GEOLOGIJA. 2004. T. 46. P. 40–47

Inžinerinė geologija • Engineering geology • Инженерная геология

Formation of Kirkilai karst sinkhole (Northern Lithuania) and the palaeoecology of its surroundings during Late Glacial and Holocene

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Balakauskas L., Mažeika J. Formation of Kirkilai karst sinkhole (Northern Lithuania) and the palaeoecology of its surroundings during the Late Glacial and Holocene. *Geologija*. Vilnius. 2004. No. 46. P 41–48. ISSN 1392-110X.

The Kirkilai karst sinkhole belongs to a composite type (comprised of several sinks). A detailed coring, pollen analysis and radiocarbon dating of its sediments showed that the sinkhole was formed during the Aleröd warming, providing the first evidence of Late Glacial karst processes in the Karst Region of Northern Lithuania. A sink in the central part of the sinkhole was formed much later than the main sinkhole – during the end of Atlantic and joined the main sink-hole later due to the abrasion of its banks.

Vegetation in the area and immediate surroundings of the sink-hole was mainly influenced by natural factors during the Late Glacial and the Holocene. Human impact is evident only in the Subatlantic and possibly Atlantic chronozones.

A significant activation of karst processes took place in the end of Atlantic. One of its causes can be a more open landscape in the area at this stage, creating favourable conditions for erosion.

Key words: pollen analysis, radiocarbon dating, karst, peat, Holocene, Late Glacial, sink-holes, Northern Lithuania, Kirkilai

Received: 05 January 2004, accepted 09 February 2004.
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INTRODUCTION

The Kirkilai karst sinkhole is situated in the karst region of Northern Lithuania, an area which extends over 500 km^2 and covers a few thousands of surface karst forms (Taminskas, 2000). Karst processes in this region are active even nowadays. Investigations of formation and palaeoecological history of the post-glacial karst forms and their surroundings are essential for a better understanding of modern karst processes in Northern Lithuania. Such investigations are rather sparse in the territory of the karst region (Тюремнов и др., 1959; Kondratienė ir kt., 1998; Balakauskas, 2003) and the palaeoecological information is limited. It is based only on single-proxy pollen investigations (not supported by other proxy data or dating techniques such as radiocarbon analysis).

Pollen and radiocarbon investigations of sediments from the Kirkilai sinkhole provided new data on environmental history in Northern Lithuania spanning the Late Glacial and the Holocene.

SITE DESCRIPTION AND METHODS

The Kirkilai karst sinkhole is located 5 km northwest of Biržai town, on the SE edge of Kirkilai

