, Marcinkonys, Katra and Dubas areas. The longest-lasting aeolian processes generated Musteika and Latežeris areas. The Rūdninkai, Barčiai, Varėna, Dubas, and Katra areas were fist to generate. They were followed by Palkabalis, Lynežeris, and Randamonys areas and the latter by Marcinkonys, Musteika and Latežeris aeolian areas. This complicated and uneven in terms of time development of aeolian stretch took place almost throughout the post-glacial period intensifying during the drier time spans in the Older, Middle and Younger Dryas, preBoreal and Boreal (Baltrūnas *et al.*, 1998; Baltrūnas, Pukelytė, 2001).

In the studied South Lithuanian territory and in the described stretch of continental dunes, areas with specific geological and geomorphological features and genetically and morphologically comparable lithological and geomorphological complexes (lithomorpho-genetic micro-regions) were distinguished. The investigation of lithomorphogenetic structure of South Lithuanian geomorphological regions was aimed at revealing the heterogeneity of geomorphological regions and structural grounding of their identification.

The investigation carried out within the present dissertation was based on detailed analysis of cartographic material, borehole data and palaeogeography of the territory. In the individual lithomorphogenetic map of South Lithuania, 69 lithomorphogentic micro-regions were distinguished which structurally ground the boundaries of six geomorpho-logical regions. Comparison of this map with earlier maps compiled in Lithuania showed that most of the authors distinguished in South Lithuania similar geomorphological regions (Basalykas, 1965; Lietuvos…, 1981; Guobytė, Kavaliauskas, 2007 and other). At the level of micro-regions, the differences are more conspicuous due to ill-definition and ambiguity of taxonomic units and due to application of different criteria.

Geomorphological region of Medininkai (Ašmena) Upland. The relief of this region was generated at the junction area of penultimate Ašmena and South Lithuanian

glacier lobes. In the interglacial and Early and Middle Nemunas, the relief was reworked by intensive erosion and periglacial processes (Kudaba, 1964; Švedas *ir kt.,* 2004). Under the periglacial conditions, the upland was affected by solifluction, periglacial erosion, physical weathering and other processes which conspicuously transformed its surface. Eight micro-regions were distinguished in this region (Fig. 9).

The upland abounds in large hills with gentle slopes, ridges, many ravines and boggy valleys (Šumskas, Piktakonys-Akmenynė, Medininkai, Grigaičiai micro-regions). The Paneriai erosional hill terrain situated in the northern part of the region is somewhat different. It is predominated by steep-sloped hills and very dense network of ravines, gullies and small valleys between them. The Nemėžis Plateau bordering on its southern edge also is marked by specific features. It is predominated by high waves and shallow boggy valleys. Similar relief is characteristic of the central part of the region near Turgeliai and of the Paškonys-Girdžiūnai micro-region in the south-eastern part of the region. The Medininkai Upland has no big river valleys. Merkys is its largest river.

The Rukainiai and Kalveliai environs situated at the NE edge of the studied area for a long time has been regarded as parts of Medininkai Upland. More thorough investigations revealed that they belong to the geomorphological complex of the last glaciation extending beyond the limits of the studied area.

Geomorphological region of Eišiškės (Lyda) Plateau. It is situated at the south-eastern edge of the territory. It was generated by glaciers of the last glaciation and transformed by processes taking place later. The surface of the region is smoothed. The present surface of Eišiškės (Lyda) Plateau is rather homogeneous. Only three lithomorphogenetic micro-regions were distinguished in this region. They are characterised by large bouldered waves and wide valleys with gentle slopes. The surface is dissected by many ravines opening into the valleys (Šalčininkai-Jašiūnai micro-region). The relief in the central and south-western parts of the region is younger, formed by glaciofluvial flows during the last glaciation. It is predominated by small hills with gentle slopes, small waves separated by ravines, small valleys and closed depression (northern parts of Eišiškės and Kalesninkai micro-regions). The valleys of rivers – Ditva, Verseka, Rodūnė and Nočia – are boggy, the flood plains are turfy. Flowing along the edges of the plateau, marked by younger relief, the rivers cut deeply into the ground forming sectors of terraced valleys (Fig. 9).

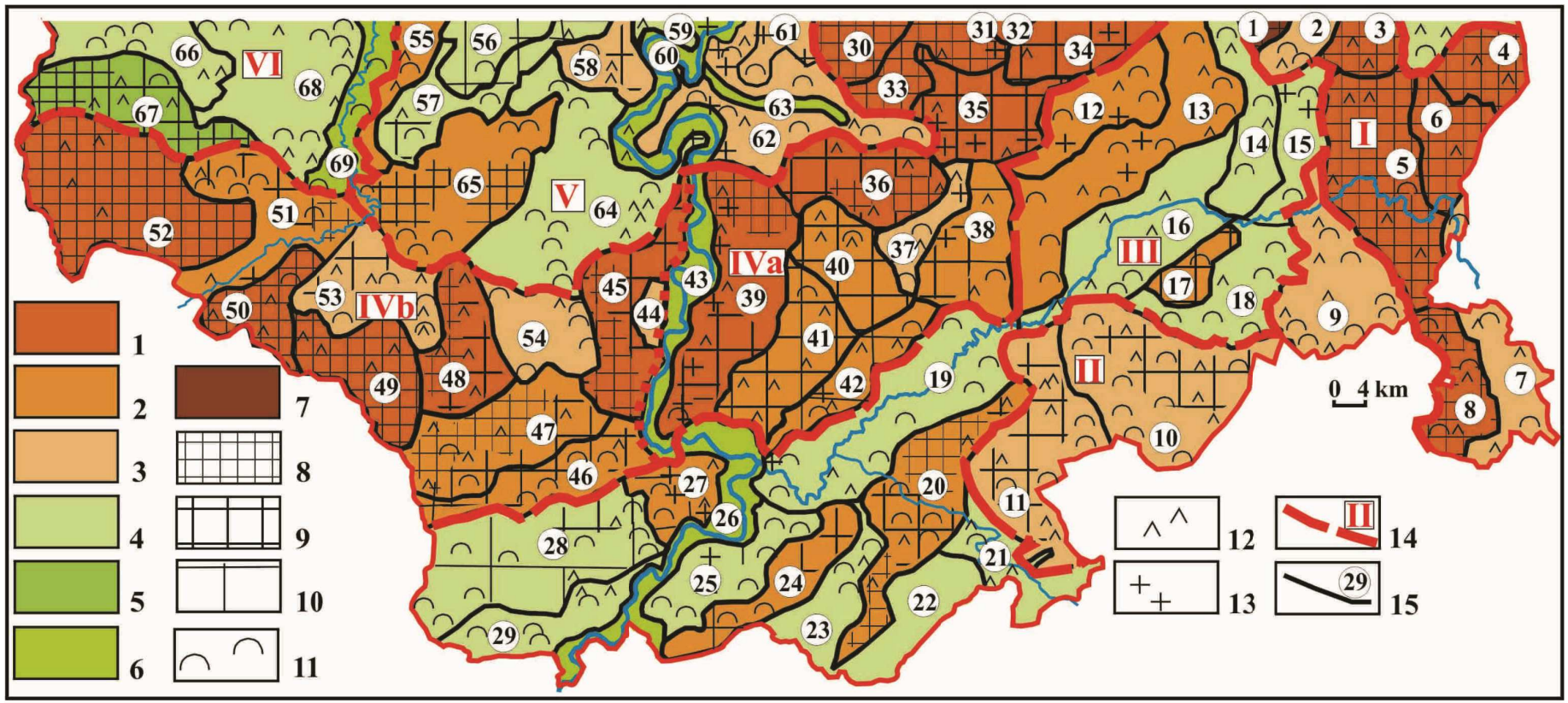

Fig. 9. Map of lithomorphogenetic micro-regions of South Lithuania (Pukelytė, 2001). Conventional signs - see next page

Conventional signs of the map of lithomorphogenetic micro-regions of South Lithuania (Fig. 9):

