HABILITATION THESIS

Lake sediments and glacial cirques in the Romanian Carpathians and their climatic implications

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Abstract

The main focus of the candidate's research during the past decade (2006-2015) was the study of glacial relief and lacustrine sediments from the Romanian Carpathians. In the former field he introduced the detailed morphometric analysis of landforms, which resulted in the creation of a morphometric and morphographic database comprising all glacial cirques from the Romanian Carpathians (631 items); the database contains the names and unique codes for each cirque and information about each item, including data regarding glacial deposits. To date, this is the largest cirque database (in terms of the number of items) cited in the international literature. Whereas glacial features and landforms had been studied previously by Romanian researchers, the same cannot be said about the study of lacustrine sediments, where the candidate first introduced and developed the analysis of lake sediments (palaeolimnology) as a standalone topic in the Romanian school of geography. Throughout this period he published several relevant papers in this field and went on to create a working group (Cirques&Lakes: www.georeview/cirques&lakes) at the university where he is based which includes experienced scientists as well as young researchers (doctoral students) whose PhD theses were centered around palaeolimnological topics.

The structure of the present thesis is simple, yet logical and fluent. The first chapter, which illustrates the analysis of lakes and lacustrine sediments, highlights the most significant contributions of the candidate to the fields of limnology and palaeolimnology. Due to the number and extent of the latter, the analysis of lake sediments is regarded as the main topic of this thesis, therefore has been granted ample space. The purpose of sediment analysis was, mainly, to infer climatic variability throughout the Holocene (but not exclusively). Thus, the first part of the chapter presents some contributions to the problem of lake genesis in Romania, including the introduction of new types of lakes, such as gravity fault lakes and kettle hole lakes which formed as a result of late melting of moraine ice cores, ensued by a thorough analysis of glacial lakes from the Romanian Carpathians, the first since the study published by Pişota (1971). This section presents the glacial lake database containing data on each lake (the main morphometric parameters of lake basins), based on which the first digital map of the distribution of glacial lakes in the Romanian Carpathians was generated. The largest section of the first chapter (1.3) is dedicated to the contributions and innovations introduced and/or employed by the candidate in the fields of limnology and palaeolimnology in a chronological order: using maps and historical documents to the study of lakes; making, updating and interpreting bathymetric sketches employing modern techniques; using GPR to assess lake basin morphology and the volume and structure of lacustrine sediments and ERT to investigate sediments and glacial deposits; scanning techniques for sediment cores; the digital analysis of sediment structure and laminae; geochemical analysis; X-ray diffraction analysis; magnetic susceptibility of sediments; dendrochronological investigation of subfossil trunks embedded in lake sediments; sediment chronology (C^{14}, ^{137}Cs, ^{210}Pb, OSL), assessing sedimentation rates in lake basins.

The following sections present the anthropogenic impact on lakes and lacustrine sediments due to improper or illegal works/management, the assessment of post-industrial atmospheric pollution and the long-term human impact inferred from sediment analyses. To a large extent, this array of analyses were performed in order to evaluate climatic variability throughout the Holocene; therefore, the closing sections focus on the most significant contributions to this topic, i.e. studies carried out in all 42 sites (lakes and peat bogs) investigated to date in Romania by the candidate and other research teams. To this effect, the last section comprises of a summary of inferred climatic changes between 26,000 and 550 cal y BP at reviewed sites from Romania. Overall, the contributions of the candidate can be regarded as a starting point for the field of palaeolimnology in Romania, and his research will continue through interdisciplinary studies carried out by research teams.

The second chapter introduces the contributions of the candidate to the morphometric analysis of glacial cirques from the Romanian Carpathians, further inferring climatic information from morphometric traits. Results derived from the detailed statistical analysis of a comprehensive database of glacial cirques are presented briefly. The sections of this chapter present the main findings regarding the distribution of cirques (including controls); the geology, shape, size and evolution of glacial cirques (cirque allometry); cirque grade, elevation, aspect etc. Furthermore, all morphometric parameters were subjected to processing and interpretation in order to find answers regarding palaeoclimate and the evolution of glaciation in the Romanian Carpathians, thus providing valuable new contributions concerning the glaciation level (during glacial phases) and deglaciation level (during the late Pleistocene) in the RC, as well as the direction of prevailing winds during glaciation (glacial blizzard). The latter was instrumental in the formation, evolution and present distribution of glacial cirques. Moreover, the candidate introduced the allometric analysis in order to decipher the phases undergone by cirque shape. Due to these achievements all the glacial cirques from the Romanian Carpathians are now part of a large database which can substantiate further comparative or/and interdisciplinary studies. The candidate envisages that he will extend the database and carry out similar studies in other glaciated mountain areas from this part of Europe, i.e. the Ukrainian Carpathians (Ukraine) and Rila and Pirin Mts (in Bulgaria) where suck data is lacking to date.

The two main research directions presented in the thesis can be regarded as complementary in the sense that they can be linked/correlated, and thus form the basis for the third chapter, which presents the perspective plan of the candidate. The underlying idea to this plan is to achieve a continuous chronology of climatic events and changes throughout the late Pleistocene and Holocene derived from linking lake sediments and glacial landforms located at neighboring sites. The most suitable areas for such studies are glacial cirques comprising lakes, which are precisely many of the sites described and investigated in the first two chapters. The closing section of chapter 3 illustrates the earliest preliminary results for this comprehensive type of research.

The professional activity of the candidate is presented in a rather brief manner in the last chapter, whereby the international visibility of the candidate as well as his abilities as an organizer for scientific events (workshops, conferences) and activity with various prestigious international organizations stand out. Other highlights of the candidate’s career include his activity within the Erasmus educational program throughout the past 16 years comprising a significant number of teaching and training missions at several well-respected universities in Europe.

Rezumat

Cercetarea reliefului glaciar și a sedimentelor lacustre din Carpații Românești au reprezentat principalele direcții de cercetare ale candidatului pe parcursul ultimului deceniu (2006-2015). În cazul reliefului glaciar acesta a introdus analiza geomorfometrică detaliată a formelor de relief ca metoda de investigare, realizând astfel o baza de date morfometrice și morfografice cuprinzând informații detaliate (nomenclatorul circurilor glaciare - un cod unic, și o serie de date specifice, inclusiv cele legate de depozitele glaciare) privind toate circurile din Carpații Romanești, in numar de 631. Aceasta reprezintă cea mai mare baza de date (ca număr) privind circurile glaciare citată în literature de specialitate la nivel mondial. Daca în cazul reliefului glaciar au existat preocupări mai vechi printre geografii români, în ceea ce privește studiul sedimentelor lacustre candidatul a avut un aport substanțial în introducerea și aplicarea metodelor de analiză a sedimentelor lacustre (paleolimnologie) în școala geografică din România. În acest interval a publicat o serie de articole importante în acest domeniu și a creat un grup de lucru (Circuri&Lacuri: www.georeview/cirques&lakes) la universitatea la care activează, din care fac parte cercetatori cu experiență, dar și doctoranzi ale căror teme de cercetare provin din domeniul paleolimnologiei.

Structura tezei de față este una simplă, dar logica și fluenta. Capitolul privind studiul lacurilor și analiza sedimentelor lacustre din Carpații Românești prezintă cele mai importante contribuții ale candidatului în domeniul limnologiei și paleolimnologiei. Avand în vedere numărul și relevanta acestora, analiza sedimentelor lacustre poate fi privită ca subiectul central al tezei de față, motiv pentru care i s-a acordat un spațiu amplu. Principalul obiectiv urmărit atunci când s-au realizat diverse analize asupra sedimentelor lacustre a fost descifrarea variabilității climatice de-a lungul Holocenului (dar nu exclusiv). Astfel, capitolul debuteaza cu câteva contribuții ale candidatului la problema clasificarii genetice a lacurilor din România prin introducerea unor tipuri de lacuri noi (de ex., lacurile formate în faliile de gravitație, sau cele de tip *kettle hole* - formate în urma topirii târzii a sâmburilor de gheață din depozitele morenaice) și continuă cu o analiză atentă a tuturor lacurilor glaciare din cuprinsul Carpaților Românești, prima de acest fel de la lucrarea lui Pișota (1971). Baza de date realizată de către candidat cuprinde nomenclatorul lacurilor glaciare și datele aferente pentru fiecare lac (principalii parametri morfometrici ai cuvetelor lacustre - altitudine, suprafață, adâncime, substrat etc), constituind fundamentul pentru realizarea primei hărți digitale a repartiției lacurilor glaciare din Carpații Românești. Corpul principal al acestui capitol (sectiunea 1.3) prezintă în ordine cronologică contribuțiile și inovațiile introduse și/sau aplicate de către candidat în cercetarea limnologică și paleolimnologică: utilizarea materialelor cartografice și a documentelor istorice pentru studiul lacurilor; realizarea schițelor batimetrice prin tehnici moderne și interpretarea lor; utilizarea radarului pentru evaluarea morfometriei cuvetelor și a volumului și structurii sedimentelor; tomografii bazate pe rezistivitatea electrică pentru evaluarea sedimentelor lacustre și a depozitelor glaciare; metode de scanare a carotelor de sediment; analiza digitală a structurii și laminațiilor

sedimentelor; analiza geochimică a sedimentelor; analiza prin difracție de raze X; analize de susceptibilitatea magnetică; analiza dendrocoronologică a trunchiurilor de arbori subfosili prelevate din sedimentele lacustre; cronologia sedimentelor lacustre (C^{14}, ^{137}Cs, ^{210}Pb, OSL) precum și calcularea ratelor de sedimentare din lacuri.

Următoarele secțiuni abordează impactul unor lucrări de amenajare improprii sau ilegale asupra lacurilor și sedimentelor acestora, evaluarea poluării atmosferice post-industriale și a impactul antropic pe termen lung determinat pe baza analizei sedimentelor lacustre. În mare măsură, analizele menționate au avut ca scop principal evalua variabilității climatice pe parcursul Holocenului; prin urmare, ultimele secțiuni ale capitolului prezinta rezultatele studiilor efectuate in toate cele 42 de situri (lacuri și turbării) investigate până în prezent în România, inclusiv de către candidat, cât și un sumar al schimbărilor climatice determinate pe baza acestor studii între 26,000 and 550 cal y BP în siturile menționate. Ca notă generală, contribuțiile candidatului la acest domeniu pot fi privite ca un punct de start pentru paleolimnologia din Romania, acestea continuând și în perspectivă prin investigații interdisciplinare realizate în cadrul unor echipe de cercetare.

Cel de-al doilea capitol prezintă contribuțiile candidatului la analiza morfometrică a circurilor glaciare din Carpații Romanesti, cu privire specială asupra informațiilor climatice care derivă din aceasta. Sunt prezentate succint rezultatele obținute în urma analizelor statistice detaliate asupra bazei de date complete a circurilor glaciare din România. În această parte sunt aduse în discuție cele mai relevante rezultate privind repartiția circurilor glaciare (inclusiv factorii de control); geologia, mărimea, forma, evoluția (alometria circurilor); gradul de dezvoltare, altitudinea și orientarea circurilor. Analiza nu s-a mărginit însa la descrierea parametrilor morfometrici, aceștia constituind ulterior baza pentru studii privind paleoclimatul și evoluția glaciației din Carpații Românești, rezultand astfel date noi despre nivelul altitudinal de glaciație (din timpul fazelor glaciare) și deglaciație (de la sfârșitul Pleistocenului) din Carpații Românești, precum și informații privind direcția vântului dominant din timpul glaciației (*viscolul glaciar*), acesta din urma avand un rol determinant pentru formarea și evoluția circurilor, și pentru repartiția actuala a acestora. De asemenea, candidatul a utilizat pentru prima data analiza alometrică pentru a decripta fazele prin care trece forma circurilor. Ca urmare a acestor contributii, Carpații Românești dețin in prezent un inventar complet al circurilor glaciare care poate fundamenta o varietate de studii comparative și/sau interdiciplinare. Candidatul intentioneaza extinderea acestei baze de date a circurilor glaciare și în alte arii montane glaciate din Europa, precum cele din Carpații Ucrainei si Munții Rila și Pirin (din Bulgaria), în care astfel de rezultate lipsesc.

Cele două direcții principale de cercetare pot fi considerate complementare, în sensul că permit conexiuni/corelari, constituind astfel baza pentru cel de-al treilea capitol, respectiv planul de perspectivă al candidatului. Ideea care stă la baza acestui plan este obținerea unei cronologii continue a evenimentelor și schimbărilor climatice care au caracterizat Pleistocenul Târziu și Holocenul din analiza combinată a sedimentelor lacustre și depozitelor glaciare din situri proxime. Zonele cele mai potrivite pentru astfel de studii sunt circurile glaciare clasice cu lacuri, respectiv o bună parte dintre siturile descrise și investigate în primele două capitole. În acest sens, la finalul capitolului sunt prezentate și primele rezultate preliminarii pentru acest tip de cercetare propus de candidat.

Activitatea profesională este tratată succinct și la obiect în ultimul capitol, accentul fiind pus pe vizibilitatea internațională a candidatului, dar și pe abilitățile sale de organizator de întalniri cu caracter științific (workshopuri și conferințe) și pe activitatea sa în cadrul unor organizații internaționale de prestigiu. Un alt aspect demn de mentionat îl reprezintă activitatea sa neîntrerupta în cadrul programului educațional Erasmus de peste 16 ani, cu activități de predare și formare la universități recunoscute din Europa.

Chapter 1

Lake sediments, assessment of human impact and climate reconstruction

1.1 Romanian lakes

This section is envisaged as a foray into the limnological inventory of Romania and introduces the main categories of lakes and the research carried out in palaeolimnology. Our personal contributions to the knowledge and classification of Romanian lakes, and mountain lakes, in particular, will be highlighted as we present the advances made in this field.

Rationale

Romania is a middle-sized European country whose territory comprises of a large variety of landforms, ranging from litoral to alpine glacial relief. Accordingly, the Romanian territory is endowed with an equally diverse range of lakes located in all major landforms (lowlands, hills and mountains). While during the mid-twentieth century the total estimated number of lakes was 3450 (of which 1150 anthropogenic, 27%) amounting to 2600 sq km total water body area, in 2010 it had augmented to 3650 (of which 2147 man-made, 59%) amounting to 4620 sq km (Gâștescu, 2010). This overall increase resulted from the multiplication of man-made lakes which attempted to compensate for the extinction of natural water bodies, mainly by draining and interfering with the natural evolution of most lakes located in the Danube Delta.

As regards the classification of Romanian lakes according to genetic typology, the RSR Atlas (1972-1979) lists *11 types of natural lakes* – i.e. floodplain and deltaic lakes; fluvial lakes; fluvio-marine limans and lagoons; dune lakes; loess lakes; natural dam lakes; karst lakes in salt; karst lakes in limestone; karst lakes in gypsum; volcanic crater lakes; nivation lakes; lakes formed on structural benches (many of which are in fact accommodated by gravitational faults resulting from RSFs); and glacial lakes; and *6 types of man-made lakes* classified depending on their use, as fish farms; multiple purpose lakes (hydropower and water supply); bent lakes; salt mine lakes; temporary lakes employed for flood control (polder-type); and ponds.

Romanian lakes are, to a vast extent, small-sized (with the notable exception of Razim-Sinoe lagoon complex) and shallow, such that the total amount of water contained in lakes accounts for a rather insignificant share of the total volume of water resources available countrywide. Furthermore, with such low lacustrine water resources, Romania ranks among the last countries in Europe in terms of the total available freshwater resources, and this situation is expected to sharpen in the foreseeable future as the demand for water supply steadily increases. Under these circumstances becomes apparent the importance of large reservoirs built during the socialist era which were able to provide freshwater for household consumption and industries, as well as for hydropower production.

Genetic classification of lakes

As regards the genesis of natural lakes, the range of genetic processes may be classified according to three major types of erosion/accumulation, i.e. *glacial, fluvial and maritime*; and an additional type of passive genetic process - dissolution of soluble rocks (limestone, dolomite, gypsum, salt etc.). Another type of naturally-occuring lake consists of natural dam lakes arising from landsliding processes which are typical for highland landform evolution in Romania. However, the vast majority of lakes came into existence as a result of fluvial activity, as was the case with the 800 lakes located in the Danube floodplain and delta alone, according to the assessment made prior to the great drainage projects (Gâștescu, 2010), followed by glacial lakes.

In contrast, the least number of lakes pertains to the crater genetic type, consisting solely of two items, lake Sfânta Ana and Mohoş peatbog, both of which are located close by in the volcanic Harghita Mts. This situation is somewhat paradoxic as the Romanian Carpathians enfold the longest volcanic range in Europe; the explanation could reside in the advanced aging of these volcanoes which resulted in the destruction of typical volcanic structures (craters, throat etc.).

Hence, while lakes in Romania are relatively diverse in terms of genetic typology, they are not as numerous or as large as may be expected; moreover, some categories are represented by a very small number of lakes (e.g., volcanic crater lakes), whereas other types are completely absent from the Romanian territory (such as tectonic lakes).

The two main genetic types mentioned previously are largely distributed in relation to major landforms as follows: fluvial lakes in the lowlands (plains) and glacial lakes in the highlands (alpine areas).

Among fluvial lakes the most prominent are the ones located within the Danube floodplain and deltaic area; however, lakes formed along inland rivers are also quite common, as is the case with numerous lacustrine bodies accomodated by the floodplains of rivers such as Siret, Prut, Olt, Jiu, Argeş, Dîmboviţa, Ialomiţa, Buzău etc. A remarkable category comprises fluvial and maritime limans located on the secondary valleys of rivers from the Romanian Plain (e.g., lake Amara) or along the Black Sea coastline (e.g., lake Techirghiol). The latter are accompanied by coastal lagoons which formed as a result of barrier islands separating pre-existing gulfs from the sea (e.g., Razim-Sinoe complex).

Glacial basins are among the most significant geomorphological features inherited from glaciation, which were later filled with water subsequent to the glaciers' retreat. Despite the fact that the Romanian Carpathians were exposed to glaciation only during the Late Pleistocene, glaciers were very effective in shaping glacial cirques - no less than 631 (Mindrescu, 2006), glacial valleys and rock basins. Curently, glacial lakes and glacial peatbogs amount to 270 items. Glacial lake distribution is uneven throughout the Romanian Carpathians, with the majority located in the Transylvanian Alps (Southern Carpathians) in massifs exceeding 2200 a.s.l. in the western sector and 2400 a.s.l. in the eastern sector, whereas a small number are found in the northern area of the Eastern Romanian Carpathians (Rodna and Maramureş Mts). Of the 270 lakes inventoried in the RC, 65 are peatbogs (Fig. 1.1.1a), including 9 peatbogs with pool (Fig. 1.1.1b), whereas the majority are minor shallow open lakes (114, see Fig. 1.1.1c) ranging under 1 m in depth. The remaining 91 are open lacustrine bodies with depths above 1 m, ranking as follows: 44 range from 1 to 2 m in depth, 25 between 2 and 5 m, while the maximum lake depth exceeds 5 m in just 32 cases. The latter category, known as major lakes (Fig. 1.1.1d) are regarded as the most suitable for conducting palaeolimnological investigations, particularly those located within some distance from the cirque headwall. It should be noted that the vast majority of glacial lakes in Romania are cirque lakes, and only a small fraction (i.e. 11 items) formed and persisted within glacier valleys; as a rule, glacial valley lakes are mostly small and undergoing rapid silting.


a. Peat bog, Bardăul Mare, Maramures Mts


b. Peat bog with pool, Gropile lake, Rodna Mts


c. Minor (shallow) lake, Bila lake, Rodna Mts


d. Major glacial lake, Podragu lake, Făgăraş Mts

Fig. 1.1.1. Typology of glacial lakes from Romania.

However, regardless of size and scientific value, most of these lakes are part of spectacular landscapes, albeit they are commonly rather small (the largest, lake Bucura, barely extends over 10 ha) and shallow (Zănoaga, the deepest, is 29 m deep) compared to glacial lakes from the Polish Tatra Mts, whereby largest lakes are Wielki Staw Polski (80.3 m depth and 35.8 ha area) and Morskie Oko (51.8 m depth and 32 ha area) (Pociask-Karteczka et al., 2014). The only common trait with the Tatras or the Pyrinees is that the vast majority of glacial lakes have formed on granite substrates (Mîndrescu, 2006).

A very distinctive class of lakes consists of natural dam lakes formed as a result of landsliding processes manifesting throughout the Romanian territory. Due to an ensemble of geomorphic factors which include the friable rock substrate, the temperate continental excessive climate and the relatively intense seismic activity (originating mainly in the Carpathian Curvature area) etc., landslides are a common occurrence countrywide.

Most landslide-dammed lakes are located in the outer Carpathian hills and plateaus, such as the Transylvanian Depression or Buzău Subcarpathians (Porumbenii Mari, Manta) and are usually small ephemeral lacustrine bodies. However, albeit fewer in number, landslide-dammed lakes formed in the higher Carpathian uplands (particularly in the flysch range) have considerably longer lifespans. Lacu Roşu (Red Lake) located in Hăghimaş Mts is perhaps the most famous and prised as a tourist attraction among this category; according to documentary sorces, the lake appeared in June 1837 subsequent to heavy rainfall which triggered massive landsliding and dammed Bicaz stream valley leading to the onset of lake formation (Bojoi, 1968). However, the toponym *Lacu Roşu* stream (Verestyo Patak - Red Lake) has been documented earlier on in the Austrian maps from the 17th century (Ungureanu, 2004). Therefore, in the absence of accurate determinations based on absolute dating techniques to date, the exact age of this lake remains to be established.

Such lakes are frequent in the middle elevation flysch mountain range (but not exclusively), some of which are rather impressive in terms of size and depth. The largest landslide-dammed lake is Cuejdel in Stânişoarei Mts, Eastern Carpathians - 2.2 ha area and 16 m maximum depth, which came into existence after the stream valley was completely obstructed in 1991 (Rădoane, 2002).