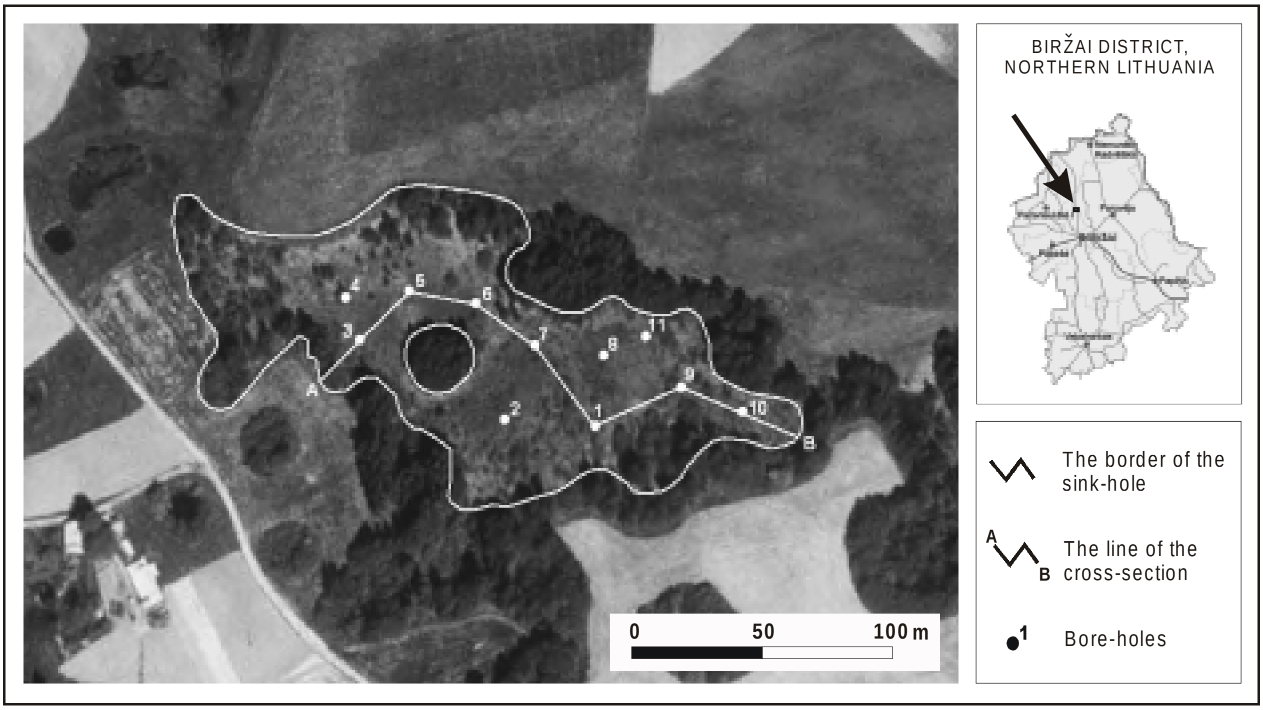

Fig. 1. Situation scheme of Kirkilai sinkhole (based on aerial image)
1 pav. Kirkilų įgriuvos situacijos schema (pagal aeronuotrauką)

village (coordinates in LKS-94 system: 543360; 6234016). The Kirkilai sinkhole is approximately 250 m long and 150 m wide. The shape of the sinkhole is rather complicated (Fig. 1). At present, it is completely overgrown and turned into a peat-bog.

Eleven cores were drilled with a Russian corer to obtain information on the lithological composition of the sinkhole. A lithological cross-section (Fig. 2) and a biogenic sediment thickness scheme (Fig. 3) were drawn according to the coring data. They show the complexity of the basin bottom. It is evident from Fig. 3 that the Kirkilai sinkhole belongs to the composite type (Taminskas, 1999), *i.e.* comprises several (at least five) sinks.

The sediment cores Kirkilai-1, Kirkilai-2 and Kirkilai-3 were chosen for further analysis. Pollen samples (3 cm^3) were taken from every 5, 10 or 20 cm of a sediment (depending on to the significance of core interval) and prepared according to a standard technique: alkaline L. von Post's treatment, V. Grichiuk's separation with heavy liquids and G. Erdtman's acetolytic preparation (Kabailienė, 1979). For Kirkilai-1 32 pollen samples 14 for Kirkilai-2 and 43 samples for the Kirkilai-3 sequence were prepared and analyzed. At least 500 terrestrial pollen grains were counted in each sample (where possible).

The peat samples taken for ^{14}C dating were dried to the air-dry weight. For further treatment, 10–15 g of dry bulk mass were separated. The ^{14}C de-

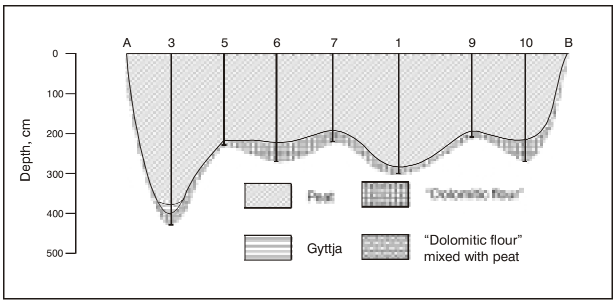

Fig. 2. Cross-section of sediments of Kirkilai karst sinkhole
2 pav. Kirkilų karstinės įgriuvos nuosėdų pjūvis

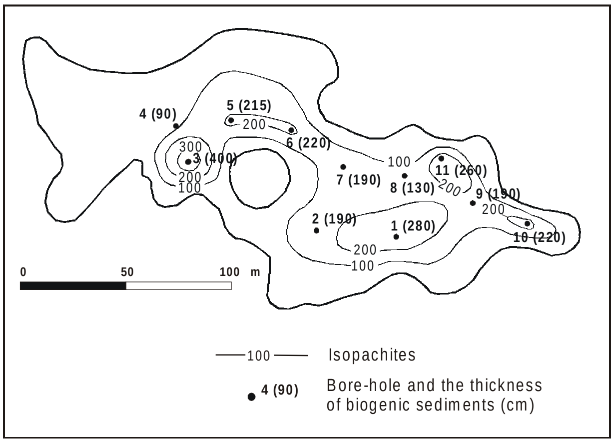

Fig. 3. Biogenic sediment thickness scheme
3 pav. Biogeninių nuosėdų storio schema

termination was based on the conventional liquid scintillation dating method described elsewhere (Skripkin, Kovalyukh, 1994).