I – **Medininkai (Ašmena) Upland**: **1** – Paneriai; **2** – Nemėžis; **3** – Grigaičiai; **4** – Šumskas; **5** – Piktakonys-Akmenynė; **6** – Medininkai; **7** – Paškonys-Girdžiūnai; **8** – Dieveniškės; **II** – **Eišiškės (Lyda) Plateau: 9** – Šalčininkai-Jašiūnai; 10 – Eišiškės; 11 – Kalesninkai; **III – Pietryčiai (South-Eastern) or Dainava Plain**: **12** – Rūdiškės-Senieji Trakai; **13** – Paluknis-Lieponiai; **14** – Pagiriai-Liudvinavas; **15** – Juodšiliai; **16** – Valkininkai; **17** – Zigmontiškės; **18** – Visinčia; **19** – Varėna-Perloja; **20** – Zervynos; **21** – Dubičiai-Rudnia; **22** – Musteika-Čepkeliai; **23** – Marcinkonys-Kabeliai; **24** – Randamonys-Jaskonys; **25** – Ratnyčia; **26** – Druskininkai-Merkinė (Nemunas valley); **27** – Vilkiautinis-Liškiava; **28** – Leipalingis-Kapčiamiestis; **29** – Didžiasalis; **IV – Pietų Lietuvos (South Lithuania) Upland: IV a – Dzūkai Upland (sub-region)**: **30** – Kruonis-Užuguostis; **31** – Semeliškės-Dainiai; **32** – Juodeliai-Leičiai; **33** – Aukštadvaris-Beižoniai; **34** – Trakai-Bagdanonys; **35** – Vilkokšnis-Tolkiškiai; **36** – Alaburdiškiai-Pivašiūnai; **37** – Onuškis-Dusmenys; **38** – Žilinai; **39** – Domantonys-Gečialaukis; **40** – Daugai; **41** – Savilonys-Ilgininkai; **42 –** Tolkūnai; **43** – Punia-Nemunaitis (Nemunas valley); **IV b – Sūduvos Upland (sub-region): 44** – Radžiūnai; **45** – Miroslavas-Javaišonys; **46** – Barčiai; **47** – Šlavantas-Seirijai; **48** – Verstaminai; **49** – Sangrūda-Rudamina; **50** – Trakėnai-Salaparaugis; 51 – Liubavas-Kalvarija; 52 – Vištytis-Gražiškiai; **53** – Pagramdai-Šeštokai; **54** – Meteliai; **V – Nemuno vidurupio (the Middle Nemunas) Plateau**: **55** – Sasnava; **56** – Stuomenys; **57** – Padoviniai-Ingavangis; **58** – Prienai; **59** – Malinava; **60** – Birštonas-Darsūniškis (Nemunas valley); **61** – Vilūnai-Jieznas; **62** – Vėžionys-Stakliškės; **63** – Verknės valley; **64** – Balbieriškis-Simnas; **65** – Daukšiai; **VI – Nemuno žemupio (the Lower Nemunas) Plain**: **66** – Kybartai; **67** – Virbalis-Keturvalakis; **68** – Vilkaviškis; **69** – Šešupė valley. 1 – upland; 2 – lift and crest; 3 – plateau; 4 – downhill; 5 – plain; 6 – valley; 7 – hilly erosional relief; relief: 8 – hilly; 9 – middle hilly; 10 – low hilly; 11 – undulating; 12 – erosion; 13 – abrasion; 14 – boundary and number of geomorphological region; 15 – boundary and number of lithomorphogenetical micro-region.

Geomorphological region of South-Eastern (Dainava) Plain. It surrounds the described sector of old relief in the west. The region includes the plains of Vokė, Merkys and Katra valleys formed by the glaciers and glacier melt water of the last glaciation. Eighteen lithomorphogenetic micro-regions were distinguished in the South-East Plain. They are composed of different age glacigenic and accumulative deposits (Fig. 9).

In the western part of the region, a wavy ridged sandur with many soggy valleys, ravines and depressions has developed in the area of hilly relief. Bouldery hills with slacks at their sides are scattered in the sandur (Paluknys-Lieponiai and Rūdiškės-Senieji Trakai micro-regions). Southward, the sandur gets lower and narrower. It is predominated by hillocks and small bouldery hills separated by ravines and small valleys. On the other bank of Nemunas River, the sandur is more complex, dissected by a multitude of furrows

with Veisiejas, Aviris, Ilgis, Ančia, Vilkinis and other lakes (Leipalingis-Kapčiamiestis micro-region). In some places, the sandur abruptly or gradually merges into the old valley with smooth surface, somewhere hillocky or wavy. In the northern part of the region, it is strongly bogged (Pagiriai-Liudvinavas and Valkininkai micro-regions) whereas south of Varėnė River it has a more complicated structure. This area includes a sector of continuous stretch of continental dunes dissected into massifs by river valleys. The region is characterised by a wavy, hillocky surface abounding in valleys, ravines, slacks, and glaciokarst depressions. At present, these depressions are occupied by Glūkas, Glėbas and Lavysas lakes (Varėna-Perloja, Dubičiai-Rudnia, Zervynos and Ratnyčia micro-regions). The oldest glaciolacustrine plain has a smooth surface somewhere interspersed with solitary waves, ravines, small valleys, and slacks (Visinčia micro-region).

Geomorphological region of South Lithuanian Upland. It is situated in the central (Dzūkai Upland) and south-western (Sūduva Upland) parts of the studied territory (Fig. 9). The Dzūkai and Sūduva (sub-regions) uplands are divided by the Nemunas River. This sector has been generated by glaciers of two stages of the last glaciation – Žiogeliai phase of Grūda stage and Baltija stage.

At present, the South Lithuanian region is predominated by hilly relief. Yet both Dzūkai and Sūduva uplands have lower and higher sectors. The Trakai and Aukštadvaris uplands represent the higher part of **Dzūkai Upland (sub-region**). Its surface is characterised by morainic forms separated by deep glaciokarst laky depressions, furrows and bogged slacks (Aukštadvaris-Beižionys and Trakai-Bagdanionys micro-regions). The lower south-western part of Dzūkai Upland is characterised by large flat hills, somewhere small flat hills, ridges, wide troughs between ridges and furrow slaks, and valleys, which often are bogged and laky (Daugai-Domantonys-Gečialaukis and Savilionys-Ilgininkai micro-regions). It also has big glacier depressions with dominant flat slightly undulating surface interspersed with valleys and lakes, in many places bogged (Onuškis-Dusmenos micro-region).

The northern part and the southern edges of **Sūduva Upland** are predominated by flat slightly undulating surface interspersed by hills, ridges and valleys (Liubavas-Kalvarijos, Šlavantas-Seirijas and Barčiūnai micro-regions). The depressions often are occupied by lakes or bogged. The Vištytis-Gražiškiai Upland represents the upper part of Sudūva Upland. It has a hilly relief predominated by bouldery ridges and kame flat waves

intersected by often bogged depressions and ravines (Vištytis-Gražiškiai, Trakėnai-Salaparaugis and Sangrūda-Rudamina micro-regions). The wide and deep trough between ridges is occupied by a big Vištytis Lake. The network of rivers is sparse (Šešupė, Varėnė, Verknė, and Kirsna) whereas lakes are present in abundance: Galvė, Šlavantas, Didžiulis, Daugai, Nedingė, Ilgis, Seirijas, Galstas, Vyštytis and other.

The Sūduva Upland sub-region includes Meteliai and Pagramdai-Šeštokai lithomorphogenetic micro-regions which earlier were attributed to the region of Middle Nemunas Plateau.

Geomorphological region of Middle Nemunas Plateau. It is wedged between the Baltija Uplands and Middle Lithuanian Plain. The surface of this region was formed by the Middle Nemunas and Baltija glacier tongues of the last glaciation which pushed together the South Lithuanian Upland (Basalykas, 1965). Eleven lithomorphogenetic micro-regions were distinguished in this region (Fig. 9). In the present surface of the region, five relief sectors can be traced which alternate moving from NW to SE. The first sector of marginal moraines – Veiveriai ridge – extends along the edge of the region. Its south-western part separates the Marijampolė and Žuvintas depressions. The dominant landforms are waves, small hills, valleys, and flat gullies covered by glaciolacustrine deposits (Sasnava micro-region). The second sector is represented by continuous flat somewhere wavy plains formed in the lower depression left by glacier lobe. The plains are intersected by a dense network of bogged river channels (Stuomenai micro-region). The hilly sector of marginal moraines covered by glaciolacustrine deposits in the central part of the region has a more complex relief. It is predominated by big hills, somewhere interspersed by flat bouldery waves, ridges, laky and boggy gullies and slacks (Padoviniai-Ingavangis and Daukšiai micro-regions), This relief sector is only partly smoothed whereas the higher sector of depression is predominated by an almost smooth surface covered by glaciolacustrine deposits and interspersed by solitary waves, gullies, glaciolacustrine slacks, furrows and troughs occupied by lakes and bogs. Nemunas, Peršekė and Verknė rivers flow across this relief (Prienai and Balbieriškis-Simnas micro-regions). The surface of the right bank of Nemunas is wavy and somewhere even with flat hills rather than smooth (Vėžionys-Stakliškės and Viliūnai-Jieznas micro-regions). The fifth sector of relief is represented by glacier plains with lobe depressions divided by recessive marginal formations. It is predominated by flat plain with solitary waves and hills with

gentle slopes. The surface is intersected by bogged river valleys, gullies and ravines (Verknė micro-region). The Middle Nemunas Plateau abounds in very unevenly distributed river valleys and bogs. The southern part of the region – Užnemunė – abounds lakes.

Geomorphological region of Lower Nemunas Plain. It represents the southern part of Middle Lithuanian Lowland. Only its small southern sector is included in the studied territory occupying its north-western part. Four lithomorphogenetic micro-regions were distinguished (Fig. 9).