As a general trait, landslide-dammed lakes have short lifespans and can thus be investigated for assessing solely short-term (i.e. under 200 years) environmental conditions soil erosion; to illustrate, Lacu Roşu (Bicaz catchment in Hăghimaş Mts) formed in 1837 (age 178 yrs), Bălătău-Nemira lake (on Izvoru Negru stream, Nemira Mts) in 1883 (age 132 yrs), Betiş lake (on Novăţ stream in Maramureş Mts) in 1957 (currently depleted), Cuejdel lake (also known as Crucii lake, Stânişoarei Mts) in 1991 (Mîndrescu et al., 2010a).

However, during recent years new landslide-dammed lakes came to light and were subjected to investigations regarding their ages based on absolute dating techniques. The oldest documented landlside-dammed lakes in Romania with stable water bodies (ranging above 4 m in depth) are the ones located in Obcina Feredeului flysch mountains in the Northern Romanian Carpathians, i.e. Iezer-Feredeu lake, 1035 yrs BP, (Mîndrescu et al., 2013) and Bolătău-Feredeu lake, approx. 6000 yrs BP (Mîndrescu et al., 2015, submitted). In the same area an additional lake of similar origin was recently discovered which appears to be equally old, based on preliminary observations on the length of the sediment profile collected, but has not been dated thus far, i.e. Paşcanul. These 3 lakes form an entity which was termed as the ‚*Bukovina millenial lake triangle*'.

20.85% of the Romanian territory consists of limestone and other types of rocks suitable for karst or clastokarst formation, of which limestones and dolomites account for 2%. Naturally, this substrate is conducive of cave formation, but also, to a lesser extent, of karst and pseudokarst lake occurrence. The karst category includes lakes formed on limestone (such as Ighiu, in Apuseni Mts and Zăton, in Mehedinți Plateau), salt (Ursu and Ocna Şugatag lakes etc.) or gypsum (such as lakes Învârtita and Nucuşoara), whereas most pseudokarst lakes formed on loess deposits which are particularly abundant in the Romanian Plain in SE Romania. A subtype of lakes which are less referred to in the limnological literature are lacustrine bodies hosted by flat or quasi-horizontal surfaces in the Moldavian Plateau on limestone-cemented sandstones or oolitic limestone (as is the case of the water-filled sinkhole in Ruginoasa, Iaşi county).

A special mention goes to the so-called *nival lakes*, whose origin is often debatable or misinterpreted. In general, a variety of lakes from the middle to high elevation mountain ranges were ranked into this category, particularly those located on high plateaus or slow summits. However, to date it has become common knowledge that nivation is unable to produce such basins by itself. Snow falling in open areas is easily relocated elsewhere, and for nivation to occur it is necessary that snow accumulate in pre-existing concavities of mountains plateaus or gently sloping summits. Most often these include concavities resulting from superficial landsliding or rock slope failures, generically known as sackungs. The term was coined by Zischinsky (1966, 1969) and promoted by McCalpin and Irvine, 1995. In Romania the terms employed were 'scochine' (Niculescu, 1965) in Godeanu Mts (albeit their genesis was quite erroneously thought to reside exclusively in nivation), or gravitation faults in Rodna Mts (Sîrcu, 1978) and correctly assimilated to sackungs. In fact, Sîrcu (1962) has earlier on outlined the role of landsliding in mountain morphological evolution, including in the formation of lake basins. Thus, according to more recent assessments (Mîndrescu and Cristea, 2011), several subtypes of lakes resulting from gravitational faults (*deep-seated gravitational slope deformations*, formerly known as *sackungen*) may be distinguished: (1) *slope pocket lakes*, formed by gravitational slope deformation (translational sliding and gravitational sagging: sag and creep), located on midslopes, elongated in shape, small-sized and superficial, such as the typical slope pockets from Corongiş area, Rodna Mts (Fig. 1.1.2a); (2) *saddle collapse lakes*, resulting from saddle collapse soon after deglaciation as a likely response to localised glacio-isostatic rebound stresses, have slighly elongated ellipsoidal shapes, but due to wind exposure they tend to become circular in time, as is the case with La Tău lake, located between Putredu and Bila glacial valleys in Rodna Mts (Fig. 1.1.2b); (3) *plateau collapse lakes*, emerging from upland plateau collapse over large areas, also as a response to localised glacio-isostatic rebound stresses or local thawing permafrost, such as lake Vinderel from Maramureş Mts, which is a typical example of old lacustrine basin (Fig. 1.1.2c); (4) *summit deformation lakes* occurring due to linear gravitational deformations of round-shaped summits from middle elevation mountain ranges, which solely affect superficial deposits. However, some of these lakes are rather old as they emerged soon after deglaciation, and as a general rule are quite ubiquitous in the mountain areas above 1600 m a.s.l. Tăul Băiţa on Pietrosu summit in Maramureş Mts is among the oldest summit lakes (Fig. 1.1.2d). A particular class of concavities includes rock basins which occur mainly in glacial areas and lack water bodies (i.e. the gravitation faults from Gărgălău, Rodna Mts - Fig. 1.1.2e). Overall, sackung lakes are diverse and frequent in the Romanian Carpathian upland landscape; in many instances, they can be regarded as evidence of morphoclimatic changes occurring in this region (i.e. shifting from cold periods to wet ones, or from wet to dry conditions etc.). As sackung lake catchments are commonly small, they are likely to have long lifespans; some of them are converted to peatbogs, which are fertile grounds for vegetation history investigations (e.g., Băiţa and Vinderel 2 in Maramureş Mts) or tree-ring fossil trunk studies (Vinderel 3, Árvai et al., 2014).

a. Slope pocket lake (Corongiș, Rodna Mts)

b. Saddle collapse lake (La Tău, Rodna Mts)

c. Plateau collapse lake (Vinderel , Maramureș Mts)

d. Summit deformation lake (Băița, Maramureș Mts)

e. Gravitational fault (Găgălău Mts., Rodna Mts)

f. Kettle hole lake (Hârdăul, Rodna Mts)

Fig. 1.1.2. Gravitational fault lakes (a, b, c, d), gravitational fault (e) and kettle hole lake (f).

Older classifications overlooked at least one type of lake; albeit few in number, kettle hole (or pothole/*crațiță*) lakes should be mentioned as part of the varied population of lakes from Romania. They are shallow sediment-filled water bodies formed by retreating glaciers or draining floodwaters. The only two lakes pertaining to this type are located in Rodna Mts within the lateral moraines of Bistricioara cirque, of which just one (Hârdău lake, Fig. 1.1.2f) has a permanent water body.

To conclude, fluvial lakes are the most widespread water bodies within the Romanian territory, dominating floodplains and river mouth areas in the lowlands, accompanied by fluvial and maritime limans and lagoons located in the same elevation range. The next most numerous group of lakes includes glacial lakes occupying the alpine domain, especially in the Transylvanian Alps, often accompanied by sackung lakes which emerge in both glaciated environments (whereby the basins are carved in the in situ rock) and non-glaciated areas (mainly in superficial deposits).

Our future research endeavors will include a database of all lakes located in the Romanian Carpathians which will comprise of both morphometric (depth, elevation, size, water volume) and qualitative variables (origin, geology, relevance for palaeolimnological and palaeoecological research). The first step to building this first inventory of all natural and man-made lakes from the high elevation area of Romania was creating the database of glacial lakes from the Romanian Carpathians which has been completed to date.

1. 2 Glacial lakes

The study of glacial lakes was one of the main research topics on which we focused throughout our activity. Whereas initially we were mainly interested in surveying individual glacial lakes or small groups located in particular glaciated areas and analyzing various limnological and geomorphological parameters, recently we have undertaken a more complex type of study which comprises the entire population of glacial lakes from Romania, including open lakes (i.e. superficial lakes: depth under 1 m, and deep lakes: depth above 1 m), peat bogs with pool, e.g., Gropile in Rodna Mts, and peatbogs, such as Muntinu in Parâng Mts, distributed across 12 mountain regions (Table 1.2.1 and Fig. 1.2.1) and grouped in 6 limnological regions (Țarcu, Godeanu and Retezat; Parâng and Șureanu; Lotru and Cândrel; Făgăraș and Iezer Păpușa; Rodna; Maramureș). Over 263 glacial basins (lakes and peatbogs) were identified in the Romanian Carpathians, the majority of which were also mentioned by Pișota (1968, 1971).

Table 1.2.1. Distribution and basic characteristics of glacial lakes from the 12 mountain regions of the Romanian Carpathians

No	Mountain range	No of items	Minimum elevation, m	Maximum elevation, m	Maximum depth, m	Total
1	Maramureș	6	1543	1670	2	7
2	Rodna	39	1540	2010	5,7	42
3	Siriu	2	1416	1458	2	3
4	Iezer-Păpușa	1	2130	2130	9	1
5	Făgăraș	62	1660	2297	18,7	64
6	Cindrel	4	1955	1998	13,3	4
7	Lotru	3	1945	2115	1	3
8	Parâng	39	1555	2155	17,6	39
9	Șureanu	3	1730	1880	7,55	3
10	Retezat	62	1718	2210	29	62
11	Godeanu	29	1675	2055	3	29
12	Țarcu	13	1540	1975	6,5	13
	TOTAL	**263**	**1700,58**	**1996,08**	**9,61**	**270**

Whereas glacial lakes are distributed between 1416 m and 2297 m a.s.l. in terms of elevation range (with an average of 1967 m), the majority are located between 1790 and 2145 m a.s.l. (180 lakes). The lacustrine site located at the highest elevation in the Romanian Carpathians is lake Scoica in Făgăraș Mts. The mean surface area of a glacial lake is just above 0.5 hectares (0.55-0.6 ha). Overall, the surface area ranges from just 0.01 to 9 ha (i.e. Bucura lake in Retezat Mts). Most glacial lakes from the Romanian Carpathians are also rather superficial, 90% of which have depths below 5 m.

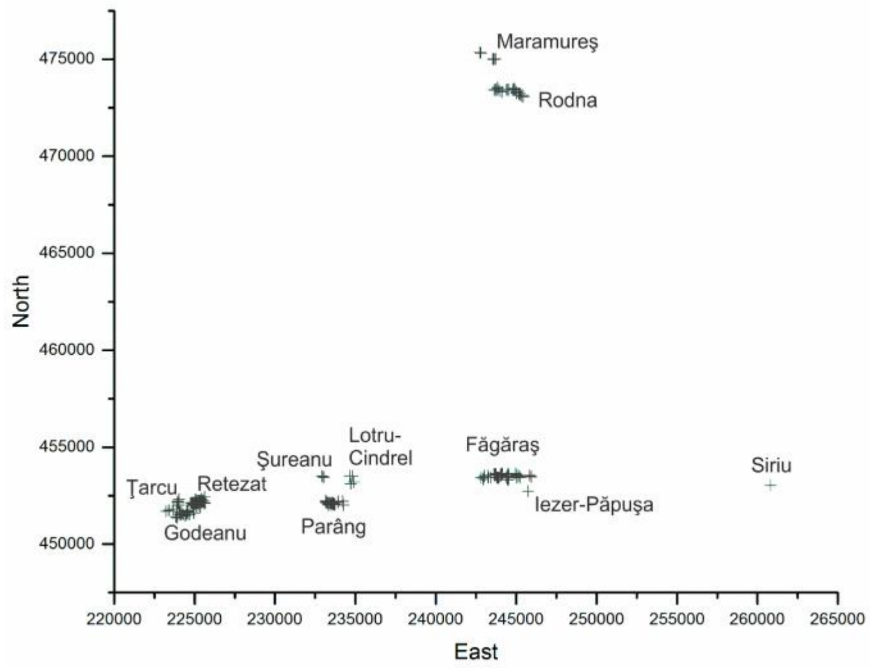
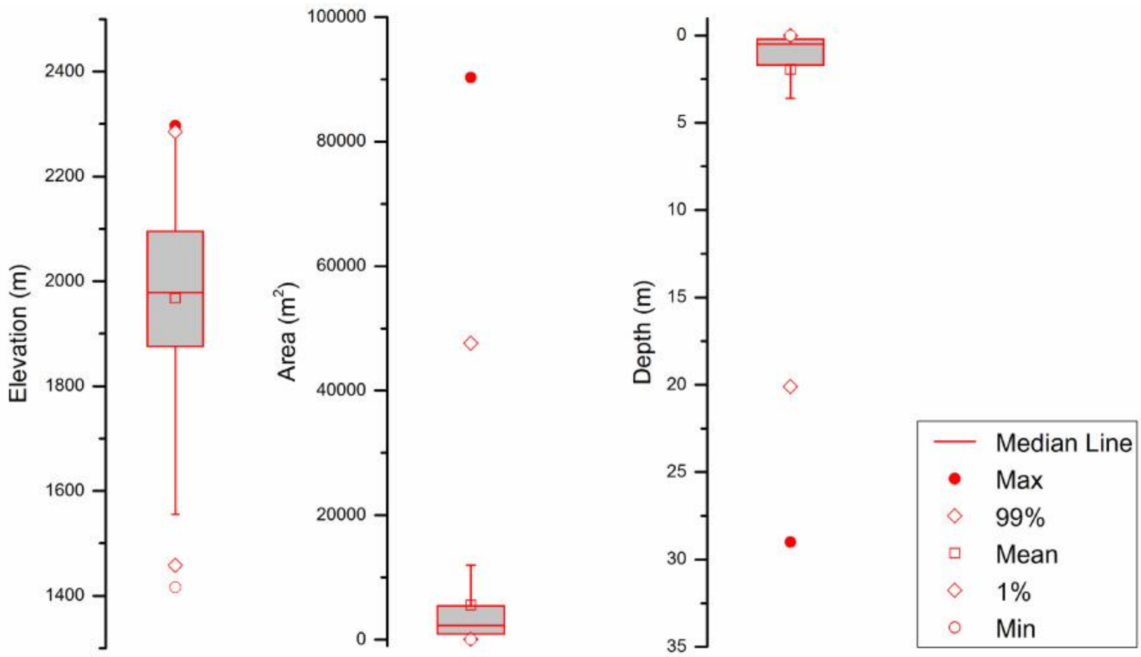


Fig. 1.2.1. Distribution of glacial lakes throughout the Romanian Carpathians.

While the mean lake depth is just 1.95 m, the profound glacial lake, Zănoaga from Retezat Mts, reaches 29 m in depth. In summary, glacial lakes from the RC are commonly small (under 1 ha) and shallow (seldom above 3 m in depth) lacustrine bodies concentrated to a large extent between 1900 and 2100 m a.s.l. (Fig. 1.2.2).

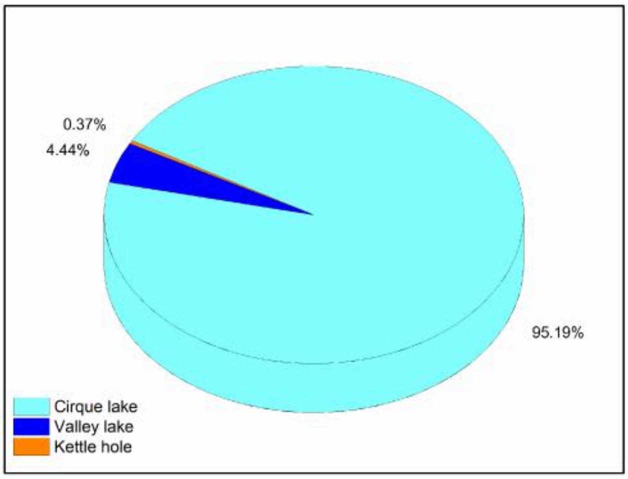


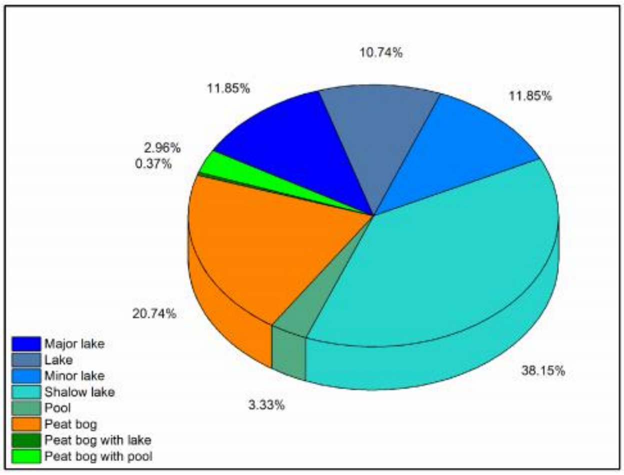
	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Altitude	270.00	1967.70	177.46	1416.00	1978.50	2297.00
Depth	270.00	1.96	3.96	0.00	0.50	29.00
Lake area	270.00	5539.83	10038.75	40.40	2328.05	90254.00

Fig. 1.2.2. Descriptive statistics of elevation, area and depth for Romanian glacial lakes.

The variables extracted from our database were further paralleled to the data regarding glacial lakes from the Polish Carpathians, as well as Rila and Pirin Mts in Bulgaria. Of the 47 glacial lakes mapped in the Tatras (the Polish side), Wielki Staw Polski and Morskie Oko are both the largest (i.e. 35.8 and 32 ha, respectively), and the deepest (80.3 and 51.8 m) among the lake population. However, ca. half of the lakes have depths below 3 m, similar to glacial lakes from Romania. In Bulgaria 254 glacial lakes were inventorized, of which Okoto, from Rila Mts is the deepest (37.5 m) and Popovo 2 from Pirin Mts is the largest (12.36 ha).

The vast majority of glacial lakes from the Romanian Carpathians are cirque lakes (ca. 95%). Just 12 items are glacial valley lakes, of which the best known are Iezerul latoriței (Parâng Mts), Lia and Tăul dintre Brazi (Retezat Mts) and Soarbele (Godeanu Mts). These lakes are usually small-sized and rank as valley lakes due to their position within the glacial valleys. Aside from these, a particular genetic type occurs among Romanian glacial lakes, i.e. the kettle hole lake, as is the case with Hârdăul lake which formed into a large lateral moraine pertaining to the Bistricioara Mare cirque in Rodna Mts (Fig. 1.1.2f).





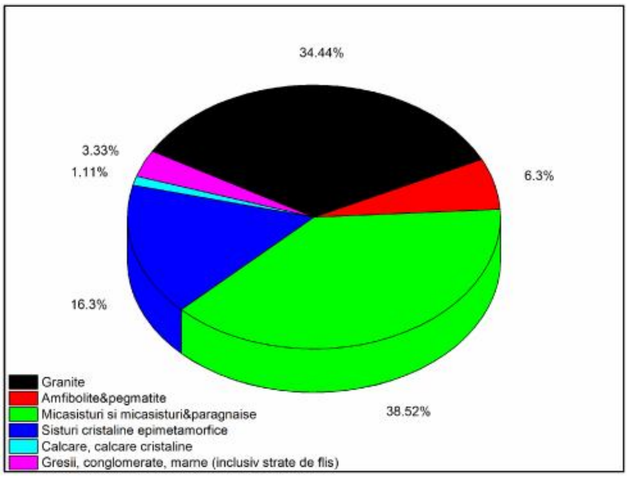


Fig. 1.2.3. Tipology, classification and geology of glacial lakes from the Romanian Carpathians.

The population of glacial lakes from the Romanian Carpathians comprises to the largest extent of open lakes (over 75%); the remaining ones are peatbogs (20%) and peatbogs with pool (3.5%). Furthermore, just 12% rank as major lakes (i.e. above 5 m in depth and containing significant water volume, Fig. 1.2.3). Among these, the largest are Podragu Mare, Capra, Bâlea, Călțun (Făgăraș Mts), Izerul Mare (Cindrel Mts), Roșiile Câlcescu (Parâng Mts), Galeș, Bucura, Ana, Tăul Negru, Zănoaga, Zănoaga Mică I (Retezat Mts). As regards the geology of the lacustrine sites, nearly 90% of all lakes formed on metamorphic rocks and granite. Moreover, the largest glacial lake basins formed on granite, which exhibit a predisposition towards the formation of rock basins during glaciation, but even more so during deglaciation. Consequently, considering the aforementioned variables and distributions, the largest, as well as most numerous glacial lakes are located in Retezat Mts (Fig. 1.2.4).