The ^{14}C dating included a few stages: 1) initial physicochemical pretreatment of bulk organic material (cleaning from secondary carbon and carbon of contamination); 2) synthesis of measuring form (benzene) from the pretreated material; 3) preparation of the scintillation cocktail and determination of ^{14}C beta activity in a sample; 4) calculation of conventional ^{14}C age and its conversion to calendar age (calibration).

The initial physicochemical pretreatment of a sample was performed by the acid-base-acid method, which included a few phases of organic matter treatment: treatment of the sample material by 10% HCl at 100 °C, rinsing with distilled water, treatment with 2% NaOH in normal conditions, rinsing with distilled water, treatment with 2% NaOH at 80–90 °C, rinsing with distilled water, treatment with 3% HCl at 100 °C, rinsing with distilled water to pH 6, drying at 100 °C.

The benzene synthesis from bulk organic included the following phases: a peat sample pyrolysis to pure carbon, its treatment with metallic Li and extraction of Li_2C_2, hydrolysis of the latter and extraction of C_2H_2, trimerization of the latter and benzene (C_6H_6) extraction, benzene cleaning with metallic Na.

The measuring form was obtained by adding scintillation admixtures (PPO and POPOP) into the prepared benzene. The ^{14}C beta activity of the benzene was determined with a low level LSC 1220 Quantulus. The quality of measurements was ensured by participation in Fourth International Radiocarbon Intercomparison (FIRI). The derivation of laboratory results did not exceed 3% compared to the consensus values.

The ^{14}C age of a sample was converted into calendar age by the 2-D dispersion method of Cologne Radiocarbon Calibration & Palaeoclimate Research Package CALPAL_A and calibration curve CalPal2001 (Jöris and Weninger, 2000a; Jöris and Weninger, 2000b).

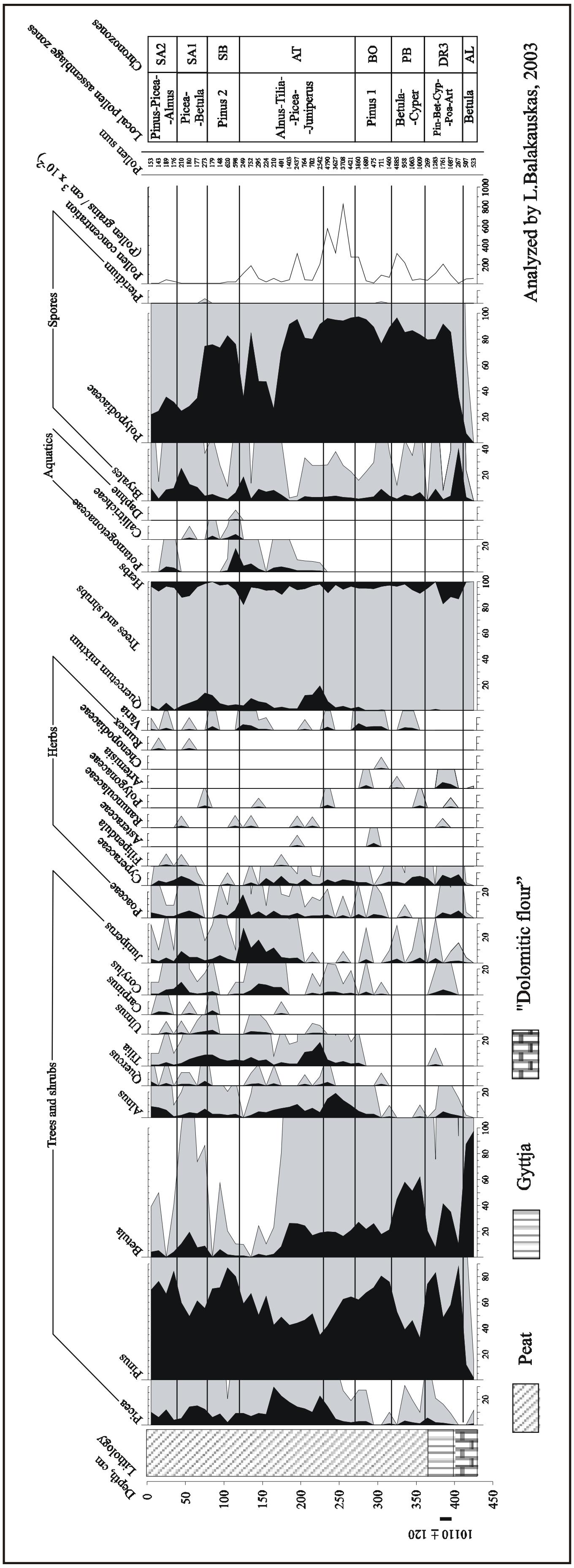

Fig. 4. Pollen diagram of the sediments from Kirkilai-3 borehole
4 pav. Kirkilų-3 gręžinio nuosėdų žiedadulkių diagrama

LOCAL POLLEN ASSEMBLAGE ZONES (LPAZ)

Pollen spectra in all diagrams correlate well despite some local differences, therefore, only the Kirkilai-3 (most complete) diagram is presented in this work (see Fig. 4). However, local pollen assemblage zones are described for all pollen sequences.