The relief of this region was formed by the Lower Nemunas glacier lobe of the Baltic stage of the last glaciation which was split into two tongues covering the entire region. The glacial depressions have low smooth surface. Only in the southern edge (northern slopes of Sudūva Upland), the forms of relief are higher, predominated by waves, somewhere hills and slacks (Virbalis-Keturvalkiai micro-region). In this region, the glacial relief has been most strongly transformed by a huge periglacial lake generated by dammed glacier melt water. It deposited thick layers of glaciolacustrine sediments. Thus the greater part of the region is comprised of smoothed glaciolacustrine plains interspersed by solitary waves and very shallow small flood plain valleys (Kybartai micro-region). Only in the Gižai-Mrijampolė sector, the surface is slightly elevated, with bigger solitary waves or even hills and slacks (southern part of Vilkaviškis micro-region and Virbalis-Keturvalkis micro-region).

The results obtained during the investigation of palaeogeographical evolution, correlation analysis of continental dunes and analysis of the lithomorphogenetic structure of geomorphological regions allow the following **generalisations**:

1. The traces of palaeogeographical events in the Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau formed during the pre-last Glaciation (*Medininkai, Saalian*) are fixed in the surface deposits and relief morphology which imply long-lasting periglacial processes.

2. The glacigenic forms of Nemunas glaciation Žiogeliai phase of Grūda stage are best preserved in the left bank of Merkys. They were bordered on by the later Baltija stage glacier. South of these forms, there already existed glacier melt water drainage zone.

3. The specific character of Baltija stage deglaciation was predetermined by a wide (30–40 km) dead ice elevation and glaciolacustrine Simnas-Balbieriškis-Stakliškės basin

which was dammed between it and the younger South Lithuanian glacier. The southward water flow from this basin sculptured a large part of the present Middle Nemunas channel. The subsequent subsidence of this basin and glacioisostatic lifting of the southern edge of the territory turned the water flow to the north where it dammed at the edge of Middle Lithuanian glacier not far from Kaunas.

4. In the Late Nemunas, the middle part of the territory extending from south-west to north-east was subjected to intensive interstadial erosion and accumulation whereas at the end of the Late Glacial it was affected by recurring glaciofluvial erosion and accumulation. These processes generated the sixth-second terraces above the Middle Nemunas and Lower Merkys floodplains.

5. The Early Holocene time was marked by glaciokarst and aeolian processes which were the last to intensively transform the relief. In boreal, the glaciokarst and furrow regeneration phenomena, which affected almost all genetic types, renewed and, eventually, came to an end in the whole zone of the last glaciation.

6. The South Lithuanian aeolian forms have developed in the South-East (Dainava) Plain. Their massifs and occupied areas show heterogeneous character of the genesis, composition and geological structure of the plain. The aeolian areas are of different age and were generated by reworking of glaciolacustrine and glaciofluvial sands by winds of different directions.

7. Geomorphological regions are represented by large geomorphological complexes formed by one or a few dominant geological-geomorphological processes and characterised by specific palaeogeographical evolution, age and post-genetic transformation. These geomorphological complexes are of different lithomorphogentic structure.

8. The lithomorphogenetic structure of geomorphological regions and lithological, morphological and genetic diversity of their parts were predetermined by changing glacial and post-glacial sedimentary environment.

9. Analysis of lithomorphogenetic structure contributed to clearer identification of some localities as belonging to various geomorphological regions.

3.4. LINKS BETWEN GEOLOGICAL STRUCTURES AND GEOMORPHOLOGICAL REGIONS

As the main goal of the present dissertation was to determine the influence of geological structure on the evolution of geomorphological regions, the evolution is understood as the evolution of the influence of geological structures on the genesis of geomorphological regions through intermediate structures (palaeosurfaces). This interpretation of evolution is an attempt to evaluate the influence of deep geological structures on geomorphological regions and to trace back the changes of their inherited palaeocontours from the geophysical anomalies through the sub-Quaternary and Pleistocene palaeosurfaces to recent surface.

The influence of geophysical anomalies (gravitational and magnetic fields) and tectonic movements, in the neotectonic stage in particular, on the evolution of geomor-morphological regions was analysed by comparison of cartographic data.

Comparison of the distribution of South Lithuanian geomorphological regions in terms of tectonic structure of this part of Lithuania shows that the Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau are situated in the Masūrian-Belorussian anteclise, i. e. at the elevated tectonic structure which is specifically split by NE and WNW faults (Lietuvos…, 2003). In the southern part of South-Eastern (Dainava) Plain the anteclise is clearly elevated and in the north it is bordered by the regional Lazdijai-Merkinė-Panočiai fault. This part of the South-Eastern Plain (geomorphological region III) is distinguished for abundance of glaciofluvial and aeolian deposits. The western part of the Middle Nemunas Plateau geomorphological region (V), the southern part of the Lower Nemunas Plain gomorphological region (IV) and the western part of the Sūduva Upland sub-region (IV b) belong to the shallow part of the Baltija sineclise (Polish-Lithuanian Basin).

Comparison of gravitational Bouguer anomalies with the contours of South Lithua-nian geomorphological regions shows obvious links between the positive anomalies of gravitation field and Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau (Fig. 10, Table 2).

Partial congruity also exists with South-East (Dainava) Plain, its eastern edge in particular, and Dzūkai Upland. The negative gravitational anomaly between Dusia and Žuvintas lakes coincides with the northern edge of Sūduva Upland.

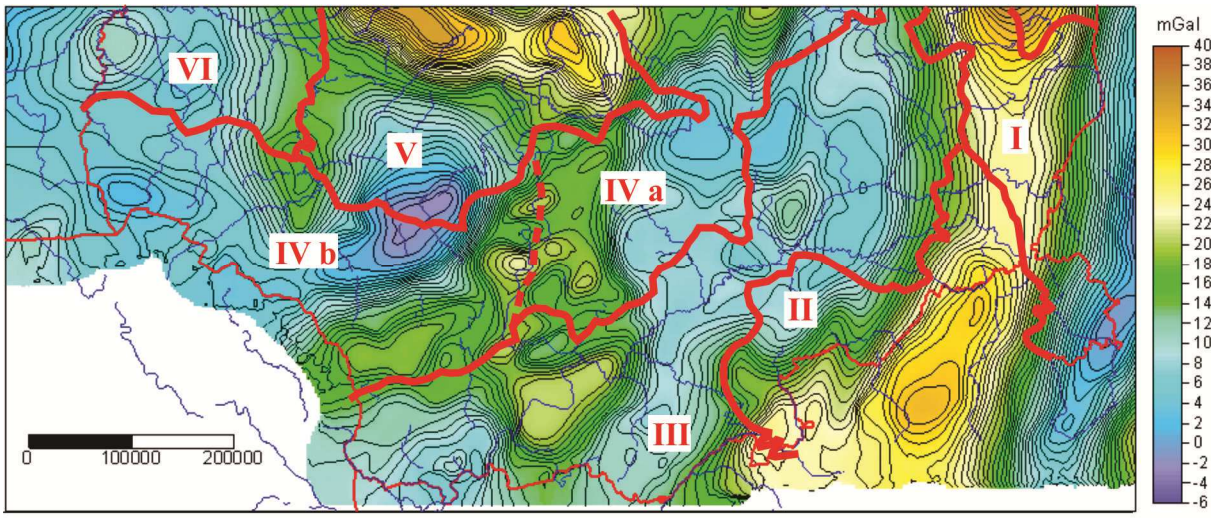

Fig. 10. Map of South Lithuanian gravitational Bouguer anomalies (Korobliova, Popov, 1997).

Red lines mark the present geomorphological ragions: I – Medininkai (Ašmena) Upland; II – Eišiškės (Lyda) Plateau; III – South-East (Dainava) Plain; IV – South Lithuanian Upland: IV a – Dzūkai Upland; IV b – Sūduva Upland; V – Middle Nemunas Plateau; VI – Lower Nemunas Plain

Comparison of the map of magnetic anomalies with the distribution of geomorphological regions shows similar links with the south-eastern part of the studied territory, where the Medininkai (Ašmena) Upland and Eišiškės (Lyda) Plateau absolutely coincides with N-NE oriented alternating anomalies of magnetic field (Fig. 11).