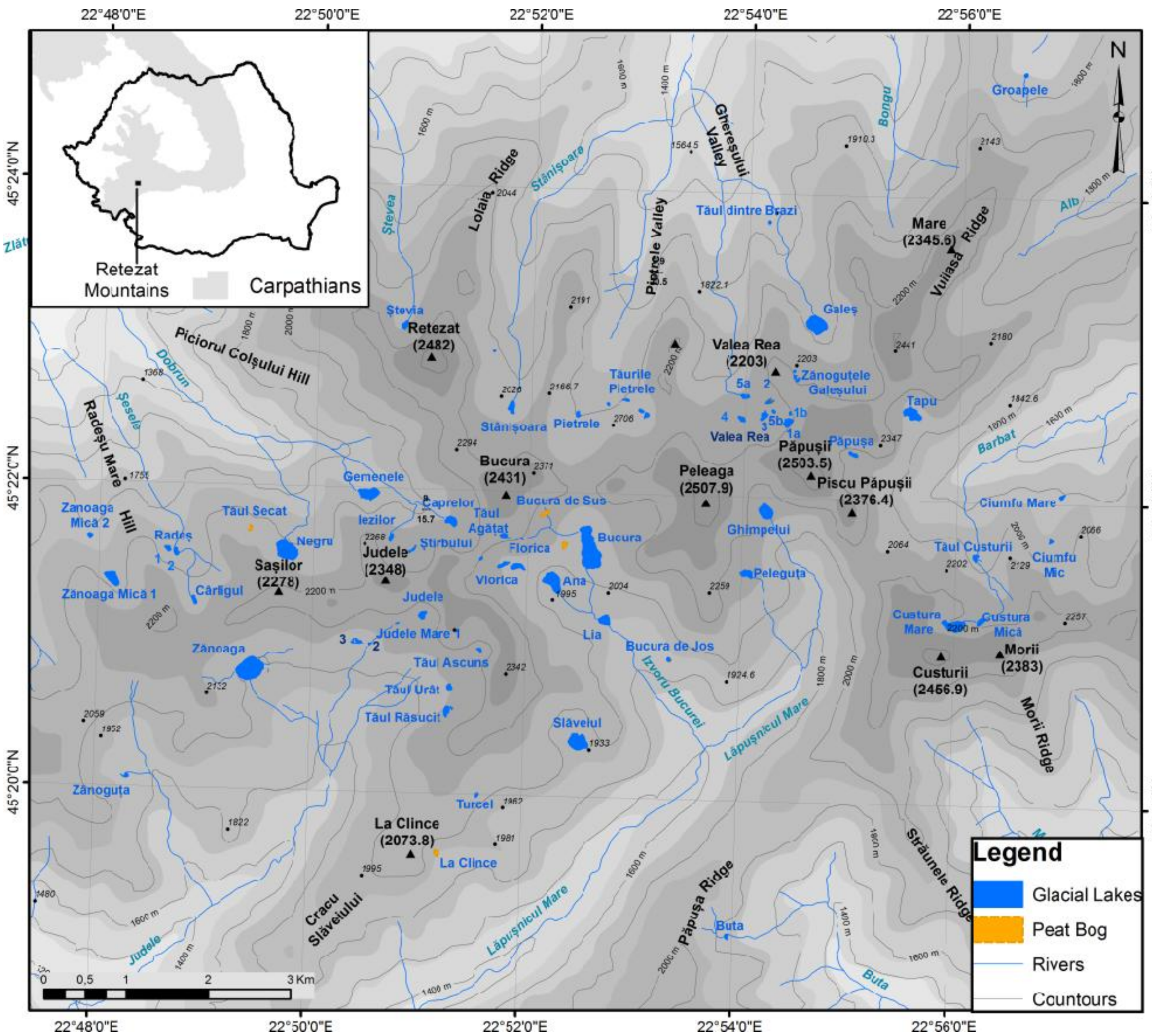


Fig. 1.2.4. Mapping glacial lakes from Retezat Mts, Southern Romanian Carpathians.

To conclude, glacial lakes from the Romanian (Fig. 1.2.5) are smaller-sized (in terms of surface area and water depth) compared to similar lakes from the Polish Carpathians, and Rila and Pirin Mts (Bulgaria). As regards the elevation range whereby glacial lakes are found, the average altitude of Romanian lacustrine sites is approx. 300 m higher compared to their Polish counteparts (average elevation = 1650 m a.s.l.), and approx. 300 lower than glacial lakes from the Bulgarian montains (average elevation for Rila and Pirin Mts = 2330 m a.s.l.). Furthermore, while Romanian lakes are more spatially compact than Polish lakes, they are in turn more scattered compared to Bulgarian lakes in terms of altitude.

Glacial lakes from the Romanian Carpathians are relics of the Quaternary glaciation and are regarded as valuable environmental archives due to the long duration of lacustrine sediment deposition in these environments which can help decipher climatic variability throughout the Late Pleistocene and Holocene.

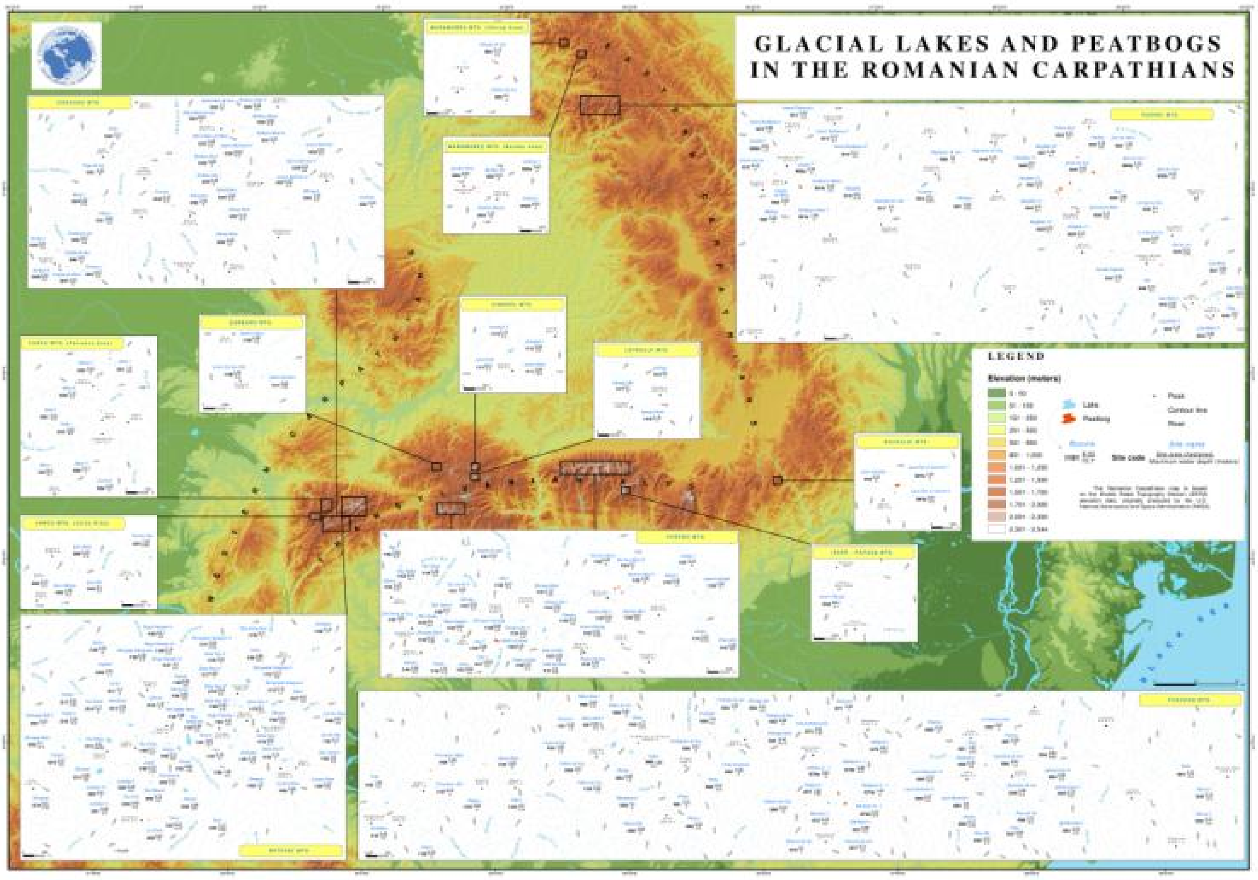


Fig. 1.2.5. Map of glacial lakes and peatbogs from the Romanian Carpathians. Available online at: http://atlas.usv.ro/geoconcept/webcarpath2/index.html.

Based on this study and the underlying data we intend to build a comprehensive database containing spatial and qualitative information on the entire population of glacial lakes from the Carpathians, Rila and Pirin Mts (Slovakia, Poland, Ukraine, Romania and Bulgaria) where each lake will be assigned a unique identification code similar to the glacial cirque inventory (Mîndrescu, 2006), which will further allow for data and image processing, statistics etc. applied on all glacial lakes from this region.

1.3 Advances in limnological and palaeolimnological research

This section introduces briefly some of the methods and techniques we have tried and applied in limnological and palaeolimnological studies in Romania. Some of these approaches are novel and have brought significant contributions to the knowledge of lakes and the analysis of lacustrine sediments. First and foremost, our research was oriented towards interdisciplinarity and multidisciplinarity in the study of lakes and lacustrine sediments, for which we have perpetually sought and utilized new data from various sources pertaining to diverse fields of study, as shown in the following subsections.

Historical background

Limnological research had a rather late start in Romania whereby the earliest attempts at approaching this field occurred before World War II. After WWII a number of significant synthetic studies were published focusing mainly on lake genesis, hydrological regime and morphometric characteristics (Pișota, 1971; Gâștescu, 1971; Breier, 1976 etc). The vast majority of studies published onwards were individual, concerning one (most often) or several lakes located close by. Later on, after the large reservoirs were built and sediments accumulated in these man-made water bodies, they became investigation objects for assessing sedimentation rates and sediment budgets (Rădoane and Rădoane, 2005). In recent decades, sediment yield and erosion and accumulation rates began to be studied in natural lakes, as well, based on new dating methods (as was the case with a large number of lakes: Lacu Roșu, Sfânta Ana, Știol, Buhăiescu Mare, Capra, Tăul Negru, Științii, etc.).

The earliest investigation on lacustrine sediments in Romania was carried out by de Martonne and Munteanu-Murgoci (1900) at lake Cîlcescu in Parâng Mts (Southern Carpathians) whereby the nature and apparent characteristics of the sediment core were observed. Unfortunately, during the following century these early attempts at establishing lake sediment analysis as a topic of study in Romania were not ensued by similar efforts until recent times. Only in the past two decades did research in field of lacustrine sediment analysis resume timidly and was performed mainly by biologists who focused to a considerable degree on vegetation history and study topics such as changes in vegetation structure and composition, treeline dynamics, land use changes, evolution of fire activity etc. Such approaches were prevalent in the lacustrine sediment research conducted in the aforementioned timeframe in Romania and have produced valuable data which could be employed for further assessments of climate and environmental changes. Further on, researchers turned their attention to subjects such as calculating precise sedimentation rates (particularly for the last 200 years) based on absolute age data acquired from radiocarbon dating and radioactive isotope dating (^{210}Pb, ^{137}Cs) or determining recent pollution history. During recent years more complex investigations have been undertaken focusing on multi-proxy approaches (geochemistry, biological proxies). Results yielded by various geochemical and physical analyses produced data on the nature, origin and transfer of sediments comprised in lacustrine archives which are dependent on a number of variables intimately connected to geomorphology (relief, geology, catchment size, site elevation, regional climate and extreme events etc.).

The current stage of palaelimnological and limnological research is marked by interdisciplinary efforts focused on the study of lakes and lacustrine sediments (CBW 2011; IGCB 2012; CBW 2014); the main approaches include a wide array of sediment geochemistry analyses, various types of biological proxies from sedimentary profiles in order to reconstruct the climatic and environmental changes but also to acquire data regarding sediment yields and sedimentation rates in Romania.

Cartographic records and lake studies

Introduction

The usefulness of cartographic resources for palaeolimnological research will be discussed in the following subsection. Cartographic sources such as old maps can provide a diversity of historical data about various elements within the landscape, such as water bodies and land use / cover of catchments. This method was employed in an interdisciplinary study regarding the evolution of two landslide-dammed lakes, i.e. Iezer – Feredeu and Bolătău – Feredeu, which were recently discovered in the flysch mountain area of Bucovina in the Northern Romanian Carpathians, and were subsequently sampled for lacustrine sediment investigations (Mîndrescu et al., 2013). In order to document the evolution of the two sites based on cartographic sources, we used the maps of Bucovina (historical region) made during the Austro-Hungarian rule which were devised mainly for military use, and thus contained valuable cadastral data. The first set of maps made for Bucovina during the late 18th century were on a scale (1:28,800) which was suitable for detailed representations of numerous elements of the landscape and contained a large density of toponyms. During the early 19th century, the reforms regarding tax collection made under Francis I were followed by more accurate triangulations, which were the base for a new set of larger scale cadastral maps (1:2,880). Both sets of maps provided important information regarding the existence of the lakes during the 18th and 19th centuries (Table 1.3.1).

Table 1.3.1. Maps of Bucovina made during the Austro-Hungarian rule (1778-1880).

No	Map name	Date of print	Scale	Section
1	Plans des Bukowiner Districts, 72 Sections	1778	1:28 800	XLIX
2	Topographische Bukowiner Kreis-Carte, 55 Sections	1790	1:28 800	134
3	Franziszeische Urmappe	1854-1856	1:2 880	Sadowa sheet
4	Specialkarte der k.u.k. Österreichisch-Ungarischen Monarchie im Maßstab	1880	1:75 000	12 XXXIII

Cartographic records and lake basin survey and evolution in Obcina Feredeului

The earliest detailed cartography referring to Bucovina, probably printed in 1778, was made by engineers of the Habsburg Imperial Army at a scale of 1:28,800 and is referred to as the

Plans of the Bukowina District (Plans des Bukowiner Districts). However, these did not contain any mention of lakes in Obcina Feredeului.

This omission may be attributed to the haste with which these surveys were carried out during 1773-1775 in a territory which, at that time, did not politically belong to the Habsburg Empire. However, Iezer Lake can be distinguished on the cadastral map (the Topographische Bukowiner Kreis-Carte), made at the same scale and printed in 1790. This lake also appears in the Austrian cartographic documents of the following century, for example the 1850s 1:28,800 scale cadastral map and the 1880s 1:75,000 scale topographic map. Romanian maps show only Iezer Lake on the polychrome 1:50,000 topographic map (1973 edition), but both lakes are represented on the 1:25,000 polychrome map (1985 edition).

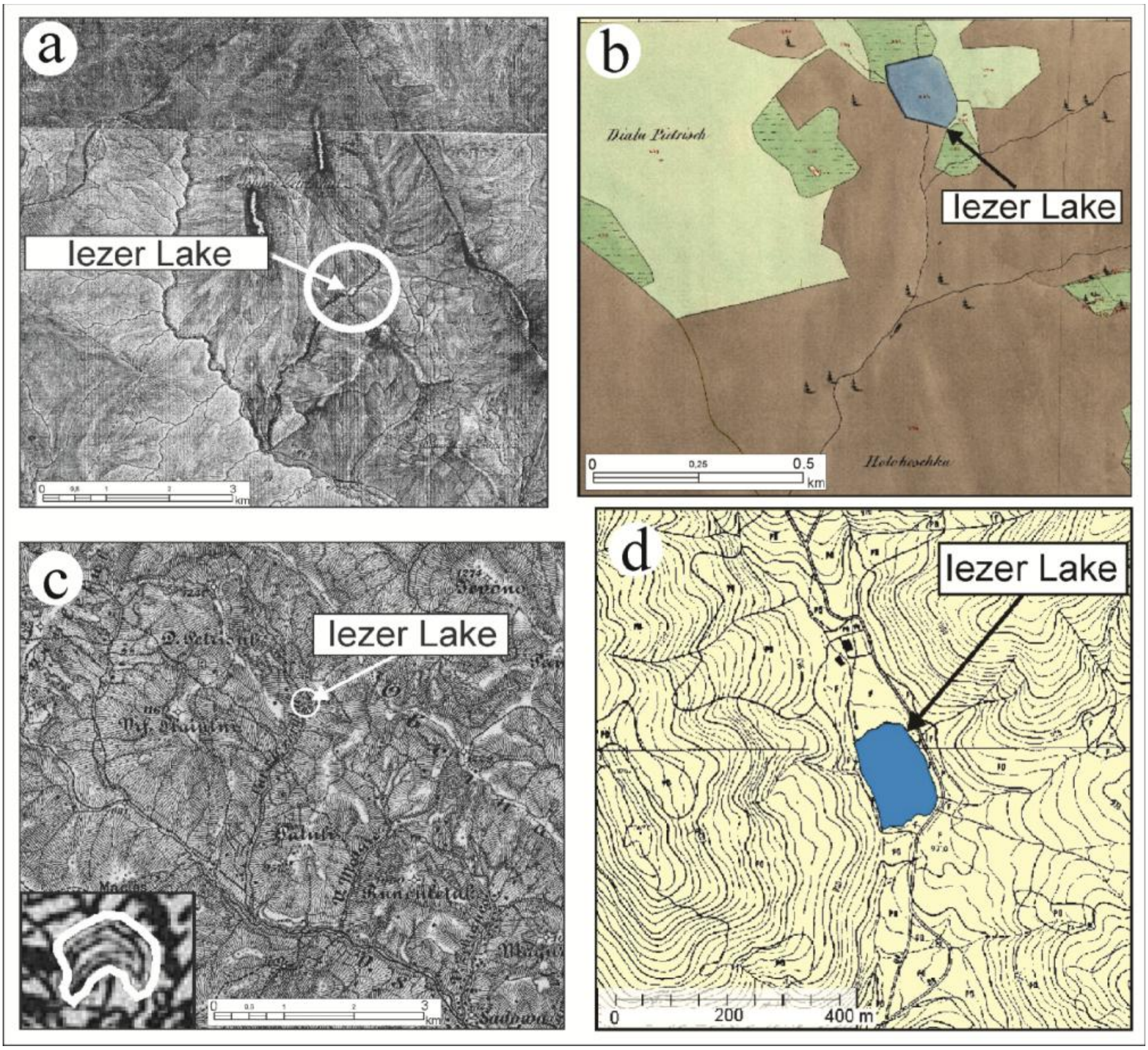


Fig. 1.3.1. Location of Iezer Lake according to old maps. a. The approximate location of Iezer Lake on the Austrian cadastral map of 1790 (Topographische Bukowiner Kreis-Carte, 1:28,800, 1790); b. Position and dimensions of Iezer Lake (section no. 134) on the Austrian cadastral map (Sadova sheet) of 1856 (Franziszeische Urmappe e Sadowa, 1:2,880, 1856); c. Location and shape of Iezer Lake on the Austrian map of 1880. Insert: note the hook-like shape of the lake (Specialkarte der k.u.k. Österreichisch-Ungarischen Monarchie im Maßstab 1:75,000 der Natur, 1880); d. Iezer Lake on the Romanian topographic plan of 1981-1982 (Planul topografic românesc, 1:5,000, 1981e1982).

The first map with the approximate location of the Iezer Lake in 1790 showed an uncertain area (Fig. 1.3.1a). In 1856 the lake was shown as roughly rectangular shaped with an area of 2.13 ha (Fig. 1.3.1b), but by the 1880s it had become smaller and hook-shaped with an area of 1.10 ha (Fig. 1.3.1c). This marked change in form may be the result of the input of material (such as a debris cone) into the lake from the landslide area that originally formed the lake. In the 1930s the Iezer lake appears to have again increased its surface area to 2.5 ha and has a regular shape (Oficiul Județean de Turism, 1935). However, by the 1960s is described as small (less than 2 ha) and partly silted (Georgescu and Georgescu, 1964). A significant recent change occurred in 1965 when the lake was drained to allow the construction of a dam wall across its outflow, and subsequently the outflow was controlled. This increased the surface area of the lake to approximately 2 ha (Decei, 1981). By the early 1980s, the lake's surface area slightly decreased to 1.8 ha (Fig. 1.3.1d). Currently, the lake is rapidly silting and has decreased to its smallest size since its formation (0.75 ha), more than half of which is covered by marsh vegetation composed by a mixture of sedges, grasses, and mosses (Fig. 1.3.3). The dam wall is now degraded and the overflow mechanism is inoperative. Consequently the lake is returning to the hookshape of the 1880s.

For Bolătău Lake, both cartographic and historical references information are limited and it first appears on Romanian topographic plans only in the 1980s. As a relatively small and more isolated lake, it is less likely to have been mapped (especially at the mapping scales used in older surveys) and, given its location within a relatively remote, forested area, it is unlikely to have became a local landmark and consequently to have been recorded in historical documents. However, it was further established that lake Bolătău is considerably older than Iezer at an age of approx. 6ka (Mîndrescu et al., 2015, submitted). To date, this is the oldest documented landslide-dammed lake in Romania which still has a well-individualized water body.

Conclusions

Our studies, as well as other sources, indicate that all the regions surveyed and mapped by Austrian topographers can successfully be investigated for historical data regarding the location and evolution of lakes in terms of size and land cover of the catchment.

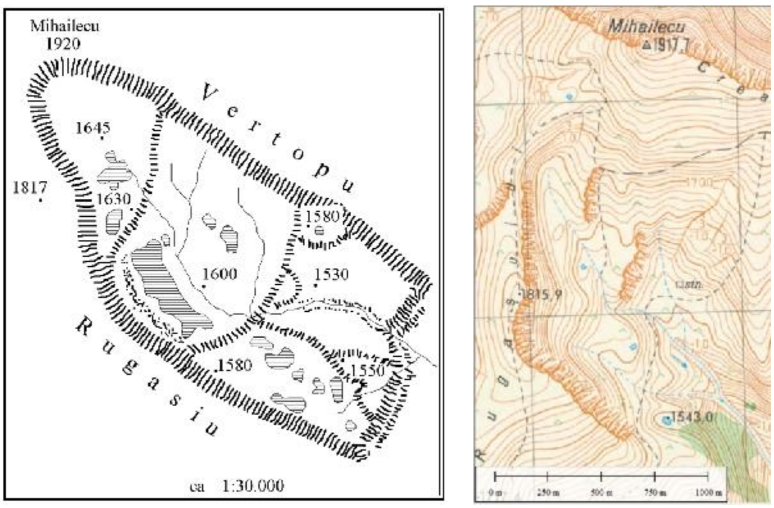


Fig. 1.3.2. Vârtop glacial cirque. Distribution and size of lakes in 1910 (after Sawicki, 1910) and 1984 (topo survey).

Furthermore, old maps can provide relevant information on the number of lakes from a certain territory at a given time. Such an example is illustrated for the lakes located in Vârtop glacial cirque from Farcău-Mihailecu massif in the Maramureş Mts (Fig. 1.3.2).