Kirkilai-1

LPAZ *Pinus*–*Betula*–Cyperaceae (300–295 cm). This zone covers only the lowermost sample corresponding to arctic-subarctic vegetation. *Pinus* and *Betula* are dominant (35.9 and 44.4% respectively). Herb pollen values, especially of Cyperaceae (9.5%) and Poaceae (2.8%), are relatively high at this depth.

LPAZ *Betula*–Poaceae (295–255 cm). *Betula* reaches its highest values (up to 71.4%), *Pinus* decreases down to 14.3%. Poaceae increase to 8.3% at the top of the zone, Cyperaceae percentages remain relatively high (up to 8.4%), also in the previous zone.

LPAZ *Pinus* 1 (255–215 cm). *Pinus* dominates (68.6–76.4%), while *Betula* decreases down to 8.4–22.5%. Herb pollen amounts fall to 2–4.8%. Small amounts of *Alnus*, *Tilia* and *Corylus* appear in the upper part of this zone.

LPAZ *Alnus*–*Tilia*–*Picea* (215–140 cm) is characterized by a distinct increase of *Picea* (up to 57.1%), *Alnus*, *Tilia*, *Corylus*, *Quercus*, *Ulmus* and a decrease of *Pinus* (down to 18.7–35.4%) pollen. Well pronounced increases of *Juniperus* (up to 11.2%), Poaceae (up to 9.3%) and Cyperaceae (13.9%) are apparent in the middle of the zone.

LPAZ *Pinus* 2 (140–100 cm). *Pinus* is dominant in this zone (53.1–60.2%), *Picea* remains significant (15.5–37.5%). *Betula*, *Alnus*, *Corylus* and deciduous tree pollen (excepting *Tilia*) are of reduced quantities. Herb pollen values are defined mainly by Poaceae (up to 11.4%).

LPAZ *Picea*–*Pinus* (100–0 cm). *Picea* (25–40.3%) and *Pinus* (35.9–43.4%) dominate. *Betula* pollen increases up to 15.8% in the middle of this zone, but declines again in the upper part. *Corylus* makes up to 10%, *Alnus* up to 5.1%, Cyperaceae to 4.4%. The Poaceae percentages fall down to 0.2–4.1%. It should be noted that pollen grains in two uppermost samples were badly corroded. Furthermore, much lower concentrations are characteristic of these samples.

Kirkilai-2

LPAZ *Tilia*–*Picea*–*Juniperus* (200–182 cm). *Pinus* dominates in this zone (23.04–39.9%), though its percentages are relatively low compared to other zones. Values of *Picea* (up to 29.2%), *Tilia* (up to 21.6%) and *Corylus* (up to 4.8%) are significant, especially at the onset of the zone. In the upper part, these values decline as the amounts of *Juniperus* (up to 28.4%) and *Alnus* (up to 16.2%) increase. Herb percentages, especially of Poaceae, Cyperaceae and Ranunculaceae, are relatively high. Bryales have its highest values here (80–92.1%).

LPAZ *Pinus*–*Alnus* (182–100 cm). *Pinus* (30.9–50.6%) and *Picea* (20.2–43.9%) prevail. *Alnus* pollen values increase up to 23.9% in the lower part of this zone. In the upper part *Alnus* is partly replaced by *Juniperus* (up to 17.6%). Herb pollen makes up to 5.5%. The amount of Bryales spores decreases, though remains significant (up to 45.3%). Polypodiaceae spore values increase up to 28.1%.

LPAZ *Pinus*–*Picea* (100–60 cm). *Pinus* (41.7–47.7%) and *Picea* (33.6–35.9%) are still the most abundant taxa, though *Alnus* and *Juniperus* are less significant. Herb percentages remain similar (up to 4.4%). Bryales increase up to 48.6%.