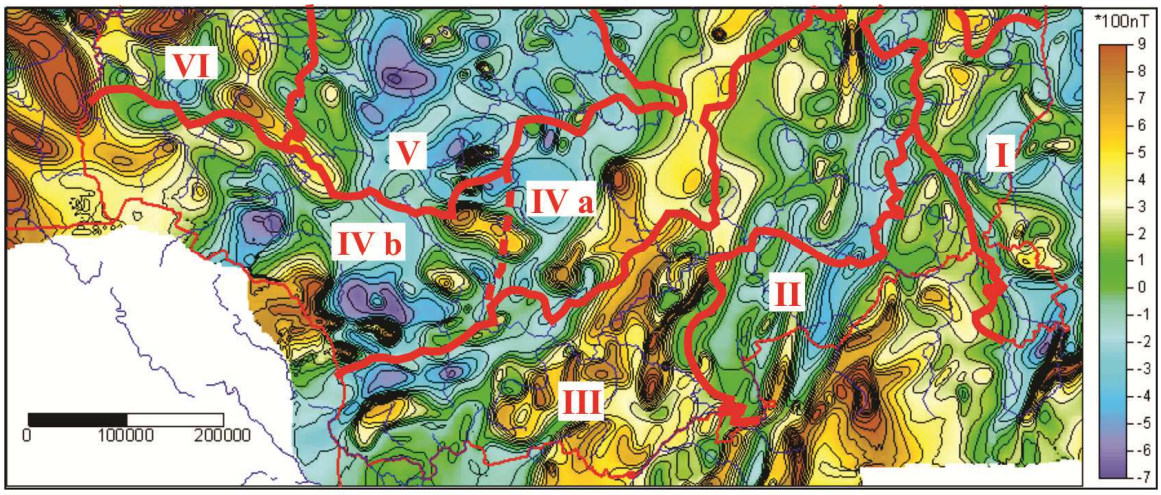

Fig. 11. Map of South Lithuanian magnetic anomalies (Korobliova, Popov, 1997). For explanation of the indices of regions see Fig. 10.

Similar congruence exists between the more intensive N-NE belt of magnetic field and South-East (Dainava) Plain. In the remaining part of the region, the magnetic field bears a mosaic character and includes smaller anomalies which can be collated only with the South Lithuanian lithomorphogenetic micro-regions. The western part of Sūduva Upland (Vištytis-Gražiškės hill terrain), with a rather intensive positive magnetic anomaly, makes an exception.

The Lithuanian Geological Survey has investigated the dependence of gravitational field on recent relief for possibility to predict the intensity of recent surface geological processes. A map of potential energy of relief for the territory of Lithuania was compiled based on V. Filosov's method (Korobliova, S. Šliaupa, 2006 b). The greater are the altitude and gravitational force of relief the greater is the potential energy. The map of the potential energy of relief displays the interaction between the surface and deep processes: the most intensive surface processes are predicted in the south-western, northern and eastern parts of Lithuania (Korobliova, S. Šliaupa, 2006 a). It is assumed that this principle also applies to South Lithuanian Pleistocene surfaces. Elevated potential energy is well-defined in the Medininkai (Ašmena) and Sudūva uplands. It is slightly lower in the Dzūkai Upland. The elevations of the surface in the central parts of Žeimena formation (Medininkai till) show the elevated potential energy of relief which was inherited from the last glaciation.

Comparison of South-Lithuanian neotectonic map compiled on the basis of sub-Quaternary surface structures, with the boundaries of geomorphological regions shows that the Middle Nemunas Plateau in its main part coincides with the Kaunas structural terrace (A. Šliaupa, 2004 a, b) (Figs 2 and 9). The Vilnius structural terrace and the South Lithuanian swell also comprise the foundation of Medininkai (Ašmena) Upland and, partly, Eišiškės (Lyda) Plateau.

Comparison of the Lithuanian map of neotectonically active linear zones (NAZ) with the boundaries of geomorphological regions shows that among the abundant zones there are many which coincide with the eastern boundaries of South-East Plain and south-eastern boundaries of Middle Nemunas Plateau (A. Šliaupa, 2004 a). Part of the South-East Lithuanian axis (old Nemunas channel) coincides with neotectonically active linear zone extending in SW-NE directions.

The influence of the tectonic structure and neotectonic activity on the lithomorphogenetic structure of geomorphological regions is clearly reflected by aeolian forms on the crystalline basement in the South Lithuanian fold zone. Their spread coincides with the northern slope of Mozūrian-Belarusian anteclise which is characterised by a markedly stronger inclination of the crystalline basement. Its northern boundary extends along the Merkys fault zone which marks the northern boundary of South Lithuanian aeolian forms (S. Šliaupa, 1997).

The structural dependence of the spread of aeolian forms becomes obvious by comparison of the area occupied and structural residual anomalies of the surface of crystalline basement. When the surface angle is large, local structures are “disguised” on the general background of subsidence. This is the case in South Lithuania where the angle of the crystalline basement is large (Fig. 12).

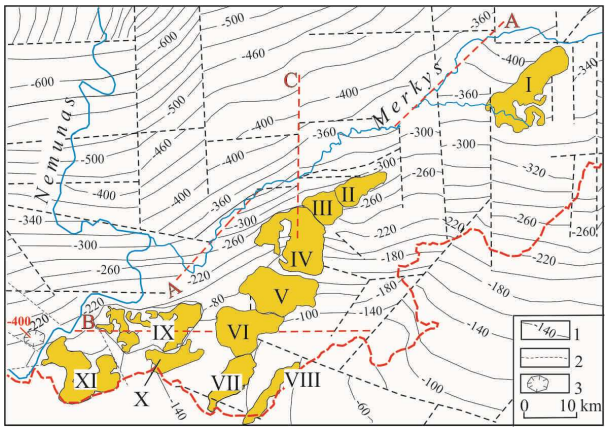

Fig. 12. Map of the surface of crystalline basement compiled *by S. Šliaupa* (Baltrūnas *ir kt.*, 1998). 1 – stratoisohypse; 2 – fault (A–C faults are mentioned in the text: A – Merkys; B – Druskininkai; C – Mergeženis); 3 – Mizarai structure with indicated depth of crystalline basement in borehole 344. Lines show dune terrains: 1 – Rūdninkai; II – Barčiai; III – Varėna; IV – Palkabalis; V – Lyneženis; VI – Marcinkonys; VII – Musteika; VIII – Katra; IX – Randamonys; X – Dubas; XI – Lateženis

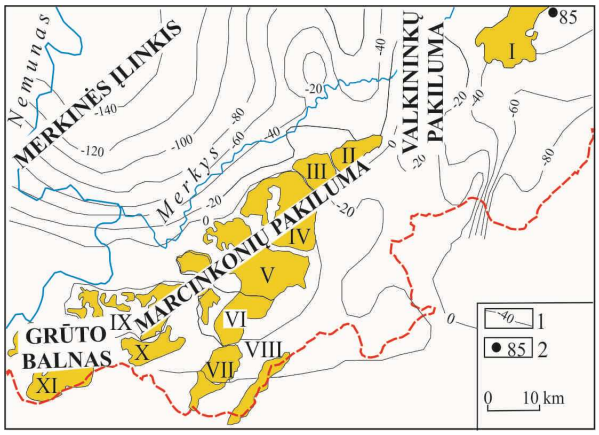

Fig. 13. Scheme of residual structural anomalies of the first order in the Lithuanian crystalline basement. Compiled *by S. Šliaupa* (Baltrūnas *ir kt.*, 1998). 1 – isanomaly; 2 – Kernavis elevation with indicated residual altitude in borehole 722

S. Šliaupa’s scheme of structural residual anomalies of the first order in the crystalline basement displays a large zone of elevations east of Merkys with the largest

Grūtas saddle and Marcinkonys and Vilkaviškis residual structures with positive values and relative amplitude of 70 m (Baltrūnas *ir kt*., 1998) (Fig. 13). Aeolian forms are spread in the structural elevation zone with positive values. Meanwhile, aeolian forms almost are absent in the zones of structural troughs.

The structural composition predetermines the occurrence of hills in aeolian relief. Comparison of the relative average altitudes of hills in aeolian areas with the residual altitudes of the surface of crystalline surface showed a very high (+0.73) correlation coefficient, i.e. the higher is the relative structural position of the crystalline basement (i. e. the higher is its relative altitude) the more dissected is the aeolian relief (Baltrūnas *ir kt*., 1998).

In the present dissertation, the structural links of the South Lithuanian geomorphological complexes (regions) with the specific features of sub-Quaternary and Pleistocene palaeosurfaces were analysed. These links were predetermined by the deep structures (geophysical fields, geological and tectonic structures, faults and their zones), recurrent glacial exaration and accumulation processes during the Quaternary, and intensive fluvial erosion and sedimentation. The latter processes could have been conditioned by the features of geological foundation, especially when glaciers split into flows, lobes and tongues, thick ice cover fissured, glaciofluvial streams washed out foundation rocks composed of looser deposits, *etc*. Palaeogeographical regionalisation of sub-Quaternary surface allows stating that the configuration of the sandy and clayey East Aukštaičiai Plateau with shallow valleys (palaeogeomorphological region VII) and dominant wavy watersheds of Dainava glaciation coincides with the surface Medininkai (Ašmena) Upland and NE part of Eišiškės (Lyda) Plateau (Pukelytė, 2009) (Fig. 14).

Meanwhile, the sandy, clayey and carbonaceous denudation Šventoji Slope (palaeogeomorphological region VIII) with shallow valleys essentially coincides with the northern part of South-East (Dainava) Plain. The southern part of the plain together with the South Lithuanian Upland and southern part of the Middle Nemunas Plateau extends above the widespread sandy and clayey erosional-exarational South Lihuanian Plain with deep valleys and in clined south-westward (palaeogeomorphological region IX). North of this palaeosurface, stretches the Great Lithuanian Lowland (palaeogeomorphological region II) with the recent Middle Nemunas Plateau above it.