Historical records and lakes

Introduction

This subsection attempts to establish the importance of historical documents from the state archives or already published in the literature regarding the study of lakes in Romania for scientific investigations in limnology and particularly palaeolimnology. In order to evaluate the age of lakes and the likely human impact on lacustrine landscapes, historical documents, mainly estate registers, were also used in our research. Estate boundaries were typically established based on elements of the local topography and other elements of the landscape, such as rivers, lakes and springs. Due to an enduring monastic life in Romania, several monasteries were built and endowed with land properties in the surrounding areas (Documente privind Istoria României, 1952). In this context, historical documents, such as monastery registers or other historical sources may prove to be valuable for environment, climate and human impact reconstruction in Romania during the last five centuries.

The historical age of Iezerul Sadovei lake (Obcinele Bucovinei)

The oldest historical document in which Iezer lake is mentioned is dated 12th July 1594 during the reign of Aron Vodă (Table 1.3.2). This document states that the Magura Mountain had been offered as a gift to the monastery by Aron's father (Alexandru Lăpușneanu, who ruled between 1552-1561 AD and 1564-1568 AD), where the lake is referred to as part of the boundary of the estate. Subsequently, Izvorul Iezerului stream and indirectly the homonymous lake (i.e., Iezer) are mentioned in another document dated 16th August 1762 (Ștefanelli, 1915). According to the documentary evidence, it may therefore be considered that Iezer lake was unequivocally formed prior to 1594 AD.

Bolătău lake is first mentioned as Bolătău Dairy (most likely a glade with a temporary shelter for shepherds, an abode or stockyard) in 1806 AD (Ștefanelli, 1915). However, according to another historical document dated May 21st 1737 AD (Ștefanelli, 1915), Bolătău lake is conceivably older (Table 1.3.2), which is in accordance with new investigations on the age of lacustrine sediments (Mîndrescu et al., 2015, submitted).

Table 1.3.2. Historical documentation of the Iezer and Bolătău lakes (Bucovina, Romania)

Lake	Date of document	Original text in Romanian/Translated in English
Iezer	12 June 1594	„Io Aron voevod, [...] domn al ţării Moldovei. Am dat şi am întărit [...] sfintei mânăstiri din Homor [...] un munte care se chiamă Măgura, cu toate poenile şi izvoarele, care sunt împrejurul lui, care [...] este danie sfintei mânăstiri din Homor dela răposatul părintele domniei mele, Alexandru voevod [...]. Iar hotarul acelui munte mai înainte numit, care se chiamă Măgura, cu toate poenile şi izvoarele, începând dela Iazer merge până la Feredeu şi de aici tot la deal Obcina [...] iarăşi până la Iazer [...]" (Documente privind Istoria României/D.I.R., 1952, p.112).

		"I, voivode Aron (…), lord of the Moldavia country. I gave and made lawful (…) to the holy monastery of Homor (…) a mountain called Măgura with all the glades and springs surrounding it, which (…) is beneficence to the holy monastery of Homor from the late lamented father of my lordship, voivode Alexandru. (…) and the bounds of the mountain previously mentioned, which is called Măgura, with all the glades and springs, starting from Iezer and going to Feredeu, and from here straight uphill the Obcina (…) and again to Iezer (…)." (Documente privind Istoria României, 1952, 112 p.).
Bolătău	21 May 1737	"au mărturisit (doi călugări bătrâni de cca. 70 de ani- n.n.) c'au ţinut cu adeat acel munte a mănăsterii anume Măgura cât ţine de la eazer (lacul Iezer- n.n.) până în Feredeu şi din Feredeu în Prislopu Secului şi opcina cea mare în gios până la fântână şi la alt ezer şi pe piciorul lui Păliean până la prag şi din prag dealul alăture cu Neagra până în gura Negrei până în Moldova şi Moldova în sus până în gura Breazi şi Breaza până la ezer..." (21 mai 1737) (Ştefanelli, 1915, 36-37). "have confessed (two old monks of about 70 years old) that they kept that mountain of the monastery, namely Măgura, from the eazer (Iezer lake) to Feredeu and from Feredeu to Prislopul Secului (Poiana Prislop) and the big ridge downhill to the fountain and to other "ezer" and to Păliean Foot to the threshold and from the threshold the hill next to Neagra, to the Neagra river's mouth to Moldova and Moldova upstream to Breaza river's mouth and Breaza to the "ezer"" (Ştefanelli, 1915, 36-37).

This document is the earliest historical documentation of a Romanian lake which provided accurate data regarding the existence of the lake at the time, as demonstrated by the recent findings on the age of lake Bolătău (ca. 6 ka). The limnological/palaeolimnological investigations on lakes Iezer and Bolătău are an example of interdisciplinary research in this field which requires complementary data from historical sources.

Bathymetric surveys on Romanian lakes

This subsection is dedicated to the historical background of bathymetric surveys, further introducing our own contributions in this field during recent years.

Introduction

The earliest and one of the main approaches to date in the study of lakes from Romania was mapping lake bathymetry and determining lake morphometric variables. The outstanding work by prof. Pișota in this regard deserves a special mention; in his PhD dissertation he made bathymetric sketches for all glacial lakes (with the exception of small ones) in the Transylvanian Alps (Pișota, 1971). Only in recent years have similar sketches been produced by employing modern techniques (Vespremeanu-Stroe et al., 2008), and the results were surprisingly similar to those published by Pișota. Furthermore, the database built by the same author was the starting point for further scientific work in the field of limnology, such as creating the lacustrine index and database comprising of all glacial lakes in the Romanian Carpathians.

Overall, the majority of Romanian lakes have been mapped and bathymetric sketches were drawn for each, thus providing valuable basic data for detailed studies on lacustrine sediments. We participated in this effort by mapping and creating bathymetrical sketches for previously uncharted lakes (Mîndrescu, 2001, 2003; Mîndrescu et al., 2013) or upgrading existing ones subsequent to anthropogenic interventions on lakes (Mîndrescu et al., 2010b).

Method

A Garmin 525 sounder was used to determine the bathymetry of lakes. The data points in the surveys (more than 1000 for each site) were registered in the Stereo 70 coordinate system and superimposed on the corresponding orthophoto. This was done in order to verify the accuracy of the topographic mapping and the lakes' contour extraction. On the perimeter of the lakes, points of 0 depth value were automatically created and used for better interpolation. In order to obtain isobaths and a 3D model of the lake basins, a method that caused the least deformation of the measured depths and which represented as accurately as possible the situation in the field was required. After a review of the methods available in ArcGIS 9.2, data point interpolation and generation of a digital model of the basin were undertaken using the Topo-to-Raster method. This method proved accurate for all the surveyed lakes.

Case studies

a. Lakes Iezer and Bolătău

Iezer and Bolătău are landslide-dammed lakes located in the flysch area of Obcina Feredeului. Table 1.3.3 shows the current dimensions of both lakes, including information on their contrasting catchment and basin characteristics.

Table 1.3.3. Lake basin characteristics

Variable	Iezer lake	Bolătău lake
Information about lakes		
Latitude, N	47° 36' 13"	47° 37' 21"
Longitude, E	25° 26' 58"	25° 25' 54"
Altitude, m a.s.l.	930	1137
Catchment area, ha	355.2	29.57
Catchment perimeter, km	8.04	2.37
Lake area in 1981 (on map), m^2	18,200	2280
Lake area in 2010 (GPS measurement), m^2	7500	2350
Water volume in 2010, m^3	11,911	5699
Max. water depth, m	4.47	5
Sediment thickness, m	3.93	5.40
Water depth at coring point, m	3.80	4.10
Estimated max. water depth of initial lake, m	12 [a]	14 [a]
Estimated max. basin depth (water + sediment), m	8 [a]	9.50 [a]

[a] Estimated values

Whereas the area of Iezer Lake has decreased markedly between the 1980s map and the survey in 2010, the dimensions of Bolătău Lake appear largely unchanged over recent decades. This is consistent with the data provided by the longer term historical maps of the area, which suggest that Iezer Lake has previously changed in size and shape (Fig. 1.3.1).

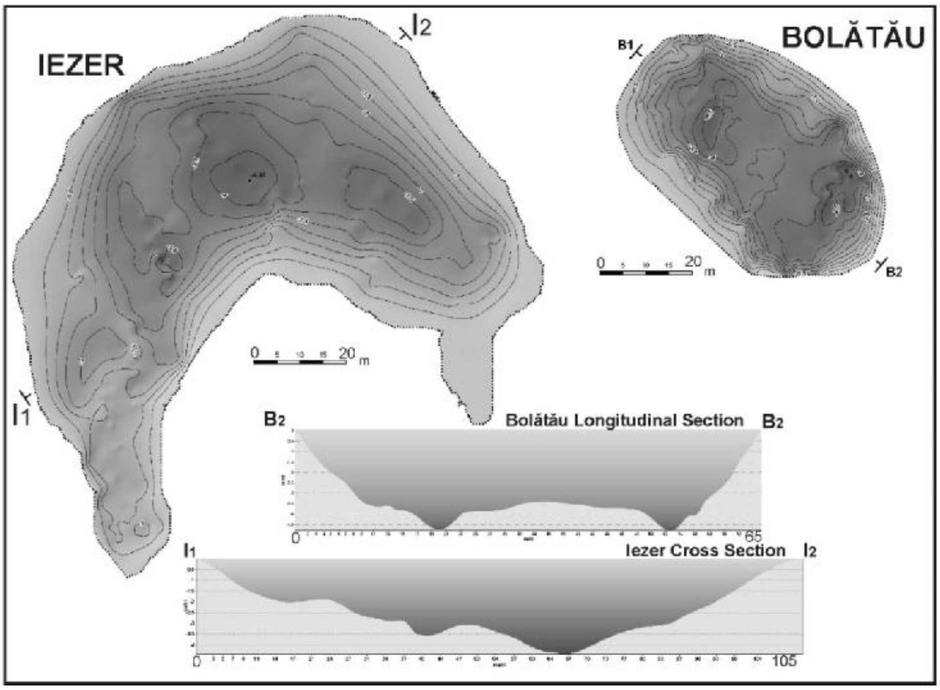


Fig. 1.3.3. Bathimetric maps of landslide-dammed lakes Iezer and Bolătău from Feredeu Mts, Northern Romanian Carpathians.

Based on the topography at the site of the lake, the initial lake bed at Iezer Lake reached a maximum water level and size (4 ha and a depth of 12 m) soon after the landslide occurred, and has subsequently reduced in size and depth as an outlet to the lake formed and deepened. The depth of Bolătău Lake (5.4 m at present) at the time of its formation may have been up to 14 m. Therefore, although there has been little change in the surface area of this lake, it has decreased significantly in depth by approximately 60%. It is evident that Iezer Lake has a more complex shape and bottom topography. Bolătău Lake is steeper sided in cross section with two marked deep points (Fig. 1.3.3).

b. Lake Ştiol

Ştiol lake is a glacial lake located in one of the largest glacial cirques in the Romanian Carpathians, Bistricioara Mare in Rodna Mts. This lake is the source of the longest Carpathian river, Bistrița, and is part of a protected area within the Rodna Mts National Park. Despite its protection status, in October 2002 the lake was modified by artificial damming in order to build up a camping area for tourists. The key parameters of the lake basin (before and after dam) are given in Table 1.3.4. By building the dam, not only have the original contours of the lake been destroyed, but its dimensional characteristics were also modified. The surface area of the lake almost doubled as soon as the dam was constructed, reaching approximately 1,100m^2 as early as October 2002.

The greatest modifications were in the volume of water (it grew 33 times) and its surface extent (increasing 18 times). Consequently, the original glacial lake, in the shape of a tear drop and of small dimensions, effectively turned into a high altitude pond, with an uncharacteristic shape (Fig. 1.3.4) and a chaotic distribution of depth points. Moreover, the current lake has significant variations in level, because the depth is controlled by an artificial channel. This has led to an increase in the level of the lake surface and the flooding of its banks which were covered with dwarf pine. At a less marked level, the depth, length and width of the lake were also modified. In terms of bathymetry, two areas distinguish themselves, one with greater depths, superimposed on the site of the pre dam lake, and the other with lower depths (under 2 m) situated adjacent to the dam wall. As a result of the increased water level, the lake's shape has been modified, from a circular to an irregular one and a small island has been formed on the ridge of the cirque moraine. Taking into consideration its new dimensions, Lake Ştiol has become the largest high altitude lake in this part of the Eastern Carpathians, surpassing Lake Vinderel in the Northern Maramureş Mountains (Mindrescu, 2001).

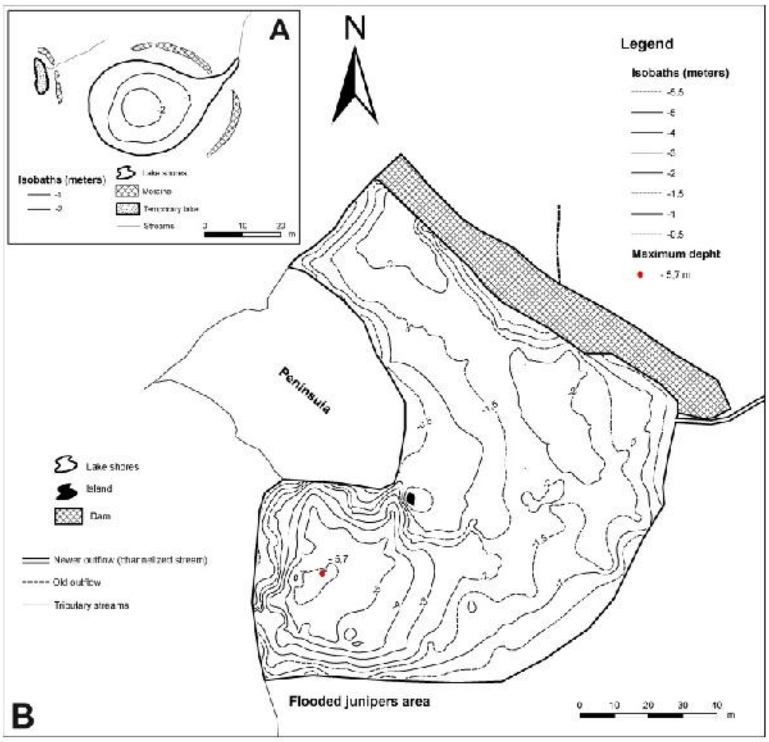


Fig. 1.3.4. Comparison of bathymetric surveys of Lake Ştiol. A. pre dam (according to Pişota, 1968); B. post dam.

Table 1.3.4. Bathymetric parameters of the two stages of Lake Ştiol

Variable	Pre dam (Pişota, 1968)	Post dam (Mîndrescu et al., 2013)	Changes
Area (A), m2	587.5	10600*	> 18 x
Volume (V), m3	610	20116.7	> 33 x
Maximum depth(zm), m	2.0	5.7	> 2.85 x
Mean depth (ž), m	1.03	1.90	> 1.84 x
Relative depth[1] (zr), %	7.31	4.90	< 1.50 x
Length, m	40	132	> 3.3 x
Longest line, m	40.6	150.9	> 3.72 x
Maximum width, m	25	125	> 5 x
Mean width, m	14.68	80.30	> 5.5 x
Perimeter, m	120	491	> 4
Shoreline development, degree	1.40	2.70	> 1.92 x
Mean slope, %	1.069	0.1688	< 6.33
Catchment area, ha	49	151	> 3
Elevation range of the catchment, m	1673 - 2158	1667 - 2158	-
Insulosity, %	0	0.009	-

Lake shapes	subcircular	irregular	changed
Origin of the lake	glacial	anthropogenic	changed
Origin of the island	-	glacial, moraine top	new island
Origin of the dam	glacial: rock basin dammed by moraine	human-induced	changed

*Measured in 2010

Ground-penetrating radar (GPR) on lakes

Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. This nondestructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures. GPR can have applications in a variety of media, including rock, soil, ice, fresh water, pavements and structures. In the right conditions, practitioners can use GPR to detect subsurface objects, changes in material properties, and voids and cracks.

GPR uses high-frequency (usually polarized) radio waves, usually in the range 10 MHz to 1 GHz. A GPR transmitter emits electromagnetic energy into the ground. When the energy encounters a buried object or a boundary between materials having different dielectric constants, it may be reflected or refracted or scattered back to the surface. A receiving antenna can then record the variations in the return signal (Fig. 1.3.5). The principles involved are similar to seismology, except that electromagnetic energy is used instead of acoustic energy, and energy may be reflected at boundaries where subsurface electrical properties change rather than subsurface mechanical properties as is the case with seismic energy.

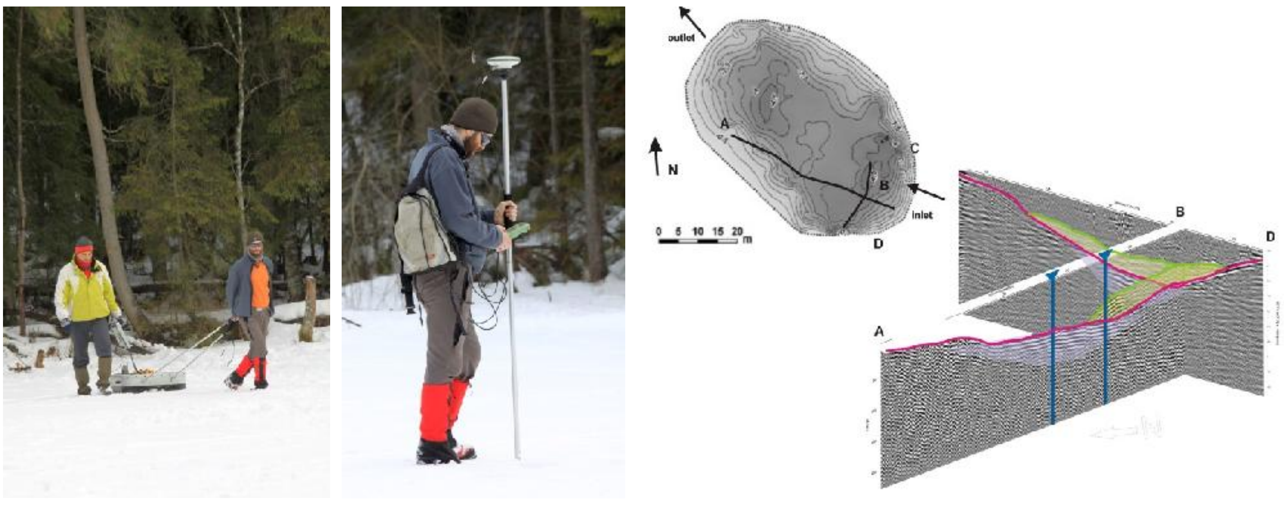


Fig. 1.3.5. Left: GPR survey on Bolătău lake (March 2014). Rigth: rutes used in order to intersect the core points and correlate the cores.

The GPR method was applied for Bolătău lake in March 2014 when the lake was surveyed from the ice bridge. This was the first survey to offer any indication on the presence and extent of lacustrine sediments and their lineation. Based on the resulting radargram we were able to compute the total sediment budget of the lake and more importantly to correlate the extracted cores (Fig. 1.3.6).

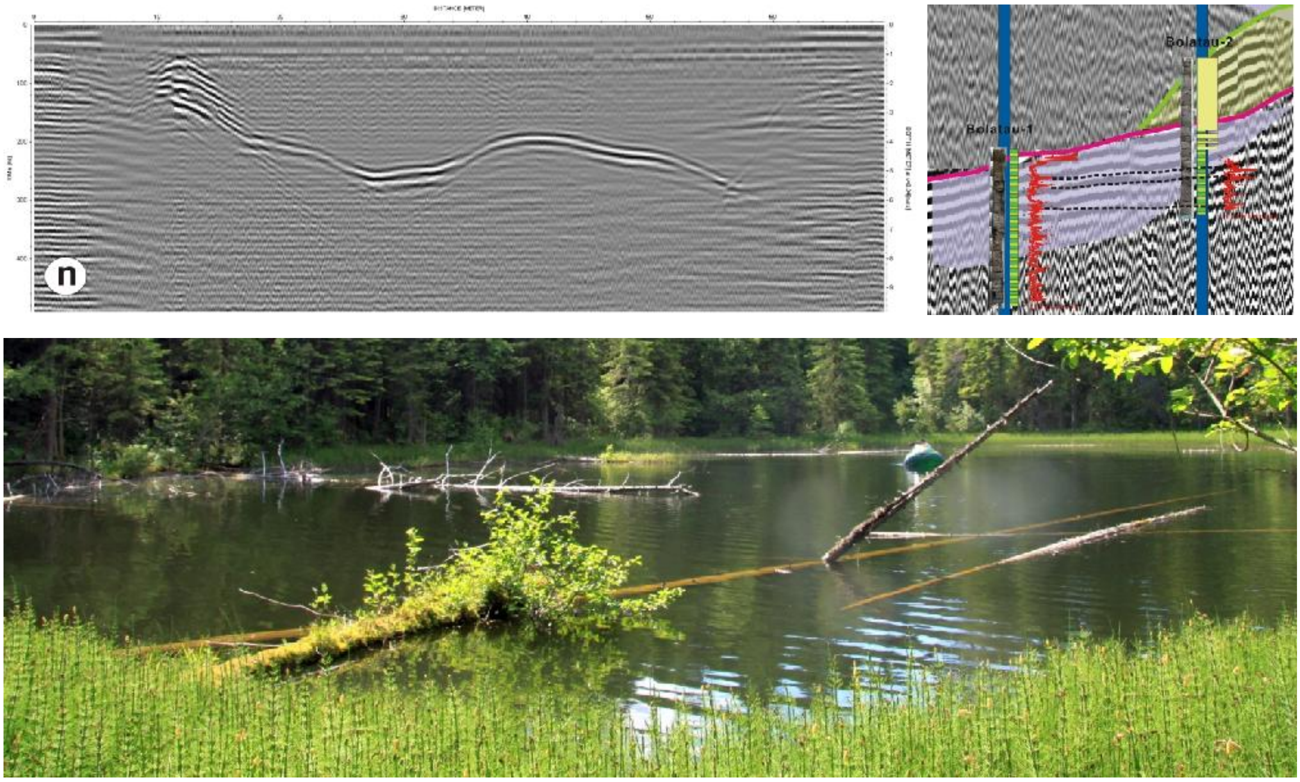


Fig. 1.3.6. Left: A ground-penetrating radargram collected on Bolătău lake. Lineations indicate the presence and extent of sediments layers. Right: Position of the cores and how they integrated into GPR profile based on marked layers (cores correlation as well). Below: Bolătău lake.