LPAZ *Pinus*–*Picea*–*Alnus* (60–0 cm). *Pinus* is predominant (58.5%). *Alnus* (up to 16.6%), *Juniperus* (13.4–18.8%) and *Betula* (up to 6.4%) increase. *Picea* falls down to 8.6% in the upper part, while herbs increase up to 5.7% at the same depth.

Kirkilai-3

LPAZ *Betula* (430–410 cm). *Betula* pollen prevails in this interval (87.5–97.3%), *Pinus* makes up to 11.8%. Only single grains of other pollen taxa were found. Bryales and Polypodiaceae spore values are up to 2.4 and 6.9%, respectively.

LPAZ *Pinus*–*Betula*–Cyperaceae–Poaceae–*Artemisia* (410–360 cm). *Pinus* (48.4–87.5%) and *Betula* (7.6–41.1%) dominates. Values of *Picea* (up to 5.6%), *Alnus* (4.8%), *Corylus* (up to 4%) and *Juniperus* (up to 3.5%) slightly increase. Herb pollen makes up to 17.3%. Poaceae (up to 5.4%), Cyperaceae (up to 8.1%) and *Artemisia* (up to 4.7%) are most abundant among the herbs. Bryales spore values increase up to 39.7% and Polypodiaceae up to 92%.

LPAZ *Betula*–Cyperaceae (360–320 cm). *Betula* (44.7–62%) and *Pinus* (32–52.4%) pollen still prevails in this zone. *Juniperus* (2.9%) and *Picea* (3.1%) are of moderate values. Cyperaceae (up to 7.3%) dominate among the herbs. Polypodiaceae spores make 83.6–96.7% and Bryales up to 8.7%.

LPAZ *Pinus* 1 (320–270 cm). *Pinus* pollen values are 62.2–80.4%, *Betula* 17.7–27%, *Alnus* up to 5.4%, *Picea* up to 2.7%, *Juniperus* up to 2.7%. Herb pollen percentages are relatively low: Poaceae up to 2.7%, Cyperaceae up to 2.8%, Asteraceae up to 2.7%. Bryales spores make up to 6.4% and Polypodiaceae 76.6–97.5%.

LPAZ *Alnus–Tilia–Picea–Juniperus* (270–120 cm). *Alnus* makes up to 19%, *Picea* up to 29.2%, *Pinus* 34.5–66.7%, *Betula* up to 26.3%. The percentages of deciduous trees (*Quercus* up to 2.4%, *Tilia* up to 18.2%, *Ulmus* up to 1.9%), *Corylus* (up to 8.9%) and *Juniperus* (up to 26.5%) pollen increase. Relatively high herb percentages are observed in this zone, especially in its top (Poaceae up to 17.7%, Cyperaceae up to 7.3%). Up to 6.3% of Potamogetonaceae pollen were found in this interval. Bryales make up to 18.4% and Polypodiaceae up to 96.6%.

LPAZ *Pinus* 2 (120–80 cm). *Pinus* (70.6–80%) is the dominating taxon in this zone. *Picea* makes 2–9%, *Betula* up to 5.7%, *Alnus* up to 3%, *Tilia* up to 8.8%, *Ulmus*, *Carpinus* and *Corylus* up to 2.9%. Herb pollen percentages are relatively low (up to 6.5%). Callitricheae pollen makes up to 3.9%. The amount of Bryales spores is up to 6.2% and Polypodiaceae 73.5–83%.

LPAZ *Picea–Betula* (80–40 cm). *Picea* pollen increases up to 5.1–14.7%, *Betula* up to 19.4%, *Juniperus* up to 9.1%. The values of *Tilia* reach 2–8.6%, *Corylus* makes up to 10.1%, Poaceae 5.5%, Cyperaceae 7.1%. The amount of Polypodiaceae spores decreases down to 24.5% and of Bryales down to 25%.

LPAZ *Pinus–Picea–Alnus* (40–0 cm). The values of *Pinus* pollen are up to 83.8%, *Picea* up to 11.9%, *Alnus* up to 8.8%. The percentages of herb pollen are 3.8–7.4%, *i.e.* lower than in the previous zone. Relatively high values of Potamogetonaceae (up to 3.8%) are observed here. Bryales reach up to 3.8% and Polypodiaceae 21.6 %–35.2%.

RADIOCARBON DATING

The ^{14}C data on the Kirkilai karst sinkhole are presented in Table including conventional and calibrated ages and are plotted in Fig. 5 in the context of palaeoclimatological proxy data. The time span covers almost all Holocene from 1820 BP at a core depth 93–103 cm (Kirkilai-2) to 10110 BP at a core depth 383–398 cm (Kirkilai-3).