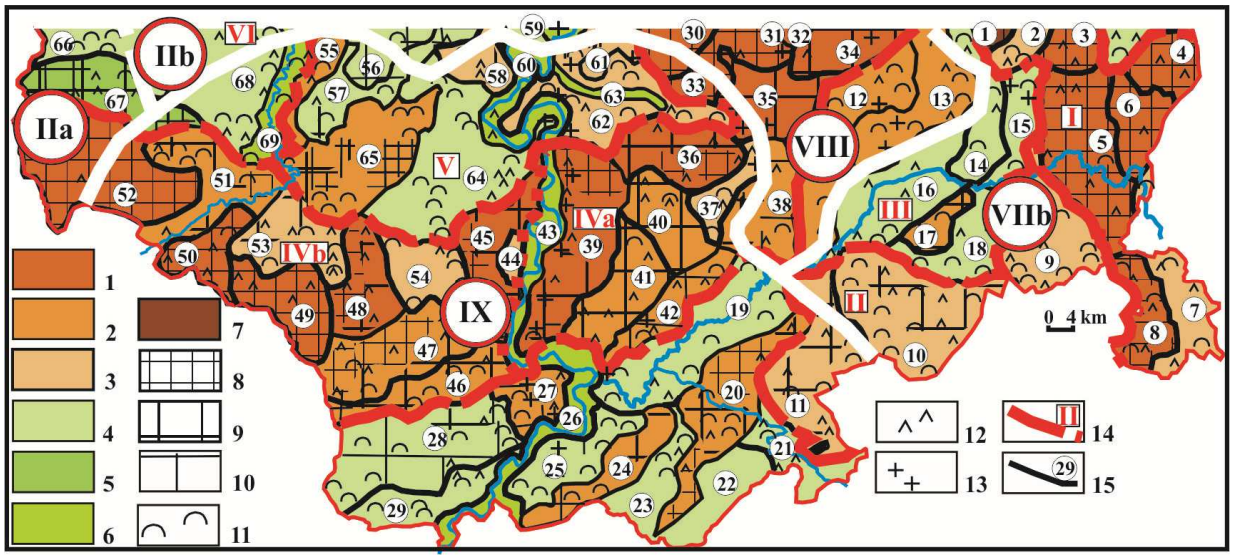

Fig. 14. Comparison of lithogenetic regionalisation of recent South Lithuanian surface with palaeogeomorphological regionalisation of sub-Quaternary surface

White lines and indices: II (II a, IIb) – Great Lithuanian Lowland, VII b – East Aukštaičiai Plateau, VIII – Šventoji Slope, IX – South Lithuanian Plain (see Fig. 4, 9)

The top of Dainava formation (till) is strongly inclined E-W and is marked by large amplitude of relative altitudes which correlates with the boundaries of present geomorphological regions. This is proved by the influence of strongly dissected sub-Quaternary surface on the present surface, i. e. the inclination in EW direction. The top of the till complex of this formation is strongly dissected: deep palaeoincisions and strongly elevated watersheds. The surface has been smoothed by Žemaitija and Medininkai glaciers. The top of Žeimena formation (Medininkai till) is less dissected and the amplitudes of the relative altitudes in the last glaciation zone are smaller. Larger local elevations of this surface were found only at the Vištytis-Gražiškiai elevation and in the northern part of Dzūkai Upland. In these areas, the Medininkai till composes part of the surface of the present elevation, which in the Middle Nemunas Plateau and Užnemunė Plain dips into lower buried palaeosurface. This palaeosurface in the Middle Nemunas Plateau is less dissected and gradually elevates in the SE direction till the Eišiškės (Lyda) Plateau.

For evaluation of the links between palaeosurfaces and present surface, statistical correlation coefficients of these surfaces were calculated based on the values of absolute altitudes determined in boreholes. The obtained results show strong correlations between the compared surfaces.

The values of correlation coefficient for 256 boreholes (N = 256) are statistically significant, i. e. higher than or equal with the established critical values: r_{kr} = 0.12 (when confidence α = 0.05), r_{kr} = 0.16 (when α = 0.01) and r_{kr} = 0.20 (when α = 0.001). The binary correlation coefficients of all investigated palaeosurfaces are considerably higher than the established critical values (Table 2).

Table 2. Comparative correlation coefficients of South Lithuanian palaeosurfaces and present surface

	Surface of the top of Medininkai till	Surface of the top of Dainava till	Sub-Quaternary surface
Present surface	0,591	0,442	0,323
Surface of the top of Medininkai till		0,619	0,485
Surface of the top of Dainava till			0,751

Thus, this index shows the actual interdependence of the compared surfaces. All correlation coefficients of compared surfaces (calculated based on the data of 256 boreholes) are positive and statistically significant. The linear regression graphs of correlation links between compared surfaces illustrate that the correlation between two points of compared surfaces is close to linear one (Fig. 15).

The territorial conformity of South Lithuanian geomorphological regions, deep structures and palaeosurfaces was evaluated by comparison of geophysical, tectonic and hypsometric maps of palaeosurfaces. It was determined that the South Lithuanian geomorphological regions can be characterised by: **1** – obvious territorial conformity; **2** – absence of conformity; **3** – partial conformity, when only some parts and boundaries of compared objects coincide with the deep structures and palaeosurfaces (Table 3, Fig. 16).

Generalising the data given in the present section it can be stated that:

1. There exist territorial links of South Lithuanian geomorphological regions with gravitational and magnetic fields and tectonic and neotectonic structures. The deep geological structure has a well-defined though varying influence on the evolution of geomorphological regions. This influence on the Medininkai (Ašmena) Upland and, partly, on

the Eišiškės (Lyda) Plateau is obvious. The influence on the South Lithuanian Upland, South-East (Dainava) Plain, Middle Nemunas Plateau and Lower Nemunas Plain is either partial or of varying significance.

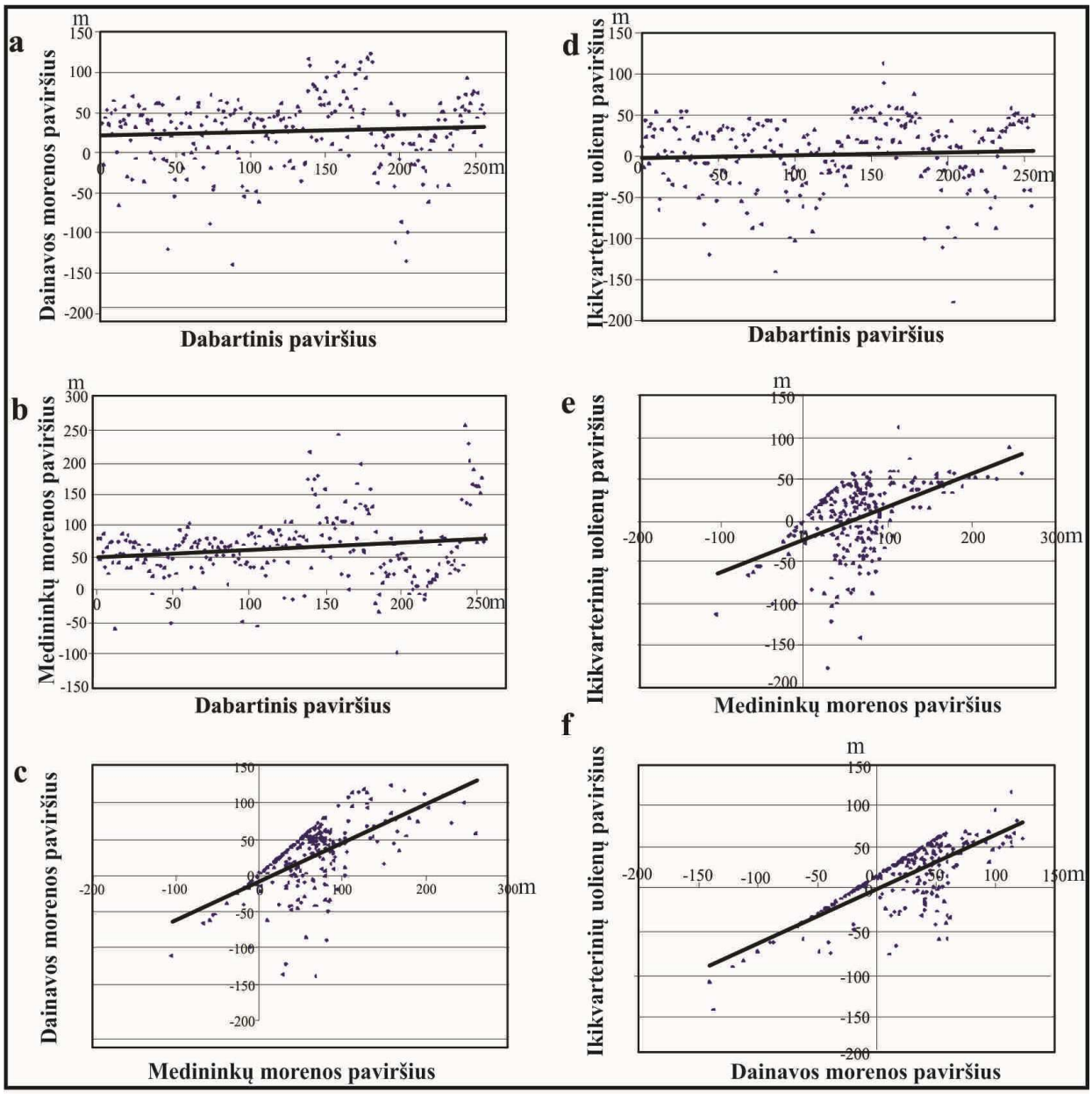

Fig. 15. Graph of linear regression of correlation links between the palaeosurfaces and present surface

a – present surface with surface of the top of the overlying Dainava till; b – present surface with surface of the top of the overlying Medininkai till; c – surface of the top of the overlying Dainava till with surface of the top of the overlying Medininkai till; d – present surface with the sub-Quaternary surface; e – surface of the top of the overlying Medininkai till with the sub-Quaternary surface; f – surface of the top of the overlying Dainava till with the sub-Quaternary surface