The same method was applied at the second lake located in Obcina Feredeu, lake Iezer, yielding similar results which indicated the width and extent of laminated lacustrine sediments (Fig. 1.3.7). The total volume of sediments estimated at lake Iezer amounted to 89200m^3 (Lesenciuc et al., 2010).

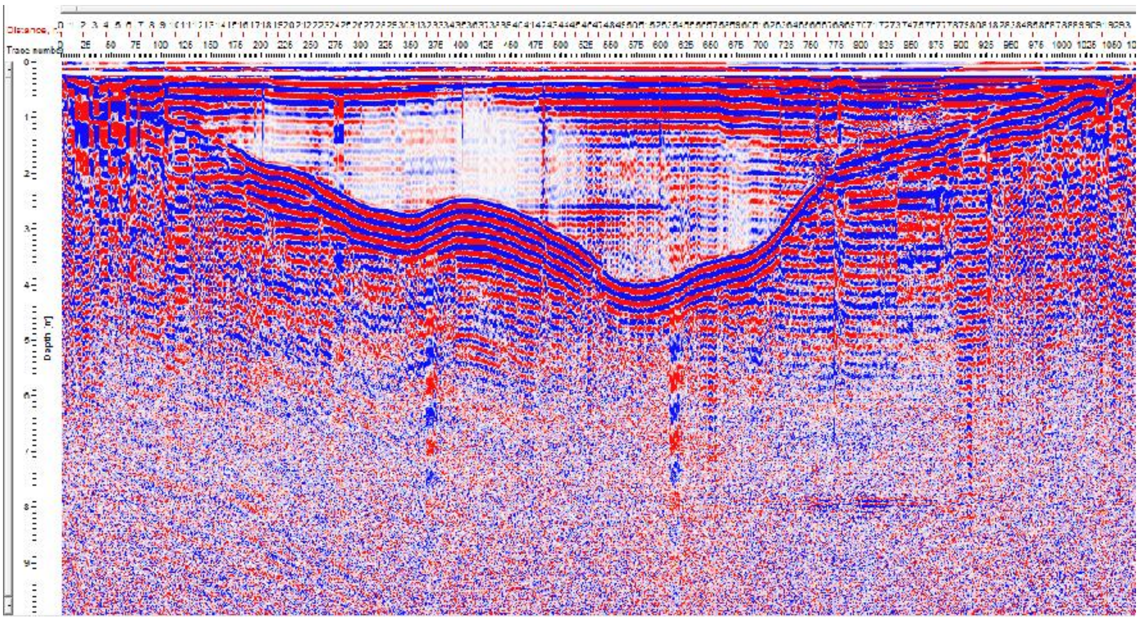


Fig. 1.3.7. A ground-penetrating radargram collected on Iezer lake (Lesenciuc et al., 2010).

We believe this investigation method has great potential for limnology and palaeolimnology; therefore, our intention is to employ GPR surveying on all the lacustrine sites we have studied thus far in order to calculate the total budget of sediments in lacustrine basins and estimate as accurately as possible the rates of sedimentation for the entire sediment profiles / throughout the existence of the lake.

Electrical resistivity tomography (ERT) surveys on lake sediments and glacial deposits

Electrical Resistivity Tomography (ERT) is an advanced geophysical method used to determine the subsurface's resistivity distribution by making measurements on the ground surface. ERT data are rapidly collected with an automated multi-electrode resistivity meter. ERT profiles consist of a modeled cross-sectional (2-D) plot of resistivity (Ω·m) versus depth. ERT interpretations, supported by borehole data or alternate geophysical data, accurately represent the geometry and lithology and/or hydrology and/or petrology of subsurface geologic formations.

Resistivity, measured in Ω·m, is the mathematical inverse of conductivity. It is a bulk physical property of materials that describes how difficult it is to pass an electrical current through the material. Resistivity measurements can be made with either an alternating current (AC) or a direct current (DC). As resistivity measurements are frequency dependant, care must be taken when comparing resistivity values collected using different techniques.

In Romania ERT surveys have been applied in the Romanian Carpathians for different glacial and periglacial geomorphological studies (e.g. permafrost detection - Urdea et al., 2008; Vespremeanu-Stroe et al., 2012), slope deformation analysis, the assessment of slip surface depths, sediment thickness, groundwater levels etc. One of the most commonly 2-D array used is the Wenner electrode configuration, which is moderately sensitive to both horizontal and vertical ground structures.

Method

Two-dimensional resistivity surveys were carried out using a GeoTom (Geolog 2000) device connected to two multi-core cables, each allowing the use of 25 electrodes equally spaced at 2 meters (Fig. 1.3.8). Electrode elevation change was determined using a Leica TC407 total station. When the length of the profile was greater than the length of the cables "roll along" sequences were used. Penetration depth achieved using Wenner electrode configuration was about 20 % of the total cable length (16 – 17 m). Once the readings were taken an inversion (interpolation) routine was run using Res2Dinv software. We evaluated several inversion algorithms and settings available in the software and the best results were achieved using the robust inversion.

Fig. 1.3.8. GeoTom (Geolog 2000) and Multi-core wires.

The first site where we employed this investigation method is lake Gropile (Rodna Mts) and its surrounding moraines. The lake is located on the uppermost step of a large glacial cirque, and consists of a water body as well as a peatbog encased by lateral and terminal moraines.

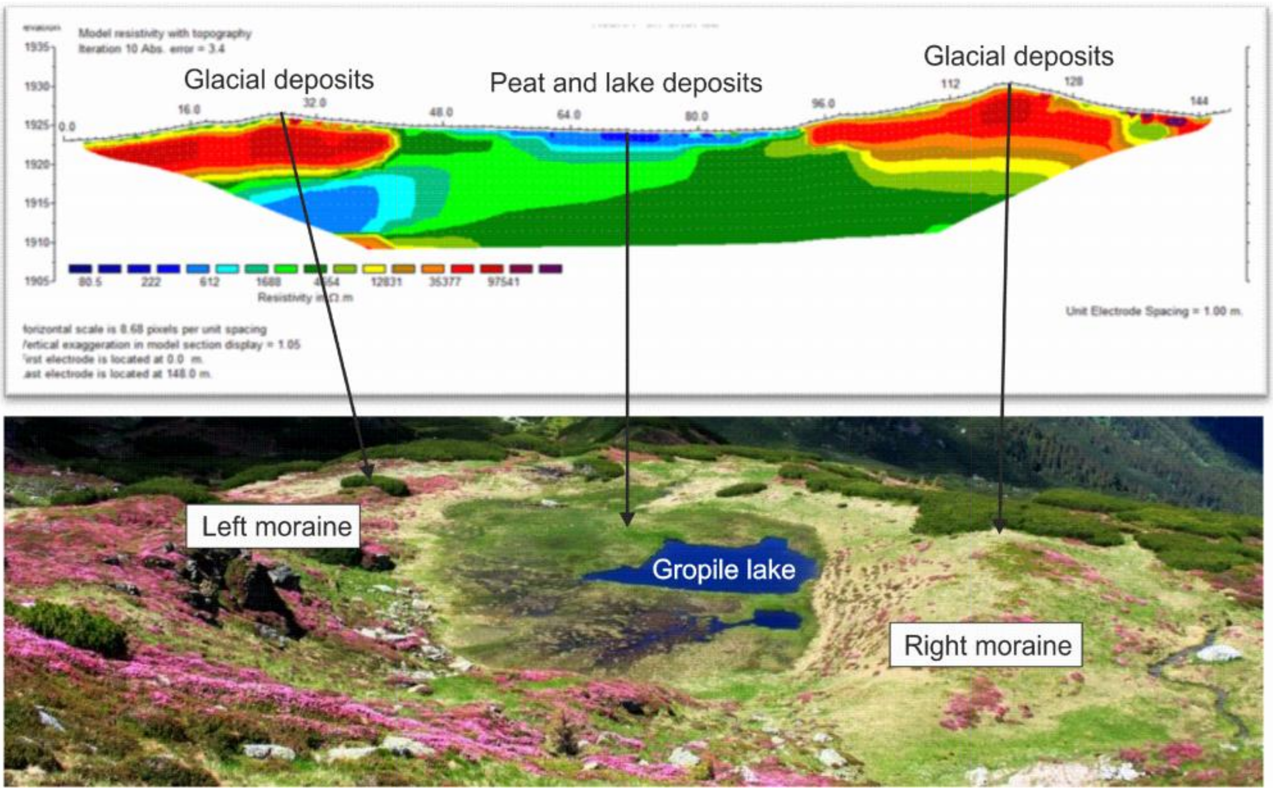


Fig. 1.3.9. Electrical resistivity tomography (ERT) survey on glacial lake and deposits (lake Gropile, Rodna Mts).

Peat deposits and glacial deposits from the lateral moraines were our focus for the ERT survey at lake Gropile, as this method can be used to infer a variety of information on the glacial features, such as the internal structure of moraines and the occurrence of the bedrock, low resistivity values in the internal structure indicating areas with high humidity, higher resistivity patches pointing towards the presence of moraine ridges, or water infiltration in the lower parts of deposits (Fig. 1.3.9).

Lake Iezer-Păpușa was another site where we conducted an ERT survey on the lake basin and the cirque floor. The profile depicting the cirque floor comprises a series of moraines and peat deposits. This is one of the longest ERT profiles of a glaciated area from the Romanian Carpathians (Fig. 1.3.10).

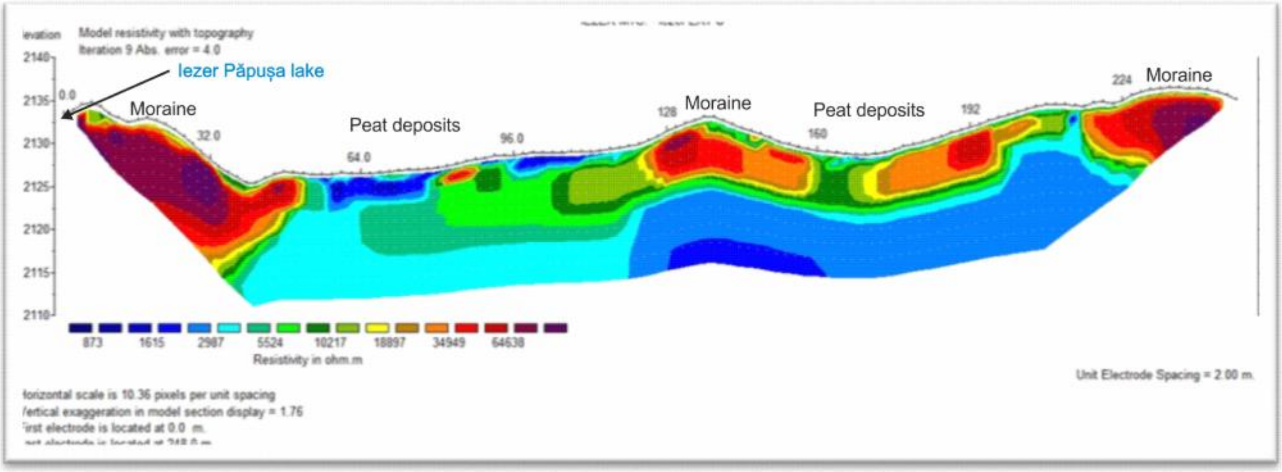


Fig. 1.3.10. Electrical resistivity tomography (ERT) survey on glacial cirque floor (Iezer cirque and lake, Iezer-Păpușa Mts).

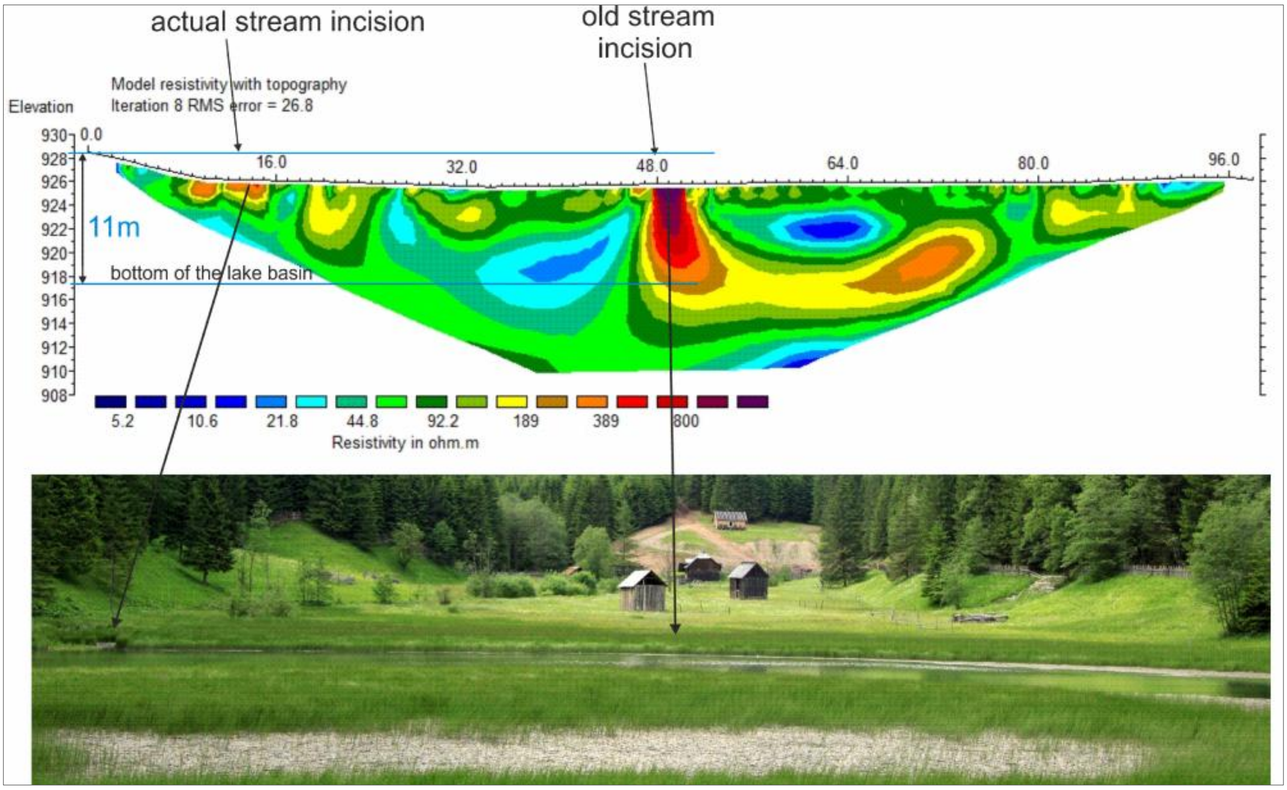


Fig. 1.3.11. Electrical resistivity tomography (ERT) survey on a landslide-dammed lake (Iezer-Feredeu lake, Obcina Feredeu Mts).

As regards the series of moraines from Iezer-Păpuşa cirque, the ERT survey profiles indicate the following: the depth of glacial deposits (moraines) reaches a maximum of 10 meters; high resistivity values occur within the moraine deposits; lower resistivity values correspond to deposits with high water content located above the bedrock. In both aforementioned sites the post-glacial and glacial deposits are highlighted (i.e. peat and glacial).

This method was further tested on the Iezer-Feredeu lake (Obcina Feredeului), in the upstream area of the current water body in May 2014, whereby we discovered that the basin now filled with sediments is approx. 11 m deep. This finding is consistent with our assessment made in 2010 regarding the maximum depth of the lake after its formation (see Table 1.3.3). We also found that the inflow stream has changes its position throughout time; whereas for most of its existence the inflow was located in the central part of the basin, in time the stream has shifted position towards the extreme right-side of the basin where it is currently located (Fig. 1.3.11).

Electrical resistivity tomography (ERT) has already proved to be an essential tool for investigating lacustrine sites, as well as surrounding deposits, either glacial or resulting from mass movement processes. During the past year we have identified two new sites which host palaeolakes, i.e. Varvata (Soloneț basin on Suceava plateau), and Vinderel palaeolake (Fig. 1.3.12) where we intend to apply ERT surveys in the near future. Based on empirical observations, we believe Varvata is a very old palaeolake which likely formed during the deglaciation, and a combination of ERT and GPR surveying would be essential for understanding the nature, depth and extent of the sediments. Basen on such results, we could further gain a better understanding of palaeoenvironmental conditions in Suceava region (Northern Romania). This type of site is a rare occurrence, as there are just two similar reported sites in Romania (Măgheruș and Turbuța sites in the Transylvanian Depression).

Fig. 1.3.12. Varvata and Vinderel palaeolake profiles.

Sediment scanning and logging

Sediment logging

The visual inspection and analysis of lacustrine sediments after collection was upgraded due to the emerging techniques which allow for digital analysis of sediments; we were able to apply such a method for gaining insight into the characteristics of sediment cores sampled in Romania (e.g., on lake sediments from lakes Iezer and Bolătău). The color-based visual analysis using dedicated software provided significant information on the nature of sediments and sedimentation rates and regularity of depositional layers (Fig. 1.3.13).

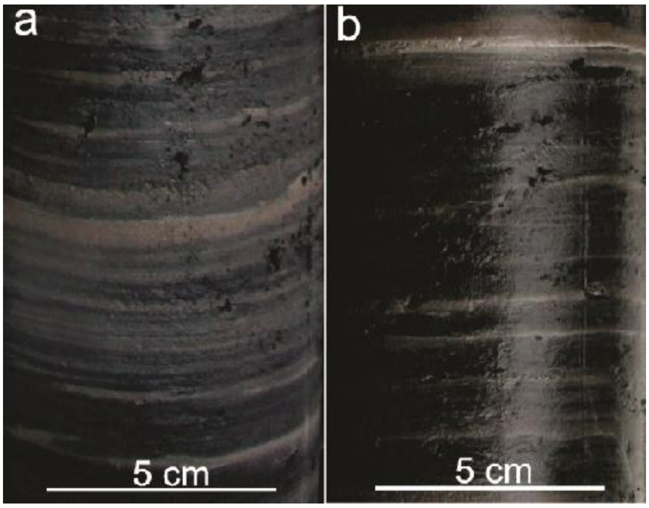


Fig. 1.3.13. Depositional layers sections of Iezer (a) and Bolătău (b).

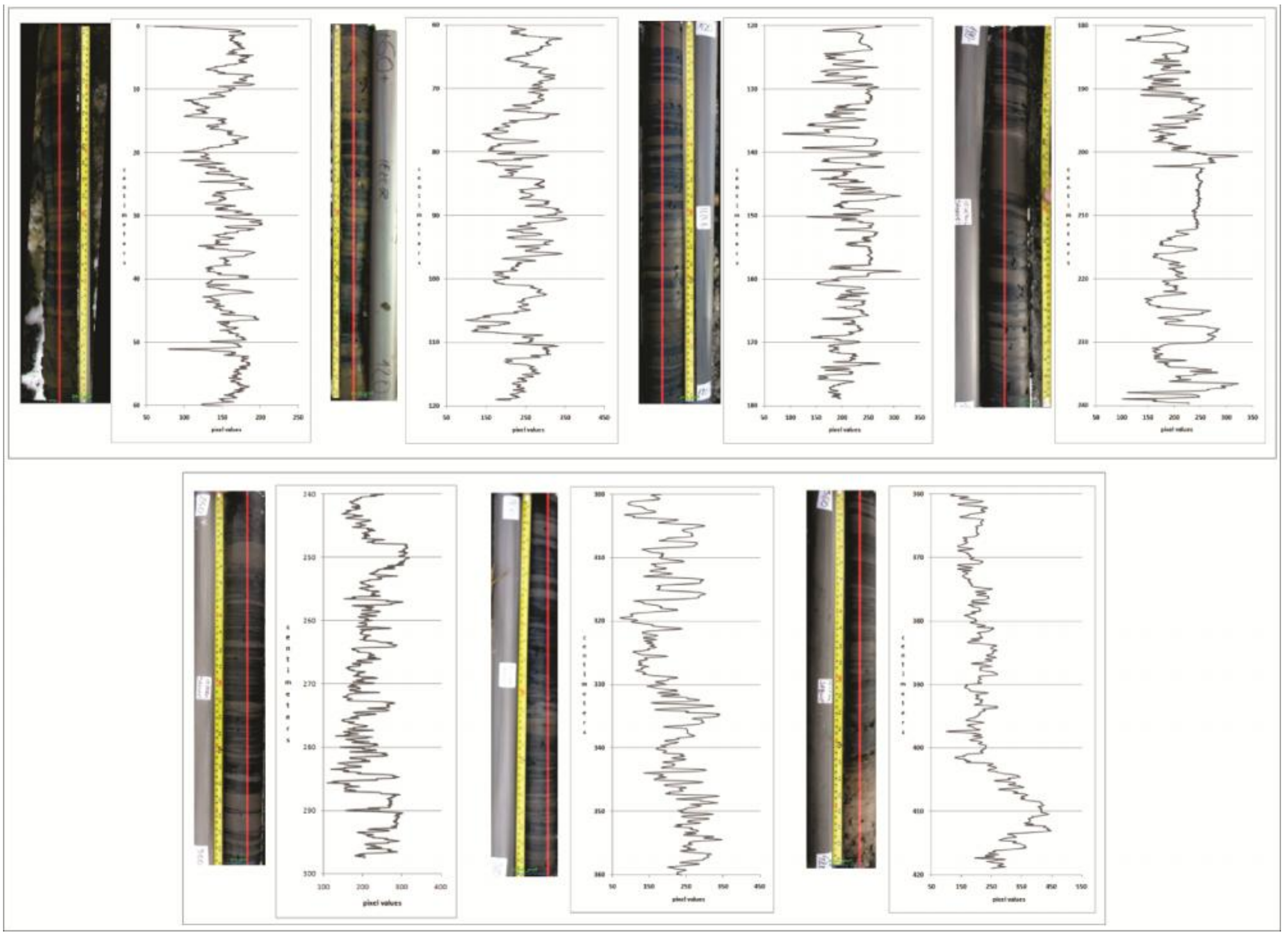


Fig. 1.3.14. Iezer lake. Digital analysis of core sections.