Table. **Conventional radiocarbon dates of peat from Kirkilai karst sinkhole**
Lentelė. **Kirkilų karstinės įgriuvos durpių radioanglies amžiaus duomenys**

Laboratory	Core	Lithology	Core depth (cm)	^{14}C age yr BP ± 1σ	Calibrated age BP (0 = AD1950) at ± 1σ
VS-1292	Kirkilai-2	Peat	93–103	1878 ± 75	1820 ± 90
Vs-1295	Kirkilai-2	Peat	172–182	3591 ± 40	3900 ± 60
Vs-1363	Kirkilai-3	Peat	383–398	9023 ± 75	10110 ± 120

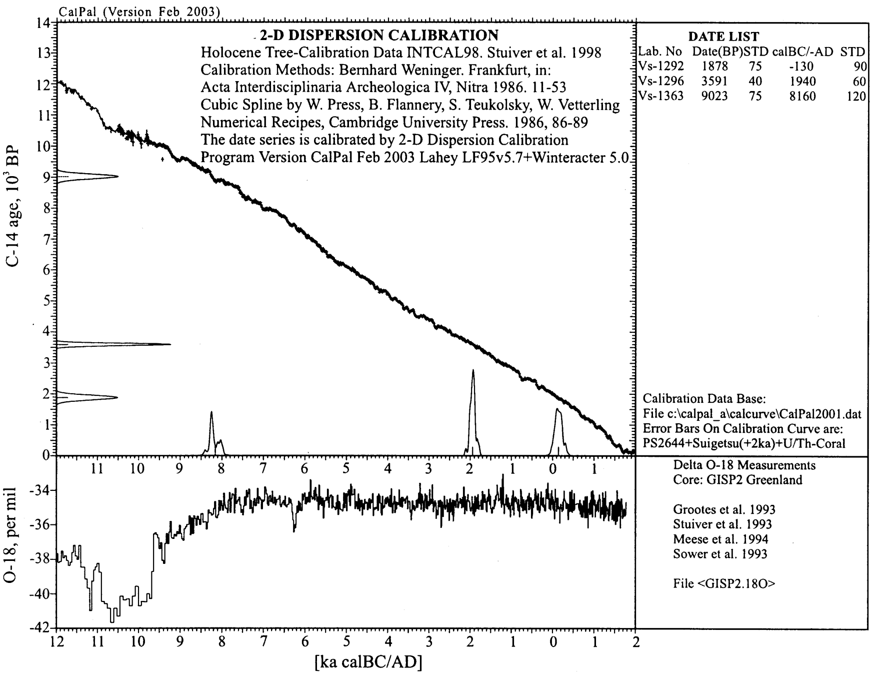

Fig. 5. Conventional and calibrated ^{14}C-ages plotted in graphic (temporal) context with palaeoclimate (^{18}O) proxy (Grootes et al., 1993; Stuiver et al., 1993; Meese et al., 1994; Sowers et al., 1993)
5 pav. Durpių mėginių nustatyto ^{14}C amžiaus ir kalibruoto (kalendorinio) ^{14}C amžiaus duomenys laiko kontekste su paleoklimatine izotopų (^{18}O) kreive (Grootes et al., 1993; Stuiver et al., 1993; Meese et al., 1994; Sowers et al., 1993)

CORRELATION OF LOCAL POLLEN ASSEMBLAGE ZONES AND INTERPRETATION

The low herb representation and the prevalence of *Betula* species in the pollen spectra of the basal LPAZ of the Kirkilai-3 core represent the Aleröd (AL) chronozone.

The following zone (*Pinus–Betula*–Cyperaceae–Poaceae–*Artemisia*) is characterized by an increase of herbs, indicating a more open landscape, showing a colder Younger Dryas (DR3) chronozone. However, pollen spectra are still dominated by tree pollen, which shows that forest was present at least in the surroundings of the sinkhole. Pollen stratigraphy is supported by radiocarbon dating: sediments at the middle of the pollen assemblage zone (383–398 cm) were accumulated 10110 ± 120 BP. A similar environment is present in the basal zone of the Kirkilai-1 pollen diagram (*Pinus*–*Betula*–Cyperaceae), which allows to relate it to the former (Fig. 6).

The Preboreal (PB) chronozone is represented by the *Betula*–Poaceae zone in the Kirkilai-1 sequence and the *Betula*–Cyperaceae zone in the Kirkilai-3 sequence. A dramatic increase in *Betula* shows forestation of the area by pioneer vegetation.

The *Pinus* 1 zones in both cores correspond to the Boreal (BO) chronozone. *Pinus* spreads again at this stage, followed by appearance of *Alnus*, *Corylus* and *Tilia*.