2. Though positive, the correlation link of the present surface with palaeosurfaces loses significance in deeper layers, i.e. it decreases with every older palaeosurface: ***r*** = 0.591 → ***r*** = 0.442 → ***r*** = 0.323. Thus, the weakest correlation link is with the sub-Quaternary surface. The same tendency was determined for the surface of Žeimena formation (Medininkai till): the correlation link decreases in deeper layers. The correlation coefficient of the adjacent surfaces increases with depth: ***r*** = 0.591 → ***r*** = 0.619 → ***r*** = 0.751.

3. The highest correlation coefficient (***r*** = 0.751) was determined between the sub-Quaternary surface and the surface of the top of the overlying Dainava till. This is related with the influence of the transforming activity of Dzūkija and Dainava glaciers on the strongly dissected sub-Quaternary surface and on accumulation of glacigenic deposits. Unfortunately, the uneven density of the used boreholes in the studied territory reduces the reliability of determining the correlation links for different geomorphological regions.

Table 3. Territorial conformity of deep structures and palaeosurfaces with South Lithuanian geomorphological regions (++ – obvious, + – partial, -- – absent)

Geomorphological region	Gravitational field	Magnetic field	Neotectonic structure	Sub-Quaternary surface	Surface of the top of Dainava till	Surface of the top of Medininkai till
	GL	ML	NS	PP	DP	MP
Medininkai (Ašmena) Upland	++	++	++	++	++	*present surface*
Eišiškės (Lyda) Plateau	++	++	+	+	--	*present surface*
South-East (Dainava) Plain	+	++	+	+	--	+
Dzūkai Upland	+	--	++	--	--	++
Sūduva Upland	+	--	++	--	+	+
The Middle Nemunas Plateau	+	+	+	+	+	+
The Low Nemunas Plain	--	--	+	--	+	--

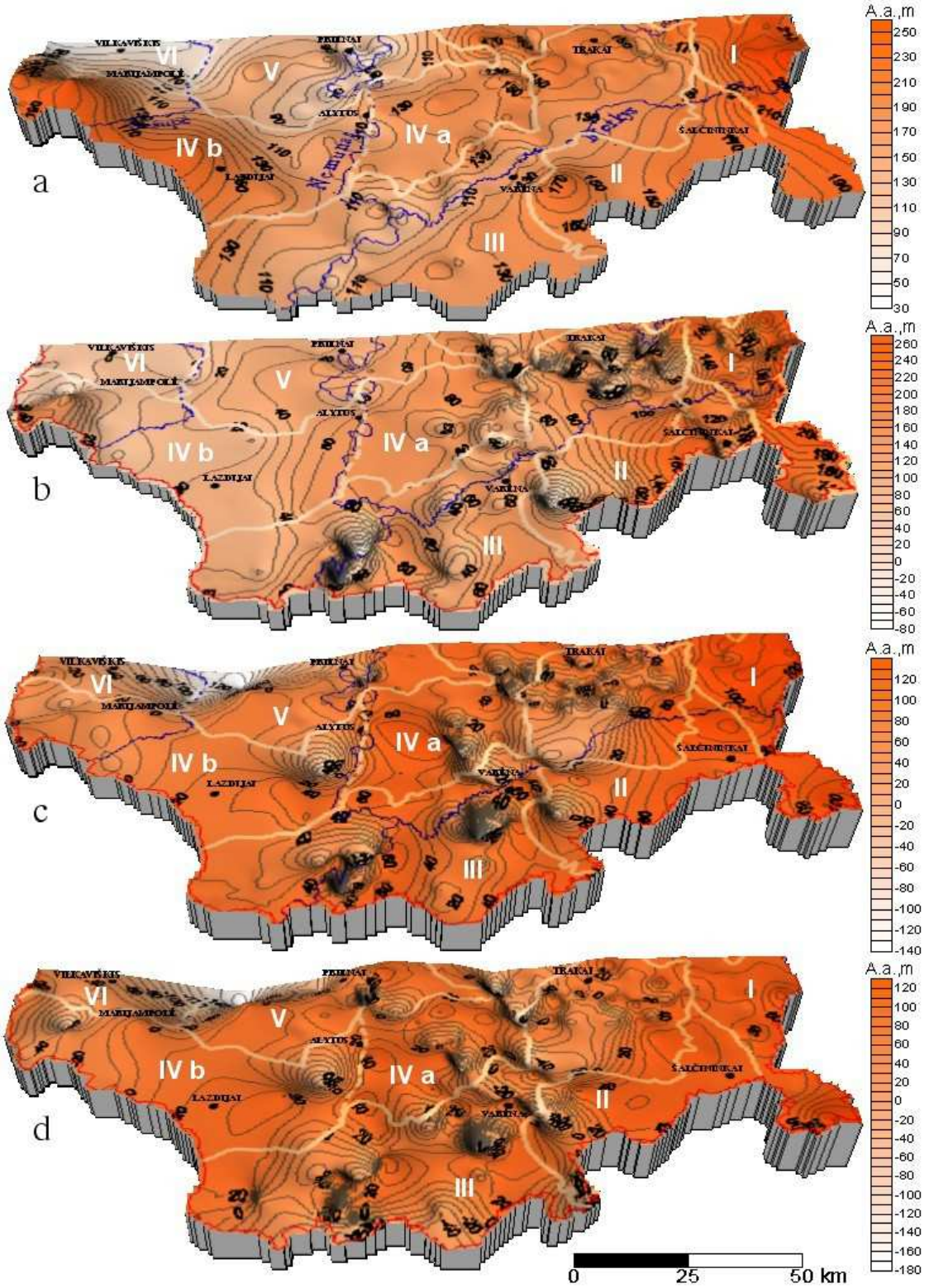

Fig. 16. The 3 D model of compared surfaces was created using *Surfer* program

a – present surface; b – top of the Medininkai till; c – top of the Dainava till; d – sub-Quaternary surface. White lines and indexes: I – Medininkai (Ašmena) Upland; II – Eišiškės (Lyda) Plateau; III – South-East (Dainava) Plain; IV – South Lithuanian Plain: IV a – Dzūkai Upland; IV b – Sūduva Upland; V – Middle Nemunas Plateau; VI – Lower Nemunas Plain

CONCLUSIONS

Evaluation of the influence of geological structure on the evolution of South Lithuanian geomorphological regions leads to the following conclusions:

1. Analysis of previous geomorphological and palaeogeomorphological investigations revealed rich experience of this kind of research in Lithuania. Yet maps compiled at different scales (usually at small scales,) following different principles, criteria and goals and applying different methods, make the obtained results ambiguous and incompatible.

2. The South Lithuanian palaeogeomorphological regions of sub-Quaternary surfaces are characterised by uneven hypsometric (often terraced) position and deposits of different composition and age. The evaluation of the genesis, composition and age of deposits, covering the palaeogeomorphological regions, and scale of exaration and erosion processes, which took place in the sub-Quaternary, shows that the Middle Pleistocene Dainava glaciation had a strong influence on the morphosculpture of palaeowatersheds and palaeoincisions and predetermined geomorphological processes in the distinguished palaeomorphological regions.

3. Analysis of lithomorphogenetic structure of geomorphological regions revealed their relative heterogeneity. 69 lithomorphogenetic micro-regions were distinguished. They are marked by specific geomorphological and geological structure and embrace genetically and morphologically similar lithological and geomorphological complexes. Analysis of palaeogeographical evolution of the territory revealed the stages and conditions of formation of geomorphological regions and lithomorphological micro-regions.

4. In their spatial distribution (size and orientation) and dissection (relative altitudes of dunes and crest length), the South Lithuanian aeolian stretch and dune massifs are related with the geological structure of the territory, specific features of tectonic structure and neotectonic activity, which created favourable conditions for intensive aeolian processes.