In this process digital grayscale images were used and the graphic processing was performed using UTHSCSA Image Tool 3.0 software which has been specifically designed to identify lacustrine varves (Ridge, 2011). The methodology involved drawing several longitudinal profile lines (with a width of 10 pixels) for each core and identifying the mean value corresponding to intersected pixels. The RGB values obtained indicate the presence (in relation to depth) of darker or lighter layers (from 0 for black to 768 for white). By plotting these data, the colour contrasts (1 pixel is equivalent to 0.03 cm) were used to estimate the thickness and number of sediment layers (Fig. 1.3.14).

By employing this technique we also identified the laminated structure (i.e. regular seasonal layers and irregular flood deposits) in the sediments collected at lake Bolătău (Fig. 1.3.15). From the data provided by the sediment logging we were able to draw some conclusion regarding the regularity of sedimentation and the nature of laminae. Basedon the dominance of warm season precipitation and the early summer discharge peak in the region we assumed that most of the allochtonous sediment input arrives into the lake during that timeframe. Consequently, this is the time when the silt/fine sand laminae form with a sharp bottom boundary on the organic material (OM) rich clay laminae. The minimum rainfall occurs in December and the lake is usually frozen from December to April (Rusu, 2002), therefore we assumed that this is the time of settling out of clay with organic particles.

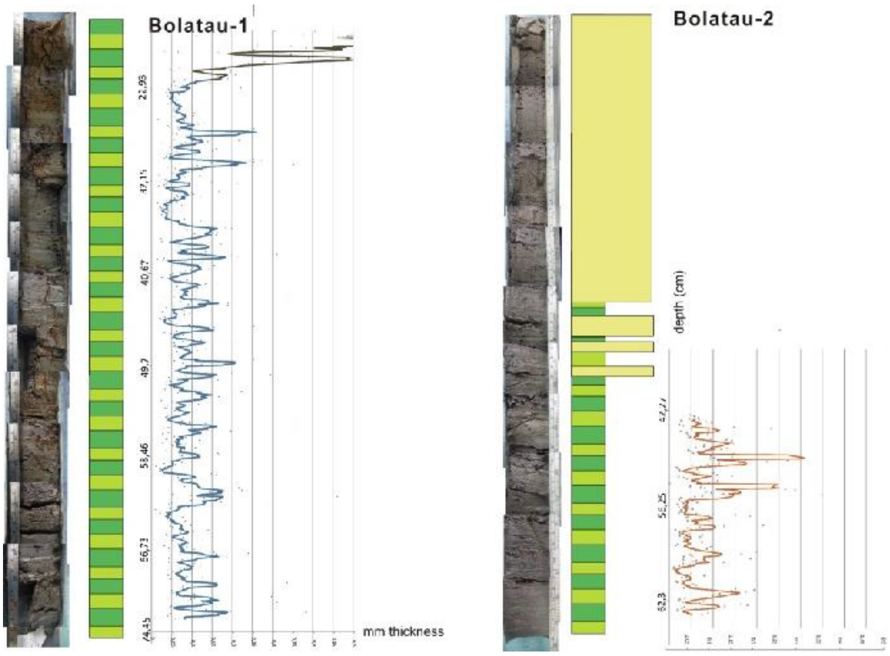


Fig. 1.3.15. Digital analysis of laminated structures in sediments from Bolătău lake.

Determining the elemental chemistry of sediments

The chemical composition of the solid sediment was determined using an X-ray spectrometer (e.g., Niton XRF – X-ray fluorescence device). However, this process may yield errors which add or substract from the respective concentrations; whereas the XRF measurement can accurately determine Pb, Fe, Zn, Cu etc, in the case of rare elements, such as Au, Ag etc, the errors are often larger than the actual measured value, thus rendering the measurements useless. Thus, it is necessary to find better ways to report errors; to this effect, for Iezerul Sadovei both the values of the measured parameter and the errors were plotted in the following diagram (Fig. 1.3.16).

The correction method applied varies depending on the type of device employed for measurements. For μXRF devices (spectrometers) this problem is reduced to a large degree; after the corrections are applied (by correlation with the concentration of Ar), the error becomes minimal.

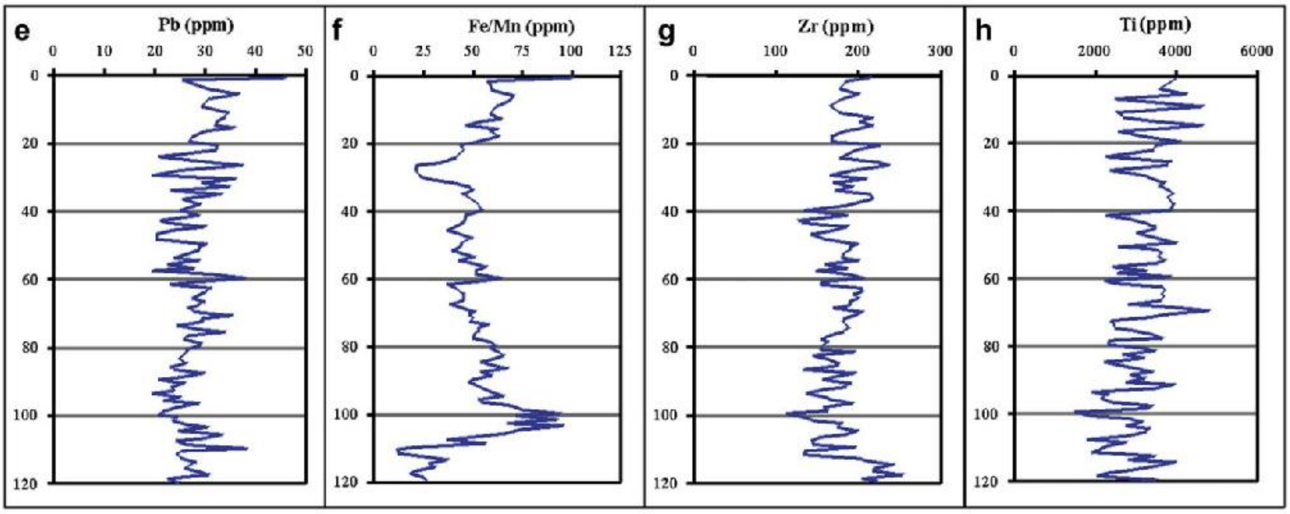


Fig. 1.3.16. Determining the elemental chemistry of sediments from lake Iezer.

Lake Florica is a glacial lake located at 2083 m a.s.l., from which two sediment cores (87 cm, and 93 cm – long, respectively) were extracted in September 2014. Each core was sectioned longitudinally and described in terms of lithology; the first half of each core (A) was wrapped and stored in the refrigerator as a sedimentary archive, while the second half (B) was tested for various physical and chemical analyses. The cores were scanned using a professional optical camera (triple sensor line scan camera smart COS 1600LS (smartcube® GmbH), 4080 pixel, 75 mm Apo Rodagon lens), and the resulting images were processed with the SmartScan software.

The magnetic susceptibility measurement was performed using an E-type Bartington MS2 scanner. The geochemistry was determined using the μ-X-ray Itrax Corescanner (COX Analytical Systems, Suedia) with X-ray and linescan cameras. The results were processed with the COX software (CoreScanner, Qspec, ReDiCore).

Preliminary results show that during sampling a few centimeters were lost between the top and bottom cores, therefore the transition between the two cores is rather sudden. The first one is composed almost entirely from dark brown organic matter, whereas the second core consists of organic matter in the top 10 cm, ensued by a 7 cm-long transition area comprising of clay and organic matter, and finally by a bottom part consisting of alternating dark grey and light grey layers with oxidation traces (dark orange). Fig. 1.3.17 shows the entire sediment sequence and the elemental geochemical composition.

The Fe and Mn contents of the sediment are dependant on both the lacustrine and lake catchment conditions; therefore, environmental processes occurring in the catchment control the amount of Fe and Mn which can be released while lacustrine limnological conditions control the Fe and Mn which will be stored in the sediments. Also relevant are the amounts of Ca from authigenic carbonate minerals and the skeletal remnants of aquatic invertebrates which can provide information about the increase of lacustrine salinity, palaeotemperature or ionic concentrations (Cohen, 2003).

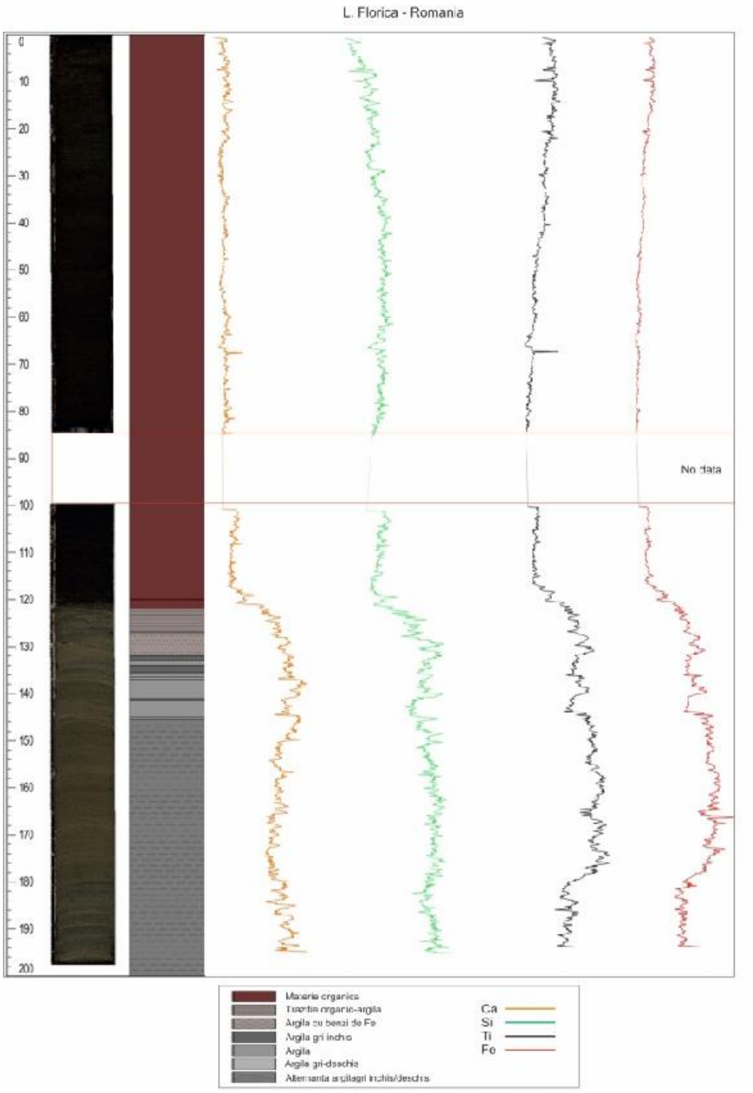


Fig. 1.3.17. XRF profile (Ca, Si, Ti, Fe) of sediments from Florica lake.

The concentrations of Ti (as well as Zr and Rb) are infleunced by various factors, such as source rock geology, distance and sediment transport energy; therefore, it is necessary to compare Zr:Ti and Zr:Rb ratios to the data resulting from grain size measurements in order to establish whether observed variations of ratio values reflect changes in particle size (Jones et al., 2011).

X-ray diffraction analysis (XRD)

This method of analysis is basically one which is performed by an X-ray diffraction data analyst working with diffractometer tracings. Computer methods in mineral identification, mineral quantification, and data tabulation are employed to perform simple, repetitive functions.

The method of sample preparation is nondestructive (except for grinding) and the sediment fractions can be recovered for further testing or refinement. An exception to this is that calcite, aragonite and, to some extent, dolomite, gypsum, and anhydrite are dissolved in the decalcification process. Typically, 25-g (10-cc) sediment samples are submitted for X-ray diffraction analysis. Approximately 1 g is kept as a reference, 5 g are taken for bulk sample preparations, and the remainder is used in preparation of decalcified, fractionated 2-20μ and <2μ samples.

We employed this method of analysis on lacustrine sediments collected from lake Bolătău whereby the mineralogical composition was determined by X-ray powder diffraction (XRD) analysis on randomly oriented samples. XRD analysis was made on a Philips PW1710 type X-ray diffractometer with the following instrument parameters: CuKα radiation, graphite monochromator, 45 kV acceleration voltage, 35 mA intensity, 1° divergence slit.

Two mineral phases attracted the attention during the detailed inspection of the sediment samples: a bluish powdery or microcrystalline aggregate and an opaque one with metallic luster. XRD analyses of two separated samples helped to identify vivianite and pyrite for the bluish and the metallic phase, respectively (Fig. 1.3.18).

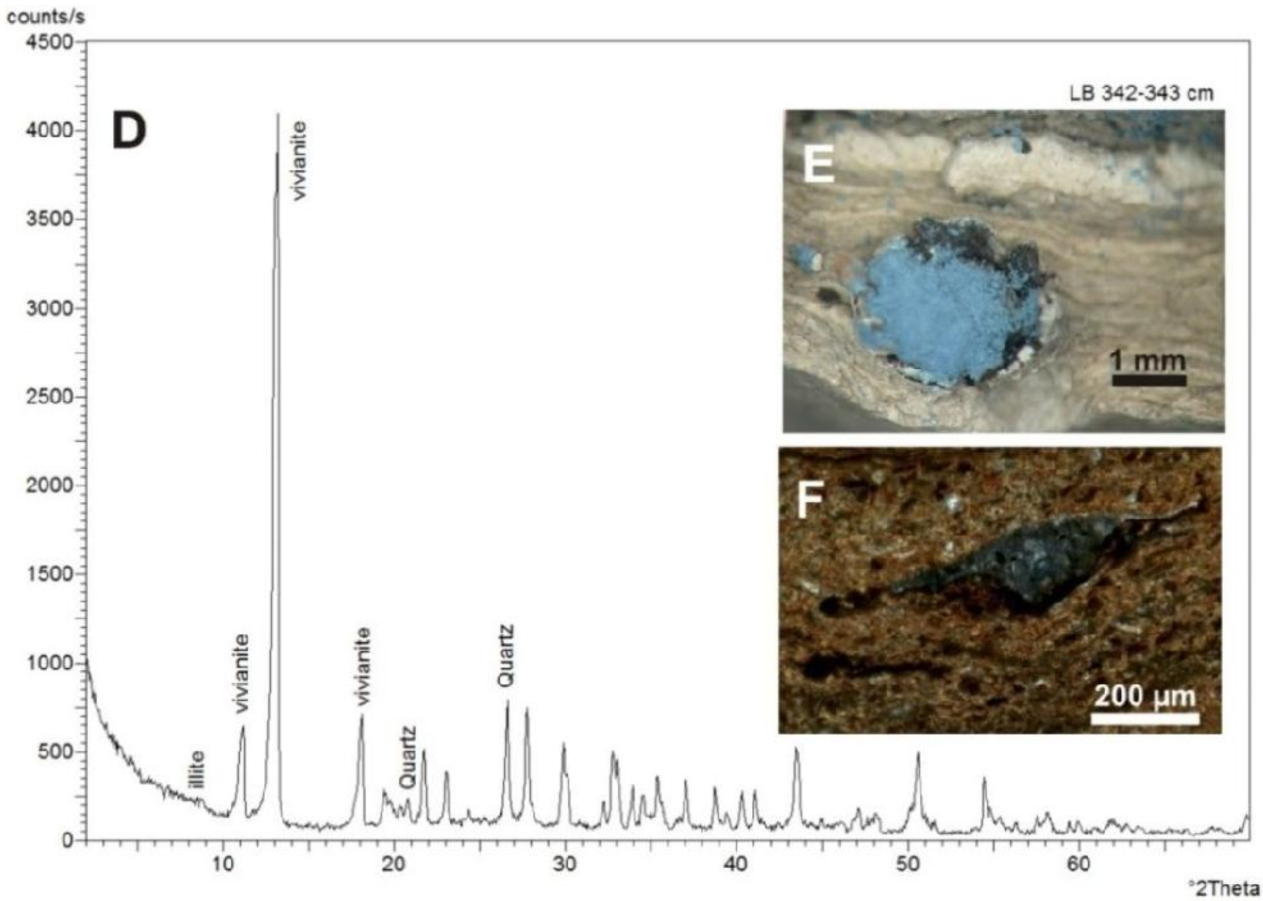


Fig. 1.3.18. XRD patterns and micrographs of authigenic minerals. Top: XRD pattern of the bulk sediment from the 353-354 cm section of the core. Inset photos show bluish microcrystalline aggregate around a seed under binocular (E).

Vivianite was macroscopically visible only under 306 cm in the core. We found this mineral is abundant as microcrystalline filling in the cavities of organic material (e.g. in seeds) (Fig. 1.3.18E).

Pyrite occurs in two different forms: it is also abundant in OM rich layers as micro-botryoidal cavity filling, however it often forms framboids in the sediment with the usual diameters of 5-10 µm. Some larger (with 30-35 µm diameter) framboids are attached to organic pellets. The space around them is often filled by micro-botryoidal aggregates; these are usually smaller than 1 µm and based on their shape and location they were clearly formed after the larger framboids. Smaller ones (d~10-15 µm) can be also found separately in the clay or silt. These particles are not associated with organic material (Mîndrescu et al., 2015, submitted).

Magnetic susceptibility

This parameter is defined as the degree of magnetization of a given material (e.g., a type of sediment) after it has been subjected to a low density magnetic field, without inducing remanence. If the values of magnetic susceptibility are positive, the material can be either paramagnetic, ferromagnetic, ferrimagnetic or antiferromagnetic, whereas at negative values the material becomes diamagnetic. In the case ofpositive values the magnetic field is basically enhanced by the presence of the material, while at negative values the field is diminished.

Magnetic susceptibility can be expressed depending on the sample weight (in which case it is known as weight-dependent susceptibility, $m^3\ kg^{-1}$), or on the frequency of the magnetic field (also called frequency-dependent susceptibility, expressed as a percentage value). The magnetic susceptibility provides an indication of the concentration of magnetic minerals, and thus of the iron content (as oxides and sulphites) in the analysed sediment.

The **frequency dependent magnetic susceptibility** (χ_{FD}) is calculated as a percentage as follows:

$$(LF-HF)/LF*100\ (\%)$$

where: LF is the result obtained for the low frequency measurement, HF – for the high frequency measurement.

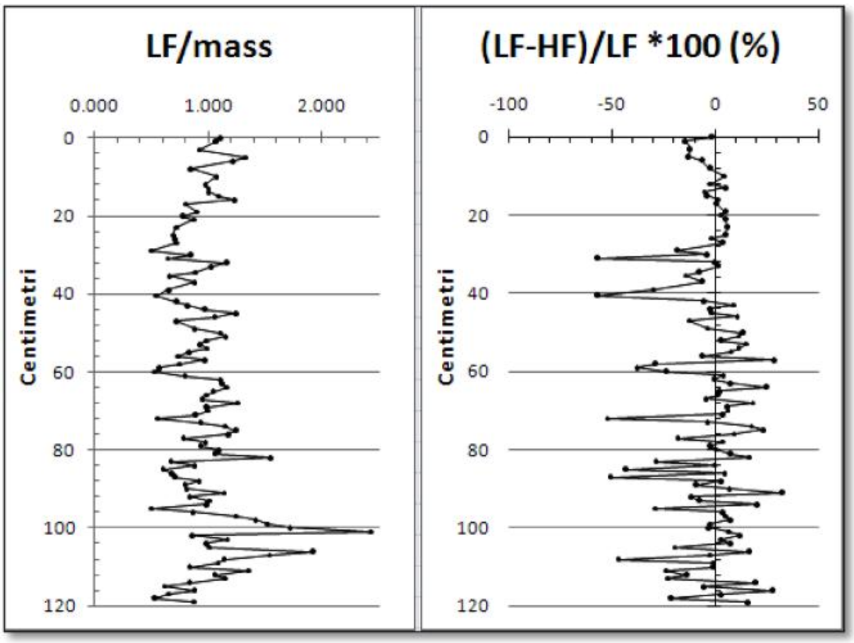


Fig. 1.3.19. Values of mass dependent magnetic susceptibility (left), and frequency dependent magnetic susceptibility (right), calculated for lake Iezerul Sadovei, 0-120 cm.

Dendrochronological assessment of subfossil coniferous excavated from peat deposits

In very few cases lacustrine sediments from Romania have successfully preserved fossil tree trunks. Thus far such instances have not been mentioned in the literature, therefore no studies exist which would analyse both lacustrine sediments and tree trunks. However, such research has been conducted on fossil arboreal trunks excavated from river terrace deposits (Rădoane et al., 2015).

Vinderel 3 peatbog

To date, after extensive field exploration, we were able to find a lacustrine site which contains subfossil trunks, i.e. Vinderel 3 (1530 m a.s.l.) located on the Vinderel mountain plateau in Farcau massif, Maramures Mts (Fig. 1.3.20). The lake formed inside a slope pocket (see Fig. 1.1.2a) within a thick layer of weathered rock which is vulnerable to changes in humidity during spring thaw or long-term climate changes.