The Atlantic (AT) chronozone is represented in all three pollen diagrams. Expansion of *Picea*, *Alnus*, *Corylus* and deciduous trees in these zones shows warm climatic conditions in Lithuania during this stage (Kabailiene, 1990). A significant increase of *Juniperus*, Cyperaceae and Poaceae evidenced in the middle of the Atlantic, while the main tree species declined. These changes could be caused by early human activity in the area, still the evidence is not very strong.

Age, BP	Chronozones	Kirkilai-1	Kirkilai-2	Kirkilai-3
1000	Late Subatlantic (SA 2)	Picea-Pinus	Pinus-Picea-Alnus	Pinus-Picea-Alnus
2500	Early Subatlantic (SA 1)		Pinus-Picea	Picea-Betula
5000	Subboreal (SB)	Pinus 2	Pinus-Alnus	Pinus 2
7800	Atlantic (AT)	Alnus-Tilia-Picea	Tilia-Picea-Juniperus	Alnus-Tilia-Picea-Juniperus
9000	Boreal (BO)	Pinus 1		Pinus 1
10000	Preboreal (PB)	Betula-Poaceae		Betula-Cyperaceae
10900	Younger Dryas (DR 3)	Pinus-Betula-Cyperaceae		Pinus-Betula-Cyperaceae-Poaceae-Artemisia
	Allerӧd (AL)			Betula

Fig. 6. LPAZ correlation scheme
6 pav. VŽZ (vietinių žiedadulkių zonų) koreliacijos schema

The following LPAZ were correalated to the Subboreal (SB) chronozone. The values of deciduous trees, *Alnus* and *Corylus*, decrease and give up the prevalence to *Pinus,* showing a colder climate unfavourable for deciduous forests. Sediments of Subboreal chronozone in the Kirkilai-2 sequence (172–182 cm) were dated to 3900 ± 60 BP.

During the Subatlantic (SA), *Pinus* and *Picea* dominates, which is typical of the vegetation of Northern Lithuania (Kabailiene, 1990). Increase of *Betula*, *Alnus* and *Tilia* can be traced in this chronozone. The two former are probably related to the vegetation of the sinkhole immediate surroundings, while *Tilia* increase in the sediments of the Late Subatlantic (SA_2) is characteristic also of other pollen diagrams from the karst region of Norhern Lithuania (Kondratienė et al., 1998; Balakauskas, 2003), thus it can be considered as regional. The inrease of herbs during the Subatlantic shows a human impact, however, it is not very well pronounced. Probably despite an intensive forest cleaning in the region (Kabailiene, 1990), trees were present in the immediate vicinity of the peat-bog during all Subatlantic. Pollen stratigraphy in the Kirkilai-2 sequence is supported by radiocarbon dating (1820 ± 60 BP at 93–103 cm).

DISCUSSION

Formation of the sinkhole

The Kirkilai karst sinkhole was formed during the Alleröd warming. The primary shape of the sinkhole was significantly different from the present-day one. As pollen and radiocarbon analyzes show, the Kirkilai-2 site was not afffected by karst during the Alleröd. The sink was formed at this site at the end of the Atlantic chronozone as a separate sinkhole. Later it joined the basin of the Kirkilai karst sinkhole due to intensive erosion of its banks, which is typical after formation of sinkholes in Northern Lithuania (Narbutas, Pranaitis, 1960). According to the palaeoclimatic and water level change data (Kabailiene, 1999; Кабайлене, 2000) such time of formation seems very reasonable: the relatively warm climate and lower groundwater levels prevailed. These conditions favour the development of karst processes (Taminskas, 1999). Moreover, these statements are confirmed by previous pollen investigations in the region: 2 of the 4 karst sinkholes presented by Tiuremnov et al. (Тюремнов и др., 1959) and the Skrebiškiai karst sinkhole (Balakauskas, 2003) were formed also at the end of the Atlantic, thus half of the sinkholes analysed in Northern Lithuania appeared at approximately the same time.

Taminskas (1999) states that the majority of the sinkholes in Northern Lithuania are deep (up to 20–30 m) but had a small diameter (usually up to several meters) right after sinking. In the course of time, intensive abrasion evidences and a sinkhole becomes shallow and wide. Often "dolomitic flour" (karstic silt) accumulates as a result of abrasion. It seems that the Kirkilai sinkhole is a case of such formation. "Dolomitic flour" deposited at the bottom of the sinkhole shows a high erosion rate. It is evident from lithological, pollen and radiocarbon data presented above in this work that abrasion took place before the beginning of the Younger Dryas at Kirkilai-3. At the Kirkilai-1 coring site it continued longer – all over the Younger Dryas, probably because of differences in the shape of the sinks and the properties of the surrounding soil.