5. The correlation links between the present surface and palaeosurfaces are positive and statistically significant. The significance decreases with greater depth. The same trend was determined by comparison of the links between the palaeosurface of the first (from top) Medininkai till (Žeimena formation) and deeper palaeosurfaces. It was established that the correlation coefficient of adjacent palaeosurfaces decreases from bottom to top ($\boldsymbol{r}$ = 0.751 → $\boldsymbol{r}$ = 0.619 → $\boldsymbol{r}$ = 0.591) what implies a gradually decreasing correlation link. The conducted research also allowed determining the common pattern – geomorphological heredity of Pleistocene palaeosurfaces.

6. Analysis of the territorial links of South Lithuanian geomorphological regions with gravitational and magnetic fields, tectonic and neotectonic structures, confirmed the significant influence of deep geological structure on the evolution of geomorphological regions. The strength of this influence on various palaeosurfaces slightly varies: it is absolutely or partly obvious in the Medininkai (Ašmena) Upland and partly Eišiškės (Lyda) Plateau but partial and unevenly significant in the South Lithuanian Upland, South-Eastern (Dainava) Plain, Middle Nemunas Plateau and Lower Nemunas Plain.

7. The performed analysis of the territorial links between South Lithuanian geomorphological regions confirmed the significant on the evolution of influence of deep geological structure to geomorphological regions through sub-Quaternary and main Pleistocene palaeosurfaces.

Geologinės struktūros įtaka geomorfologinių rajonų raidai

(Pietų Lietuvos pavyzdžiu)

S A N T R A U K A

Pastaraisiais dešimtmečiais paskelbta daug duomenų apie geologinės struktūros (geofizinių anomalijų, tektoninės sandaros, paleopaviršių morfologijos ir pan.) įtaką paviršinių reljefo kompleksų (aukštumų ir lygumų, terasinių lygių ir upių slėnių, eolinių masyvų ir kt.) paplitimui, susidarymo sąlygoms bei paleogeografinei raidai. Tačiau specialiai tuo požiūriu tirtų objektų Lietuvoje ir tam skirtų darbų nėra daug. Todėl iki pastarojo meto išlieka problema: kiek gi ši įtaka dėsninga ir būdinga žemyninių apledėjimų teritorijoms, kaip ir kokiais metodais ji gali būti įvertinama, koks geomorfologinio paveldimumo pobūdis ir mastas. Nagrinėjama problema susijusi su aktualių klausimų sprendimu kasdieninėje praktikoje. Informacija apie konkrečių geomorfologinių kompleksų sąsajas su geologine struktūra padeda aiškiau suprasti šių kompleksų atsiradimo priežastis, specifinių (smėlingų, žvyringų, moreninių, kaičios sudėties) nuogulų storymių susidarymą, geoekologines sąlygas. Tokie duomenys labai svarbūs teritorijų planavimui, vietovių geoekologinių sąlygų vertinimui, kai kurių naudingųjų iškasenų, ypač požeminio vandens, išteklių paplitimo prognozavimui. Paviršių paleogeografinės raidos tyrimai svarbūs paleoekosistemų bei paleoaplinkų raidos atkūrimui.

Disertacinio darbo tyrimo objektas – stambūs teritoriniai vienetai, pasižymintys būdinga paleogeografine raida, geomorfologine išraiška ir reljefo sąskaida, vyraujančia kilme bei amžiumi, savita litologine sudėtimi bei postgenetiniu performavimu, sąsajomis su geologine struktūra. Tai geomorfologiniai rajonai ir jų gelmėse esančios geologinės struktūros (geofizinės anomalijos, tektoniniai lūžiai, ikikvarterinių uolienų paviršius bei būdingiausi pleistoceno storymės paleopaviršiai). Tyrimui pasirinkta palyginti didele geomorfologinių rajonų įvairove pasižyminti Pietų Lietuva, kurios geologinis bei geomorfologinis ištirtumas yra bene didžiausias, lyginant su kitais Lietuvos regionais (1 pav.).

Šio darbo tikslas – įvertinti geologinės struktūros įtaką paviršiaus geomorfologinių kompleksų (rajonų) raidai Pietų Lietuvos pavyzdžiu. Tikslui pasiekti, remiantis kompleksinių tyrimų metodologija, buvo sprendžiami šie uždaviniai: atlikti ankstesnių geomorfologinių tyrimų, geomorfologinio ir paleogeomorfologinio rajonavimo darbų anali-

zę, sudaryti naują ikikvarterinių uolienų paviršiaus paleogeomorfologinio rajonavimo žemėlapį, atlikti pleistoceno storymės pagrindinių paleopaviršių analizę, įvertinti dabartinio paviršiaus geomorfologinių rajonų litomorfogenetinę struktūrą bei paleogeografinę raidą poledynmetyje, taip pat įvertinti giluminės geologinės struktūros, ikikvarterinių uolienų paviršiaus ir pleistoceno paleopaviršių sąsajas su dabartinių geomorfologinių rajonų sklaida.

Kompleksinių tyrimų metodologija akcentuoja vienalaikį kilmės, morfologijos ir litologijos kriterijų taikymą geomorfologinių rajonų litomorfogenetinės struktūros nustatymui. Darbe taikytas etaloninių objektų tyrimo principas leido kai kuriuos geomorfologinius ir geologinius procesus detalizuoti (paleoįrėžių užpildymą, eolinių masyvų susidarymą). Darbe taip pat buvo taikyti ikikvarterinių uolienų paviršiaus paleogeomorfologinio rajonavimo, geomorfologinių rajonų litomorfogenetinės struktūros tyrimo, paleoįrėžių užpildo įvertinimo, moreninių nuogulų sudėties santykinės entropijos apskaičiavimo metodai, paleopaviršių ir dabartinio paviršiaus statistinio palyginimo koreliacinės analizės metodas, panaudojant *Surfer* ir *Excel* programas.

Ankstesnių publikuotų tyrimų rezultatų Lietuvoje analizė parodė didelę geomorfologinių ir paleogeomorfologinių tiriamųjų darbų patirtį Lietuvoje. Tačiau skirtingi geomorfologinio ir paleogeomorfologinio rajonavimo tikslai, principai ir kriterijai lėmė, kad įvairiais metais sudaryti, dažniausiai smulkaus mastelio žemėlapiai yra sunkiai palyginami ir suderinami.

Atlikti tyrimai parodė, kad Pietų Lietuvos ikikvarterinių uolienų paviršiaus paleogeomorfologiniams rajonams būdinga nevienoda hipsometrinė, dažnai pakopiška, padėtis bei skirtingos sudėties ir amžiaus paleopaviršių sudarančios uolienos. Paleogeomorfologinius rajonus dengiančių nuogulų kilmės, sudėties ir amžiaus bei kvartero metu vykusių egzaracinių ir erozinių procesų masto įvertinimas rodo, kad viduriniojo pleistoceno Dainavos apledėjimas turėjo didelę įtaką paleotakoskyrų ir paleoįrėžių morfoskulptūrai, lėmė geomorfologinius procesus atskiruose paleogeomorfologiniuose rajonuose.

Geomorfologinių rajonų litomorfogenetinės struktūros tyrimas atskleidė jų santykinį nehomogeniškumą. Išskirti 69 litomorfogenetiniai mikrorajonai pasižymi geomorfologiniu ir geologiniu savitumu, jungia genetiškai ir morfologiškai panašius litologinius bei geomorfologinius kompleksus. Teritorijos paleogeografinės raidos analizė išryškino ski-

riamų geomorfologinių rajonų ir litomorfogenetinių mikrorajonų susidarymo aplinkybes ir etapus.

Pietų Lietuvos eolinis ruožas ir atskiri kopų masyvai savo erdvine sklaida (dydžiu, orientacija) bei raižytumu (kopų santykinis aukštis, keteros ilgis) yra susiję su regiono geologinės sandaros, tektoninės struktūros bei neotektoninio aktyvumo ypatybėmis, kurios nulėmė palankias sąlygas intensyviems eoliniams procesams vykti.

Pietų Lietuvos geomorfologiniai rajonai ar jų dalys turi dažną atitikimą su gravitaciniu ir magnetiniu lauku, tektonine sandara ir neotektonine struktūra, nors ir ne visada vienodą. Medininkų (Ašmenos) aukštumai, iš dalies ir Eišiškių (Lydos) plynaukštei ši įtaka visiškai ar dalinai akivaizdi, o Pietų Lietuvos aukštumai, Pietryčių (Dainavos) lygumai, Nemuno vidurupio plynaukštei ir Nemuno žemupio lygumai – dalinė ir nevienodai reikšminga.

Dabartinio paviršiaus ir paleopaviršių koreliacinis ryšys yra teigiamas ir statistiškai reikšmingas. Jo reikšmingumas einant gilyn mažėja. Tokia pati tendencija išryškėjo lyginant pirmąjį (nuo viršaus) - Žeimenos svitos Medininkų morenos - paleopaviršių su gilesniais paleopaviršiais. Nustatyta, kad gretimų paleopaviršių koreliacijos koeficientas einant aukštyn mažėja ($\boldsymbol{r}$ = 0,751 → $\boldsymbol{r}$ = 0,619 → $\boldsymbol{r}$ = 0,591), kas liudija apie palaipsniui mažėjantį teigiamą koreliacinį ryšį tarp jų. Nustatytas dažnas lokalus paleopaviršių geomorfologinis paveldimumas.