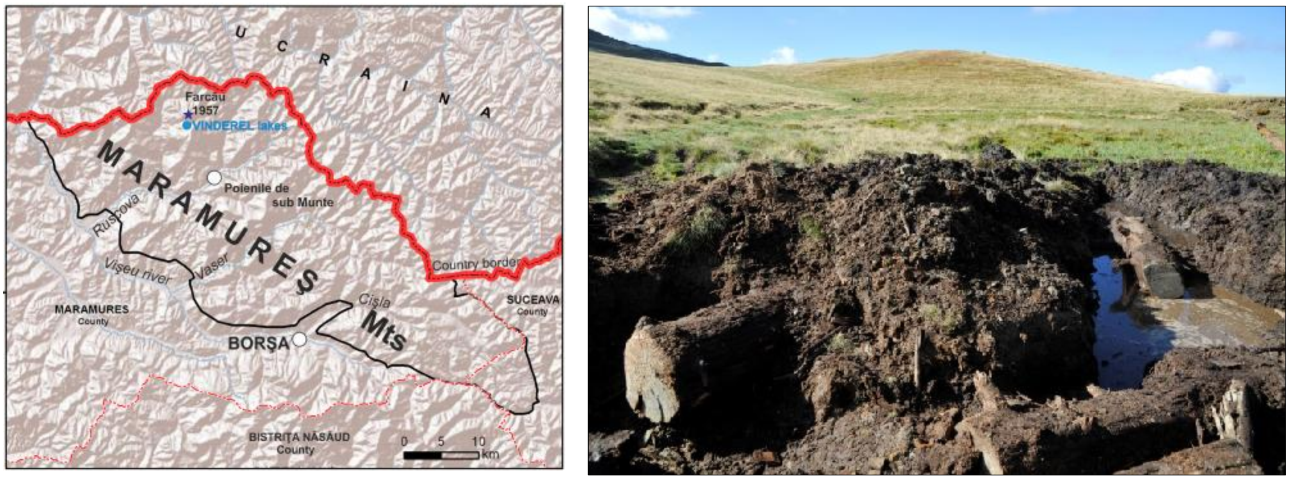


Fig. 1.3.20. Vinderel 3: location of site (left) and excavated subfossil logs (right).

Materials and methods

- The sample surfaces were polished until the tree-ring structure became clearly visible (Fig. 1.3.21a)
- The anatomical texture identified tree species: most of the samples were Norway spruce (*Picea abies*) and Silver fir (*Abies alba*)
- The tree-rings were checked and counted (two radiuses)
- Annual ring width was measured (using LINTAB table and TSAP 4.68 software)
- Crossdating and overlapping of chronologies were performed
- Floating chronologies were builtRadiocarbon (^{14}C) analysis was conducted (Fig. 1.3.21b): seven samples were selected for radiocarbon analysis (performed at the Hertelendi Laboratory of Environmental Studies in Debrecen, Hungary) and the calibraton of ^{14}C

dates to calendar years was carried out using the OxCal v.4.2 program with Intcal13 dataset.

Young trees that have 40 to 60 rings are not optimal for dendrochronological crossdating; just one third of the samples were promising for dendrochronological assessment and just a small number had more than 100 rings. Samples with fewer rings are a challenge when attempting to achieve successful sychronisation (Arvai et al., 2014).

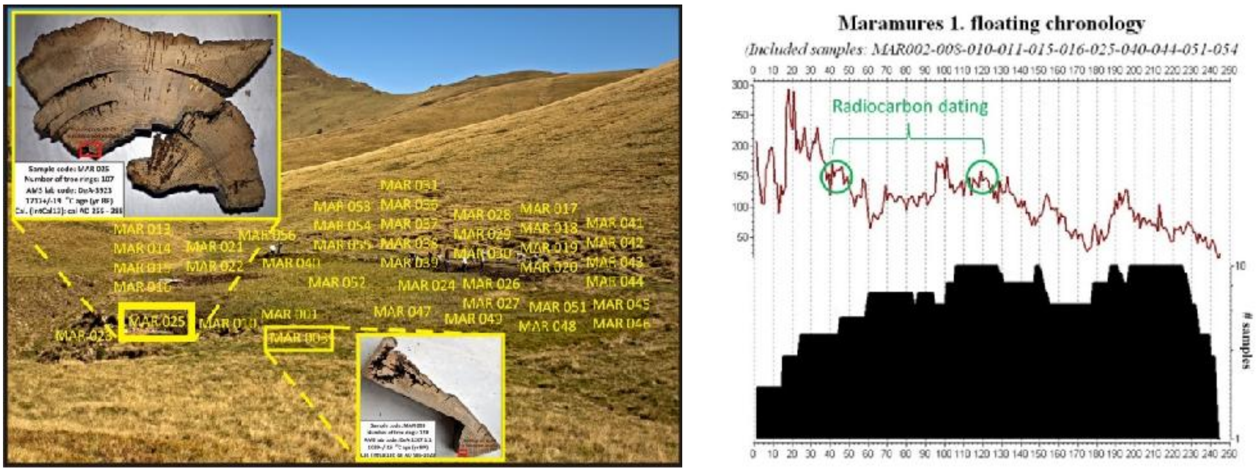


Fig. 1.3.21. Samples collected (a) and quarter millennium-long conifer chronology (b).

Conclusions

- The radiocarbon age of the oldest sample (MAR025) is 1717 +/- 19 years BP whereas the youngest sample's is (MAR003) 1039 +/- 16 years BP (Fig. 1.3.21).
- Six floating chronologies were built; however, they cannot reach the end of the regional master chronology. The regional Norway spruce chronology dates back to the end of the 16th century.

Lake Iezer-Feredeu

The most recent instance where subfossil logs were found in lacustrine sediments occurred in 2014 at lake Iezer-Feredeu. The lake underwent anthropogenic interventions aimed at turning the lake area into a touristic/leisure spot for the locals, without taking into account the environmental value of the site. As the lakewater was progressively drained through a channel excavated in the outlet area, a number of subfossil trunks surfaced (Fig. 1.3.22). These logs, which on closer inspection appeared to be very well preserved, engrained the climatic signal of the time period prior to the landslide which resulted in the formation of the lake basin.

Considering the preliminary observation that the age of the oldest trunk is ca. 300 years, the period we are referring to in 550-850. Tree rings were already sampled (Fig. 1.3.22) and will be studied in order to extend the existing chronologies and climate reconstructions from Obcinele Bucovinei up to 1.500 years BP.

Fig. 1.3.22. Lake Iezer-Feredeu after human interventions, with subfossil trunks surfacing from lowered lakewater (left), and sample from the oldest subfossil trunk found at the site (right).

Lake sediments chronology

Age-depth models are used in Romania primarily by researches interested in the history of vegetation. In our own research, this method of investigation was employed with the purpose of extracting other types of information, such as sediment age, origin, rate of sedimentation, ^{137}Cs flux, geochemical signals etc.

Radiocarbon and Cs-dating

Radiocarbon dating of organic remains within various types of deposits, e.g., lake sediments, has proven very useful in inferring information such as the time of onset of organic sedimentation in the lake subsequent to its formation and establishment of vegetation.

One of our research projects involved the study of finely laminated sediment records from a small landslide-dammed lake (Bolătău) located in Obcina Feredeaului, Eastern Carpathians, Romania. **An age-depth model** for the Bolătău sediment record was established based on 8 AMS radiocarbon dates from terrestrial macrofossils and the double peaks of the ^{137}Cs flux (i.e. mid-1960s: global fallout maximum; 1986: Chernobyl accident). The onset of the lacustrine sedimentation is estimated to ~5-6.5 ka while the landslide event can be constrained by ~6.8-7 ka as an inferior age estimate (Mindrescu et al., 2015, submitted).

AMS radiocarbon analysis. Nine organic macroremains have been separated from the cores for AMS radiocarbon analysis. Eight samples were picked out from the lacustrine sediment profile (1 from the gravity core, 7 from the Russian core) while one piece of wood was found in the landslide mass reached after penetration of the lacustrine deposit.

The radiocarbon ages were calculated according to Stuiver and Polach (1977) using the Libby half-life (5568 years) and corrected for isotope fractionation using the AMS measured $^{13}C/^{12}C$ ratio which accounts for both natural and machine fractionation.

Calibration and age-depth modelling. Calibration of ^{14}C dates to calendar years and age-depth modelling were performed using P_Sequence function from the OxCal v.4.2 (Bronk Ramsey, 2009) program in conjunction with the Northern Hemisphere IntCal13 (Reimer et al., 2013) dataset. Calibrated ages are reported with two standard deviations (2σ).

We assumed a core-top age of 2012 AD, the last entire year preceding core collection. Two distinct ^{137}Cs peaks were found in the uppermost 20 cm of the sediment core and used as independent time markers to validate the poorly constrained upper section of the ^{14}C based age-depth model (Appleby, 2008).

As an exception, the ^{14}C date obtained from the deepest sample (DeA-2636.1.1) has been calibrated separately following the classical single-date calibration scheme since this sample does not belong to the lacustrine sediment profile.

Chronology of the Bolătău sediments. The measurement and calibration results of the radiocarbon analyses are presented in Table 1.3.5 and Fig. 1.3.23. The calibrated age of the wood fragment obtained from the underlying landslide body is 6947-6783 cal BP. It provides an inferior limit for the age model and a time constraint for the landslide event of the basin genesis.

Table 1.3.5. Radiocarbon activities and calibration results of the analyzed samples from the Bolătău sediment profile

AMS Lab Code[a]	depth (cm)	C-14 pMC abs.	conv. C-14 age (yrs BP)	Unmodelled age (cal BP)	modelled (cal BP)	A (%)[b]
DeA-2637.1.1	26-27[c]	98.77±0.31	100±25	264-219 or 143-23	254-219 or 145-27	**100.5**
DeA-2638.1.1	41-42	97.92±0.30	169±25	288-254 or 225-136 or 115-106 or 100-73 or 34-<0	290-252 or 225-165 or 157-141	**103.6**
DeA-2639.1.1	50-51	95.35±0.31	383±26	506-427 or 378-320	392-315	**74.9**
DeA-2640.1.1	61-62	96.1±0.30	320±25	463-306	468-350	**100.4**
DeA-2641.1.1	126-127	86.11±0.27	1201±25	1225-1212 or 1183-1060	1230-1210 or 1184-1062	**98.3**
DeA-2642.1.1	156-157	80.44±0.27	1749±27	1718-1569	1715-1591 or 1586-1570	**101.8**
DeA-2643.1.1	170-171	79.43±0.27	1850±27	1865-1715	1865-1720	**100.3**
DeA-2644.1.1	305-306	60.73±0.22	4006±29	4527-4419	4525-4419	**99.8**
DeA-2636.1.1	wood from the landslide	47.28±0.18	6018±31	6947-6783	-	-

[a]: individual laboratory code of Debrecen radiocarbon lab for samples measured with accelerator mass spectrometry (Molnár *et al.,* 2012); [b]: Individual agreement percent of the Bayesian age-depth model; [c]: depth beneath the top of the gravity core.

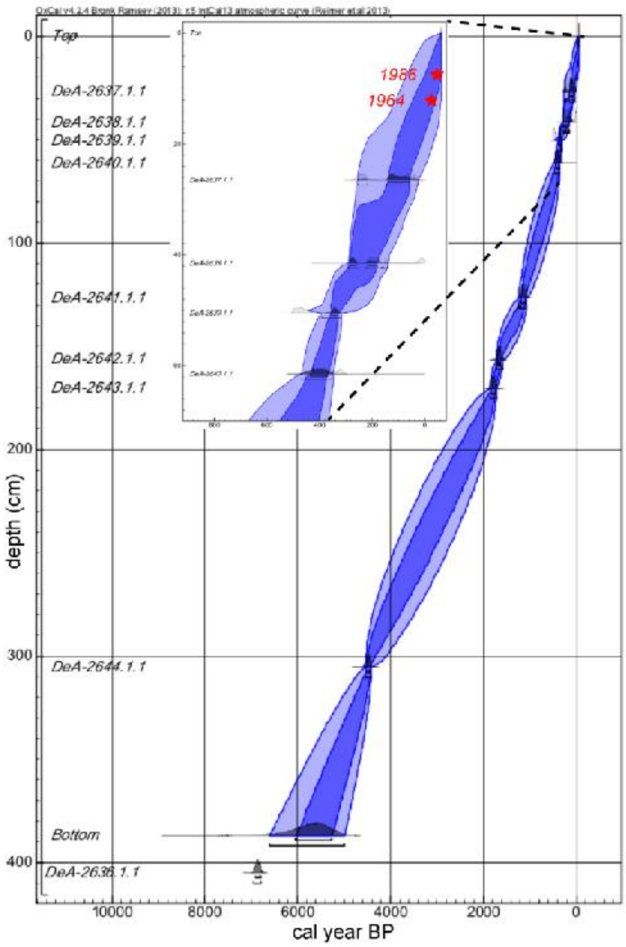


Fig. 1.3.23. Depth-age model of the Bolătău sediment sequence. Light (dark) shading shows the 95% (68%) confidence range of the Bayesian model. Original and modelled probability density functions of the calibrated ^{14}C ages are plotted by white and dark grey, respectively. Uppermost 70 cm is enlarged and the assigned of ^{137}Cs marker horizons (see Fig. 1.3.24) are indicated by stars. The sample below the 'Bottom' position presents the calibration results of the ^{14}C analysis of the wood sample obtained from the landslide body.

Two distinct ^{137}Cs peaks were found at 6-7 cm and 11-12 cm depth interval (Fig 1.3.24). The deposited inventory of bomb-derived fallout of ^{137}Cs has been about 5-7 kBq/m^2 for sites with medium latitudes and continental climate (Ritchie and McHenry 1990). The radiocaesium release of the accident of the Chernobyl NPP affected the areas far off according to short-term plume trajectories and weather conditions (De Cort el al., 1998). Regarding the territory of Romania the highest deposits were found in Transylvania (>80 kBq/m^2) while measured average deposition in Suceava following the event was 13.5 kBq/m^2 (Cosma, 2002).

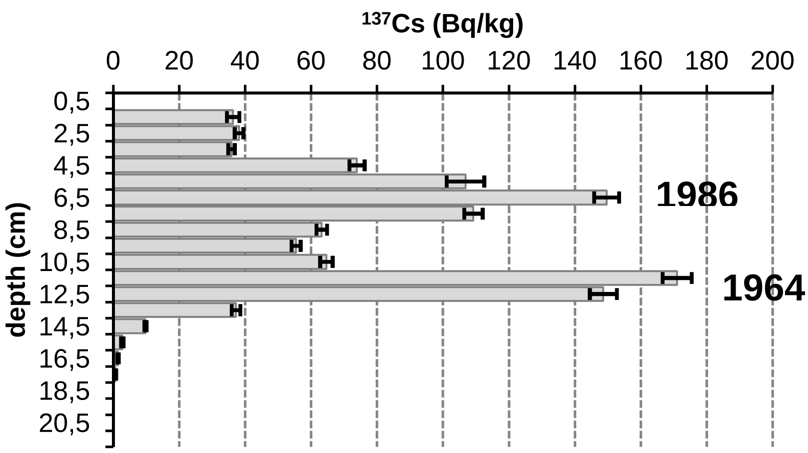


Fig. 1.3.24. Radiocaesium specific activities along the 20 cm topmost section of the Bolătău sediment sequence. Whiskers indicate the estimated analytical error. The distinct concentration peaks supposed to be coincident with 1986 (Chernobyl accident) and 1964 (north hemispheric fallout maximum) are indicated.

This double peak pattern of ^{137}Cs profiles is quite typical for the undisturbed sediment profiles in the broader region (Begy et al. 2011, Blebea-Apostu et al. 2012, Alhajji et al., 2014). Thus, in line with the usual practice, the higher and the deeper ^{137}Cs peak horizons were assigned to 1986 AD and 1964 AD, respectively.

The OxCal agreement indices for the individual ^{14}C samples ranged from 74.9 to 103.6% (Tab. 1.3.5), while the overall series OxCal agreement index (A_{modell}=93%) proved to be satisfactory.

Established age model allowed estimating the achieved temporal resolution corresponding to the 1 cm sampling units. The 1 cm samples integrate 6-7 years over the uppermost 50 cm, 20-22 years between 170 and 300 cm depth interval while a 10-15 years resolution is obtained over the rest of the core. As a consequence, present sampling strategy offers (sub)decadal resolution for the last 1200 years, while the finest achievable uniform temporal resolution is bidecadal from the current dataset. If a decadal-scale environmental history is desired to decipher from this sedimentary archive then finer sampling resolution (e.g. 0. 5 cm slicing) is needed for future cores (Mindrescu et al., 2015, submitted).

Other dating techniques: OSL

Radiocarbon dating was used extensively for lake sediments chronologies, particularly vegetation history and climate variability studies.

However, due to the lack of organic matter (or/and pollen) in some types of deposits, this method cannot be successfully employed for dating; it is the case with the bottom part of glacial lakes sediment sequences or other types of old lakes from Romania, where we were unable to determine the exact time of the onset of sedimentation using radiocarbon, particularly in the transition period from the Plistocene to the Holocene. Therefore, we employed a new dating technique, i.e. **optically-stimulated luminescence (OSL)**, mainly for dating the onset of sedimentation in lake basins following glacier retreat, but not exclusively.

Figure 1.3.25. OSL sampling using plastic tubes.

Thus far we used OSL for dating the records from two lacustrine sites in Romania: Florica glacial lake from Retezat Mts, and Varvata palaeolake (Suceava county) from the Moldavian tableland. In order to be able to use this technique, a large lacustrine catchment is required which allows for long distance transport of the sediments before settling down in the lake.

For OSL sampling we used 15-20 cm plastic tubes, 7.5 in diameter, dark coloured (black or dark grey) and thick enough to prevent sunlight or other types of light from penetrating the walls after sampling. The sampling procedure varies according to the type of sediment being sampled; however, as a general rule, the samples should contain material which has not been subjected to the freeze-thaw cycle, exposed to light or affected by cracks etc. (see Fig. 1.3.25). A general lithological description of the site, as well as photos of the site, are also needed when collecting samples for OSL dating.

The investigations on the two lacustrine sites using OSL dating yielded two absolute dates for lake Florica and one for Varvata. At lake Florica, the age of the profile bottom is 16.0±2.8 ka (180-195 cm), whereas the transition from clastic to organic material occurred at 12.3±2.2 ka (122-135 cm) (Fig. 1.3.26).

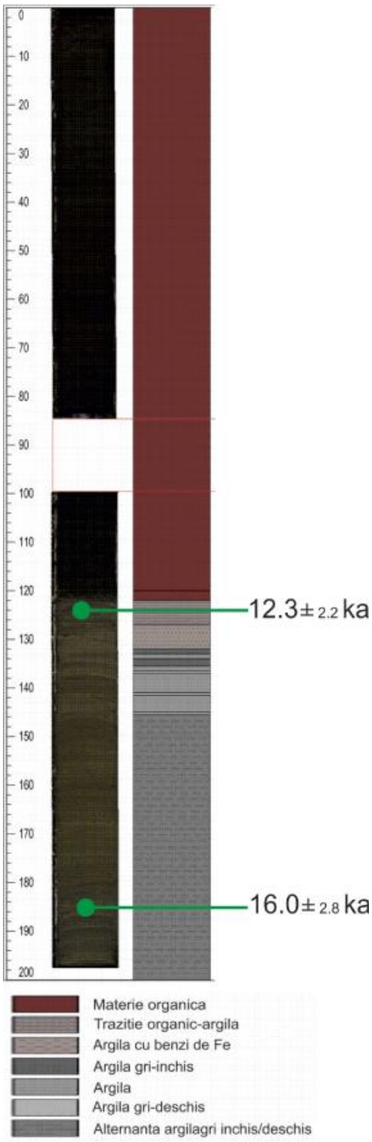


Figure 1.3.26. Optically-stimulated luminescence dating of glacial lake Florica, Retezat Mts (OSL measurements: Timar-Gabor Alida, UBB Cluj).

In the case of Varvata palaeolake, the OSL sample was collected from the middle of sediment profile (approx. 100 cm depth), where the determined age was 15.6±2 ka (Fig. 1.3.27b).

Despite inherent errors which oftentime interfer with the accuracy of OSL dating, some conclusions can be drawn from the dates we obtained thus far. The onset of sedimentation in glacial lakes from Retezat Mts occurred rather early, which would indicate that during Young Dryas the glacial lakes were already ice-free. It is however possible that some small-sized hanging headwall glaciers still existed, but not as extensive as was suggested by Reuther et al., 2007.