According to lithological data, peat started to accumulate upon the "dolomitic flour", which shows that the abrasion processes slowed down at this stage. Only in the bottommost depths peat is mixed with lacustrine sediments (gyttja). Therefore a lake existed in the sinkhole only during the Late Glacial. At the beginning of the Preboreal it started to overgrow, and a bog environment completely prevailed by the beginning of the Boreal.

Similar changes took place in the Kirkilai-2 sink. The sink formed during the Late Atlantic was filled with water approximately before the Atlantic–Subboreal transition. During the Subboreal and Subatlantic, peat accumulated there.

Vegetation in the vicinity of Kirkilai sinkhole during the Late Glacial and the Holocene

The pollen spectra in the Kirkilai sinkhole clearly represent patterns of regional forest history, though local bog vegetation was even of a greater significance. The evidence of human impact on vegetation is not very well pronounced. Nevertheless, it seems to have taken place during all Subatlantic and possibly in the end of the Atlantic chronozone, when pollen spectra show more open landscapes to prevail in the area. Such a change could trigger the higher erosion and thus activation of karst processes, which took place in the Late Atlantic according to the earlier investigations.

ACKNOWLEDGEMENTS

Authors are sincerely grateful to Prof. Habil. Dr. Meilutė Kabailienė and Dr. Vytautas Narbutas for valuable advice and remarks. Dr. A. Linčius and G. Bičkauskas aided a lot in the fieldworks.

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KIRKILŲ KARSTINIO DURPYNO (ŠIAURĖS LIETUVA) SUSIDARYMAS IR JO APYLINKIŲ PALEOEKOLOGINĖS SĄLYGOS VĖLYVUOJU LEDYNMEČIU IR HOLOCENE

S a n t r a u k a

Kirkilų karstinė įgriuva priklauso sudėtiniam tipui (susidarė susijungus keliems prasmegimams). Detaliu nuosėdų gręžimu, žiedadulkių bei radioanglies datavimu nustatyta, kad smegduobė susiformavo aleriodo atšilimo metu. Tai – anksčiausiai susidariusi datuota smegduobė, kurios tyrimai suteikė pirmuosius duomenis apie karstinius reiškinius vėlyvuoju ledynmečiu Šiaurės Lietuvos karstiniame regione. Prasmegimas smegduobės centrinėje dalyje atsirado gerokai vėliau nei likusioji smegduobė – atlančio pabaigoje, ir tik vėliau dėl krantų abrazijos susijungė su likusiąja dabartinės smegduobės dalimi.

Rajono ir apylinkių augaliją vėlyvuoju ledynmečiu bei holocene daugiausia nulėmė natūralūs veiksniai. Žmogaus poveikis pasireiškė tik subatlančio ir galbūt atlančio chronozonų metu.

Atlančio pabaigoje pastebimas karstinių procesų suaktyvėjimas, kurio viena iš priežasčių galėtų būti tuo metu vyravę atviri kraštovaizdžiai, sudarantys sąlygas erozijai.

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ФОРМИРОВАНИЕ КИРКИЛАЙСКОЙ КАРСТОВОЙ ВОРОНКИ (СЕВЕРНАЯ ЛИТВА) И ПАЛЕОЭКОЛОГИЯ ЕЕ ОКРЕСТНОСТЕЙ В ТЕЧЕНИЕ ПОЗДНЕЛЕДНИКОВЬЯ И ГОЛОЦЕНА

Р е з ю м е

Киркилайская карстовая воронка относится к составному типу (образована из нескольких соединенных между собой воронок). Детальное бурение, пыльцевой и радиоуглеродный анализ ее отложений показали, что воронка образовалась в течение аллеродового потепления. Это самая древняя из датированных воронок, изучение которой позволило впервые получить данные относительно позднеледниковых карстовых процессов в карстовом регионе Северной Литвы. Составная воронка в центральной части образовалась значительно позже, чем основная, – в позднеатлантический период, и только позже присоединилась из-за абразии их берегов.

Растительность в районе воронки и непосредственно рядом с ней в течение позднеледниковья и голоцена обусловливали природные факторы. Влияние человека проявилось только в субатлантический и, возможно, в атлантический периоды.

Значительная активизация карстовых процессов имела место в конце атлантического периода. Одной из причин этого мог стать более открытый ландшафт, способствующий развитию эрозии.