Atlikta Pietų Lietuvos geomorfologinių rajonų teritorinių sąsajų analizė patvirtino reikšmingą gelmių geologinės struktūros įtakos raidą geomorfologiniams rajonams per ikikvarterinių uolienų ir pagrindinius pleistoceno storymės paleopaviršius.

Disertacinį darbą (154 psl.) sudaro: įvadas, ankstesnių tyrimų apžvalga, darbo metodika, tyrimų rezultatai (keturi skyriai, vienuolika poskyrių), išvados ir literatūros sąrašas (318 pozicijų). Jis iliustruotas 48 paveikslais ir 11 lentelių.

LIST OF PUBLICATIONS BY V. PUKELYTĖ BALTRŪNIENĖ REPORTING THE RESULTS OF THE PRESENT DISSERTATION

1. Scientific articles published in refereed scientific periodical publications included by the *Institute for Scientific information – ISI* – in the database *Thomson Reuters Web of Science* ***(ISI WOS)*** and have an index of impact factor in the database of *Journal Citation Report*.

- Česnulevičius A., Švedas K., Morkūnaitė R., Paškauskas S., **Pukelytė V.,** Vekeriotienė I., Karmazienė D., **2011.** Lietuvos geomorfologijos raida XX amžiaus idėjų kontekste. *Baltica*, 24: Special Issue. Vilnius. 19–22. ISSN 0067-3064. IF – 0,607.
- **Pukelytė V., 2011**. Senųjų žemyninių kopų tyrimai Lietuvoje. *Baltica*, 24: Special Issue. Vilnius. 147–150. ISSN 0067-3064. IF – 0,607.
- Baltrūnas V., Karmaza B. and **Pukelytė V., 2008**. Multilayered structure of the Dzūkija and Dainava tills and their correlation in South Lithuania. *Geological Quarterly*, 52 (1). Warszawa. 91–99. ISSN 1641-7291. IF – 0,892.
- Baltrūnas V., Švedas K., **Pukelytė V., 2007.** Paleogeography of South Lithuania during the last ice age. *Sedimentary Geology*, 193. 221–231. ISSN 0037-0738. IF – 1,757.

2. Scientific articles published in refereed scientific periodical publications included by the *Institute for Scientific information – ISI* – in the list of **main publications** of the database *Thomson Reuters Web of Science*.

- Švedas K., Baltrūnas V., **Pukelytė V., 2004.** Pietų Lietuvos paleogeografija vėlyvojo pleistoceno Nemuno (*Weichselian*) apledėjimo metu. *Geologija*, 45. Vilnius. 6–15. ISSN 1392-110X.
- Baltrūnas V., **Pukelytė V., 2003.** Pleistoceno morenų granuliometrinės sudėties santykinės entropijos kaitos ypatumai Pietų Lietuvoje. *Geologija*, 42. Vilnius. 45–50. ISSN 1392-110X.
- Baltrūnas V., **Pukelytė V.**, Šliaupa S., **1998**. Pietų Lietuvos eolinių nuogulų susidarymo ir paplitimo ypatybės. *Geologija*, 23. Academia, Vilnius. 106–118. ISSN 1392-110X.
- Baltrūnas V, **Pukelytė V., 1998**. Lietuvos pokvarterinio paviršiaus paleogeomorfologinis rajonavimas. *Geologija*, 26. Academia, Vilnius. 105–113. ISSN 1392-110X.

3. Scientific articles published in other refereed periodical, serial and one-off scientific publications.

3.1. Conference proceedings:

- Valentinas Baltrūnas, Kęstutis Švedas &Violeta Pukelytė, 2007. Periglacial conditions and deglaciation process in South Lithuania during the Last Ice Age. *Special Paper*, 46. Geological Survey of Finland, 39–46. ISSN 0782-8535 (Applied Quaternary research in the central part of glaciated terrain: proceedings of the INQUA Peribaltic Group Field Symposium, 2006, September 11–15, Finland. ISBN 978-952-217-006-4).

3.2. Scientific periodicals:

- Baltrūnas V., Karmaza B., **Pukelytė V., 2003**. Nemuno kilpų regioninio parko geologinis pagrindas. *Geologijos akiračiai*, 2. Vilnius. 41–46. ISBN 1392-0006.

3.3. Monographs:

- **Pukelytė V., 2001.** Reljefo įvairovė ir geomorfologinis rajonavimas. *Akmens amžius Pietų Lietuvoje (geologijos, paleogeografijos ir archeologijos duomenimis)* (red. V. Baltrūnas). GI, Vilnius. 89–101. ISBN 9986-615-28-3.
- Baltrūnas V., **Pukelytė V., 2001**. Eolinių darinių susidarymo ir paplitimo ypatybės. *Akmens amžius Pietų Lietuvoje (geologijos, paleogeografijos ir archeologijos duomenimis)* (red. V. Baltrūnas). GI, Vilnius. 107–114. ISBN 9986-615-28-3.
- Baltrūnas V., **Pukelytė V.**, Karmaza B., **2001**. Paviršiaus genetinė, litologinė ir geomorfologinė įvairovė. *Ar tikrai Raigardas prasmego? (kompleksinių tyrimų duomenys)* (sud. V. Baltrūnas). VDA, Vilnius. 16–23. ISBN 9986-571-65-0.

4. Summaries of presentations at scientific conferences:

- **4.1. Pukelytė V.,** Baltrūnas V., **2013.** Palaeogeomorphology of interglacials in Lower Merkys area, South Lithuania. *Palaeolandscapes from Saalian to Weichselian, South Eastern Lithuania.* **Abstracts** of the INQUA Peribaltic Working Group Internaltional Field Symposium. June 25–30, 2013, Vilnius-Trakai, Lithuania. Lithuanian Geological Survey, Vilnius. 80–81.
- **4.2.** Karmaza B., **Pukelytė V.,** Zinkutė R., Katinas V., Baltrūnas V., **2012.** Palaeoenvironmental changes, cyclicity and dynamics during Quaternary warm periods in Lithuania. *Geomorphology and palaeogeography of polar regions:* **proceeding** of the Joint International Conference "Geomorphology and palaeogeography of polar regions", Symposium "Leopoldina" and the INQUA Peribaltic working group Workshop. Saint-Petersburg, September, 2012 (eds. A. Zhirov, V. Kuznetsov, D. Subetto, J. Thiede). Saint-Petersburg, State University, p. 432. ISBN 978-5-4391-0029-3.
- **4.3. Pukelytė V., 2011**. Palaeogeographical development of geomorphological districts in South Lithuania. *Late Pleistocene Glacigenic Deposits from the Central Part of the Scandinavian Ice Sheet to Younger Dryas End Moraine Zone*: excursion guide and **abstracts** INQUA Peribaltic Working Group Meeting and Excursion Northern Finland, Rovaniemi, 12–17 June, 2011. Geological Survey of Finland, Rovaniemi. 126–127. ISBN 978-952-217-163–4.
- **4.4.** Česnulevičius A., Švedas K., **Pukelytė, V.** and Kulbickas, D., **2011**. Post-glacial relief evolution of South-East Lithuania glaciolacustrine basins and moraine uplands. *Late Pleistocene Glacigenic Deposits from the Central Part of the Scandinavian Ice Sheet to Younger Dryas End Moraine Zone*: excursion guide and **abstracts** INQUA Peribaltic Working Group Meeting and Excursion Northern Finland, Rovaniemi, 12–17 June, 2011. Geological Survey of Finland, Rovaniemi. 83–85. ISBN 978-952-217-163-4.
- **4.5. Pukelytė V., 2010**. Geological structure and distribution of aeolian relief in South Lithuania. *Ice, water, humans – Quaternary landscape evolution in the*

Peribaltic Region: 35th Bi-annual conference of the Deutsche Quartär-vereinigung DEUQUA e.V. and annual Conference of the INQUA PeriBaltic Working Group: conference **proceedings,** Greifswald, September 13–17, 2010. University of Greifswald, Greifswald, p. 148.

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INFORMATION ABOUT THE AUTHOR

Violeta Pukelytė graduated from Kretinga secondary school No 1 in 1980.

In 1980–1985, she studied landscape geography at the Faculty of Natural Sciences of Vilnius University. She graduated from the university acquiring the qualification of geographer, teacher of geography.

Since 1989, she has been employed as a researcher at the Institute of Geology which has been reorganised into the Institute of Geology and Geography of Nature Research Centre. At present, the author is working as a junior researcher at the Laboratory of Quaternary Research.

Contacts:

Nature Research Centre, Institute of Geology and Geography,
Laboratory of Quaternary Research, room 410.
T. Ševčenkos str. 13, LT–03223, Vilnius, Lithuania.
Telef. +370 (5) 2104699, +370 8 684 13631