As regards the Varvata site, based on the OSL measurements performed thus far, it appears that this is likely one of the oldest palaeolake sites from Romania, and we believe it came into existence as a lake basin during deglaciation (Last termination), when the melting permafrost often triggered large-scale landsliding which blocked the early drainage network. In this case, a large landslide-dammed lake of ca. 45 ha formed (Fig. 1.3.27a). Further on, we intend to compare the palaeodata from the Varvata site woth the results obtained at Măgheruș (Lascu et al., 2014); the two sites are similar in terms of elevation range, appearence (palaeolakes), and are located on opposite sides of the Carpathian range, to the east, and the west, respectively, which is a good situation for a palaeoclimate transect across the Carpathians.

a b

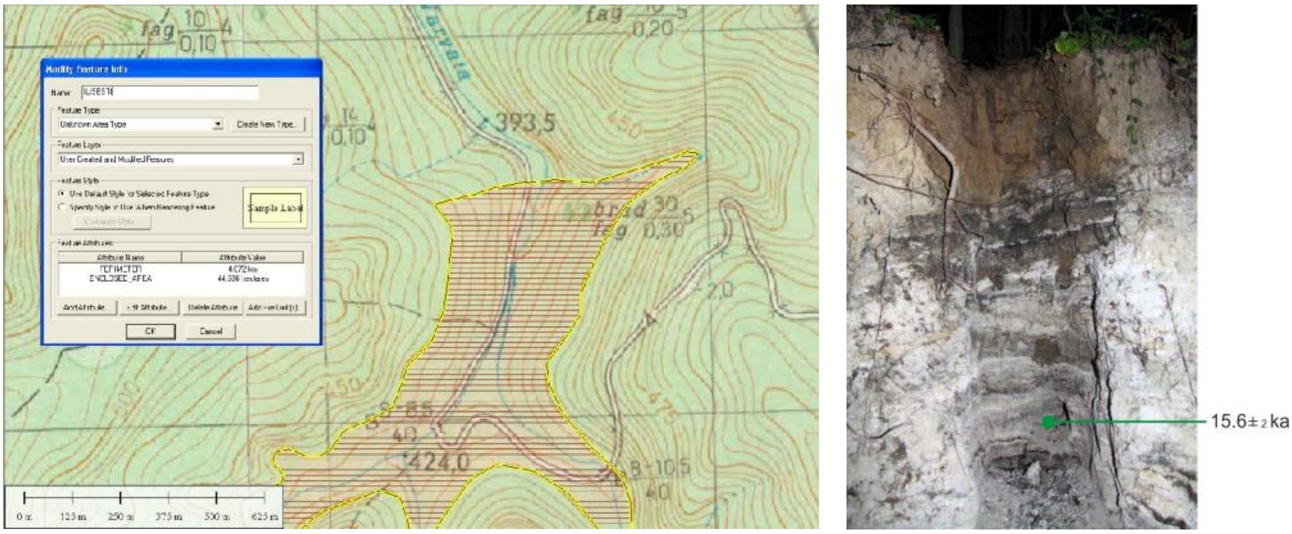


Fig. 1.3.27. Varvata palaeolake location and size (a) and OSL dating of palaeolake sediments (b).

Assessment of sedimentation rates

Based on the data published in the limnological/palaeolimnological literature conjunctly with our own results we proceeded to estimate sedimentation rates in all investigated lacustrine and peatbog sites (i.e. 40 sites) from Romania for the longest duration available (see Fig. 1.5.1 and Table 1.5.1) which varies according to the extant chronological data.

The earliest estimates on sedimentation rates and sediment sources were made for the landslide-dammed lake Lacu Roşu, in the Eastern Carpathians (Bojoi, 1968). 40 years later the sedimentation rate at Lacu Roşu was assessed again using radiometric dating techniques

(^{210}Pb and ^{137}Cs), yielding a mean sedimentation accumulation rate (SAR) of 0.87 ± 0.17 g/cm^2 yr (11.70 mm/yr) which would indicate that the lake will be 80% silted in 81 ± 30yrs if the current rate is maintained (Begy et al., 2014). ^{137}Cs originating from both sources (Chernobyl, 1986 and nuclear weapon tests from 1963) was determined; the first peak appears at the depth of 23 cm whereas the second was observed at 42 cm (Begy at al., 2009).

At Iezer-Feredeu lake, a landslide-dammed lake located in the Northern Carpathians, the average estimated sedimentation rate (SR) amounted to 3.73 mm/yr during its 1035 yrs cal BP lifespan (Mîndrescu et al., 2013). Iezer-Feredeu greatly differs from Lacu Roșu in terms of mean SR values, mainly due to size differences between their catchments: Lacu Roșu has a catchment (3880 ha) more than 10 times the size of Iezer catchment (355 ha).

In the vicinity of the Iezer-Feredeu lies Bolătău-Feredeu lake, with similar origins as the former but considerably older according to the latest findings, i.e. 6.8-7 k yrs BP (Mîndrescu et al., 2015, submitted). Its mean calculated sedimentation rate is 0.70 mm/yr during the past 4500 yrs BP. The sediment accumulation rate assessed solely for the last millenium is ca. 0.1 mm/yr, almost 4 times lower compared to lake Iezer, both of which were estimated based on radiocarbon dating of the profile bottom. As the two lakes evolved under very similar topographic (elevation, relief), geological and vegetation cover conditions, the sole difference between the two is lies in the size of the catchments - 30 ha in the case of Bolătău vs 355 at Iezer, demonstrating the importance of catchment size in relation to the magnitude of sediment accumulation. The two ^{137}Cs isotope peaks were determined at 6.5 and 12 cm depth (Mîndrescu et al., 2015, submitted). Compared to Lacu Roșu, whereby similar data is available, it should be noted that during the past 50 years the mean rates were constant in both lakes but very different in terms of value: 8.5 mm/yr in Lacu Roșu and 2.4 mm/yr in Bolătău-Feredeu.

A similarly high sedimentation rate was documented in glacial lake Ştiol, Rodna Mts, which was modified through human intervention (disabled lake) by building a dam in a strict scientific reserve. Between the creation of the dam (October 2002) and the sediment sampling in July 2006, an approximately 25 mm thick sediment layer has accumulated on the bed of the lake. The rate of sedimentation in this period may therefore be calculated as 6.25 mm/yr and it would appear that sedimentation has increased at least 16 times since the creation of the dam (Mîndrescu et al., 2010b).

Sedimentation rates in natural lakes and peat bogs are paralleled to the same parameters determined for reservoirs. Relevant contributions to the study of lacustrine sedimentation in reservoirs were made by Rădoane and Rădoane (2005) whose approach focused on the silting degree and silting rates of 138 reservoirs. It was estimated that the areas producing the largest amounts of sediments which consequently result in high lacustrine sedimentation rates are the Southern and Curvature Subcarpathians whereby many of the reservoirs are located (Fig. 1.5.1). The study determined that Romania ranks among the countries with high reservoir sedimentation rates (min. 6 - max. 3208 $m^3km^{-2}yr^{-1}$). Moreover, the total sedimentation rate (21.670 hm^3yr^{-1}) ranges among the highest in Europe (Verstraeten et al., 2006). The magnitude of sedimentation in reservoirs is also high in the Moldavian Plateau (eastern Romania) as a result of intensive soil erosion, ranging from 15 to 115 mm/yr, particularly in Tutova Hills, whereby the rates determined based on ^{137}Cs determinations are commonly above 60 mm/yr (Ioniță et al., 2000). Overall, sedimentation rates in natural lacustrine sites are significantly lower compared to their counterparts in reservoirs due to a variety of factors of which the most relevant are the size of the catchment (considerably greater in reservoirs) and the type of water and sediment supply.

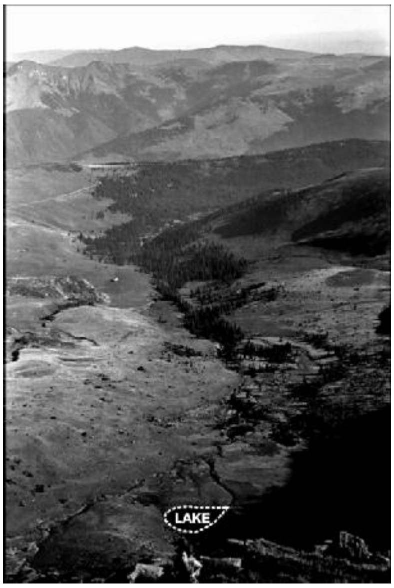
Altogether, based on the data provided by all reviewed studies, the *long-term sedimentation rates* were computed for 40 natural open lake and peat bog sites which have been investigated during the past decades, the majority of which were obtained based on radiocarbon dates, and to a lesser extent ^{210}Pb dates (in the cases of lakes Ştiol, Capra and Lacu Roşu) (see Table 1.5.1 and Fig. 1.5.1). According to our review, the mean values range from 0.04 (lake Sfânta Ana) to 11.7 mm/yr (Lacu Roşu); the intermediate mean sedimentation rates are ranked in 4 classes, as follows: *(1) SR under 0.21 mm/yr*, typical for the two volcanic crater water bodies, lake Sfânta Ana and Mohoş peatbog, as well as some glacial lakes (e.g., Buhăescu Mare in Rodna Mts) and plateau lakes fed by very small-sized catchments, such as Tăul dintre Brazi or Padiș-Sondori; *(2) SR between 0.28 and 0.49 mm/yr*, documented in glacial lakes such as lake Cristina (Maramureş Mts), sackung lakes and large peatbogs (Luci, Harghita Mts); *(3) SR between 0.52 and 0.76 mm/yr*, typical for the majority of glacial lakes, as well as landslide-dammed lake Bolătău-Feredeu; *(4) SR above 1 mm/yr*, characteristic for glacial lakes Ştiol from Rodna Mts and Capra from Făgăraş Mts (whereby the sedimentation rates were determined for the past 160 years), Molhașul Mare peatbog (mid-Holocene age), as well as landslide-dammed lakes Iezer-Feredeu (3.73 mm/yr for the past 1.150 kyr) and Lacu Roşu.

1.4 Assessment of human impact using lake sediments

Physical impact on lakes recorded by lake sediments

As a result of the Carpathian glaciers retreating numerous water bodies were left behind in the Romanian Carpathians. Some were large and deep, but many more were simply small water-filled hollows. Underlain by moraine deposits or rock, these young ecosystems have matured during the course of the Holocene.

We were interested in understanding how these lakes were impacted on by various physical changes. One of the glacial lakes we investigated was lake Stiol from Rodna Mts, which represented a typical glacial cirque lake (*Pre dam Lake Stiol* - Fig 1.4.1, left), circular and with considerable depth (by comparison with its horizontal dimensions), that was formed towards the end of the Quaternary glaciations of the Eastern Carpathians. It took shape behind a cirque moraine, whose left 'wing' appears today as a peninsula inside the post dam Lake Stiol. Its origins were mixed being a result of both glacial erosion processes and moraine related damming. Although it was formed within a large cirque, the pre dam lake was relatively small (approx. 600 m^2 in 1968), and its catchment was only 32% of the surface of the outer cirque, situated above the lake.



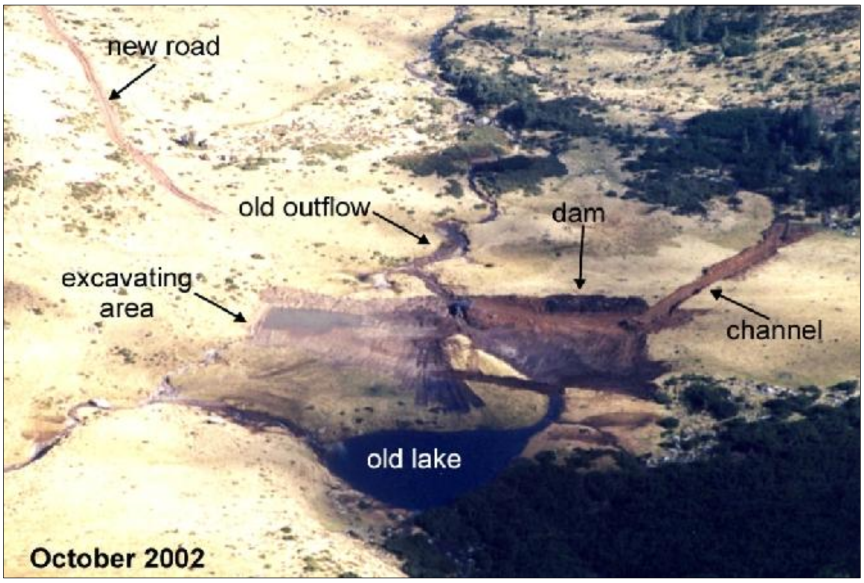


Fig. 1.4.1. Left: Lake Stiol on 21st September 1975 (photo: Pascu D.). Right: Construction works at Lake Ştiol on the 3rd of October 2002 (photo: Goja L.).

In September-October 2002 a dam was built (Fig 1.4.1, right), resulting in the artificial increase of the water level of the lake. The dam is situated at a distance of 80 m downstream from the old lake. Moreover, the materials used for the construction of the dam were taken from the lake basin. Furthermore the road built from Prislop Pass facilitated access to the lake, suh that, in time, the lake became a place not only for recreation, but also an area for picnics and camping, although the lake site is part of the protected area of Rodnei Mts

National Park. Nevertheless, this has increased visitor pressure at the site. Trampling of vegetation is one of the most widespread environmentally degrading repercussions of recreation in the Bistricioarei cirque and can also lead to excessive soil erosion.

By building the dam, not only have the original contours of the lake been destroyed, but also its dimensional characteristics have been modified. Even during the period of dam construction it almost doubled its surface area reaching approximately 1,100m^2 in October 2002. The greatest modifications were in the volume of water (it grew 33 times) and its surface extent (increasing 18 times). Consequently, the original glacial lake, in the shape of a tear drop and of small dimensions, effectively turned into a high altitude pond, with an uncharacteristic shape (Fig. 1.4.2).

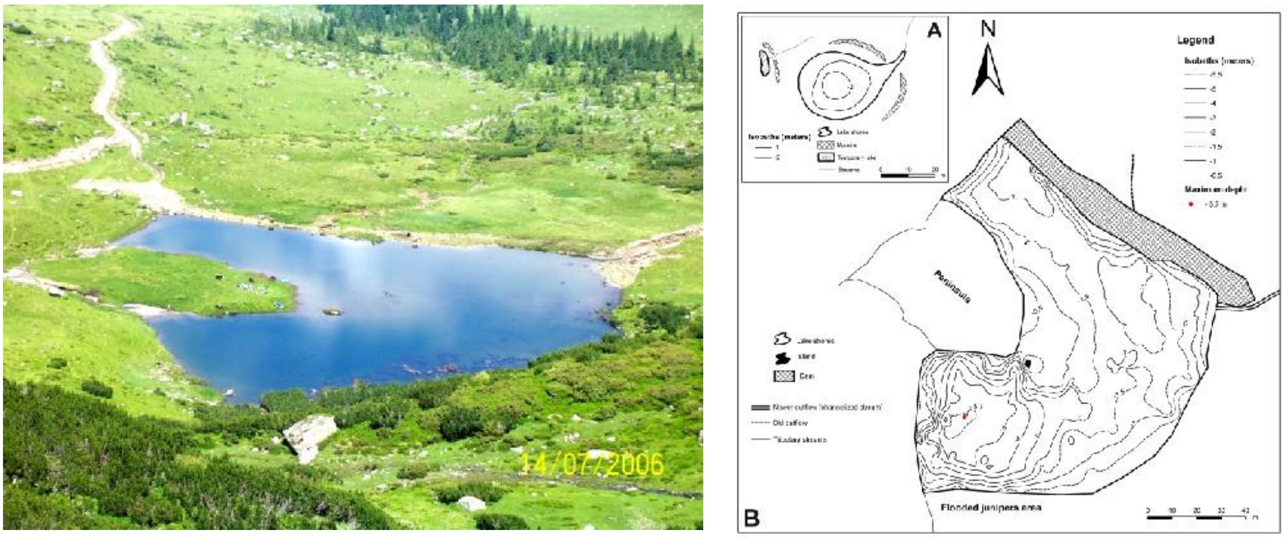


Fig. 1.4.2. Right: Post dam Lake Stiol (July 2006) (Photo: Mîndrescu M.). Left: Comparison of bathymetric surveys of Lake Știol. A: pre dam (according to Pișota, 1968); B: post dam.

The impact of dam building not only modified the physical characteristics of the lake, but also appears to have affected the properties of its sediments and the rate of sedimentation. Figure 1.4.3 shows the mineral magnetic properties of a short sediment core. The the subsurface peak in the concentration parameters *X* (magnetic susceptibility), ARM (Anhysteretic Remanent Magnetisation) and SIRM (Saturated Isothermal Remanent Magnetisation) reflects the impact of the artificial raising in the lake's level.

Between the creation of the dam (October 2002) and the sediment sampling in July 2006, an approximately 25 mm thick sediment layer has accumulated on the bed of the lake (Fig. 1.4.3). The rate of sedimentation is this period may therefore be calculated as 6,25 mm y^{-1} and it would appear that sediment yield has increased at least 16 times since the creation of the dam (Mîndrescu et al., 2010b).

Later on, we used radiometric measurements and the characterisation of sediment (top core = 20cm) properties from Știol with the aim to assess temporal and spatial variability in sediment accumulation rates (SARs) (Hutchinson et al., 2015).

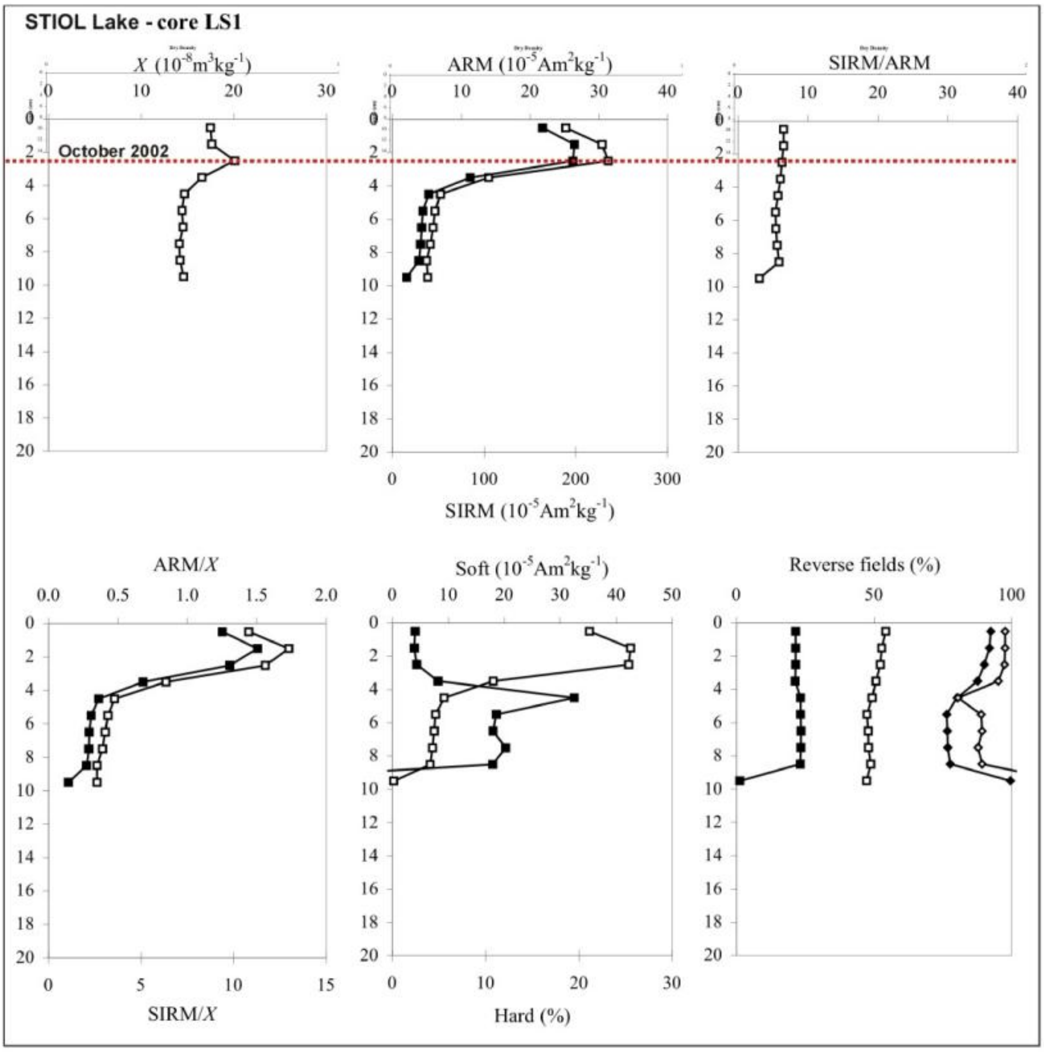


Fig. 1.4.3. Mineral magnetic properties of a short sediment core from post dam Lake Stiol (core LS1) (Key: SIRM, SIRM/*X* and Hard shown as solid symbols. Reverse field measurements at -20mT (closed squares), -40mT (open squares), -100mT (closed diamonds) and -300mT (open diamonds).

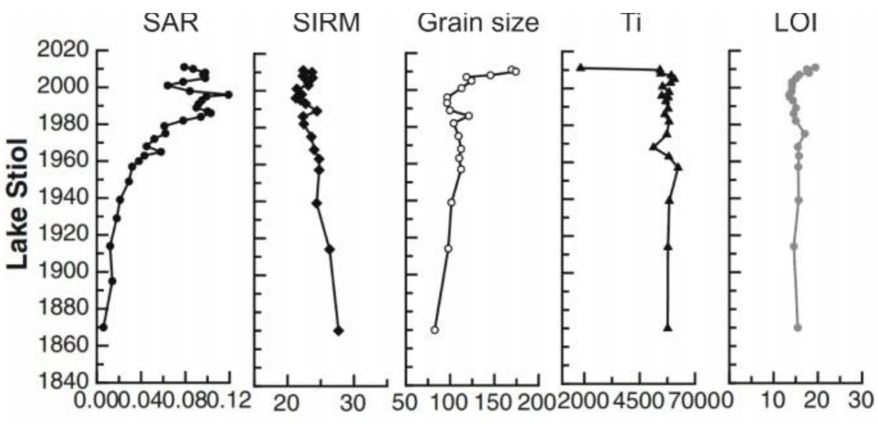


Fig. 1.4.4. Ştiol lake: sediment accumulation rate (SAR) (g cm^{-2}year^{-1}), saturation isothermal remanent magnetisation (SIRM; 10^{-5} Am^2 kg^{-1}), median grain size (micron), Ti content (mg kg^{-1}) and organic matter content (%) for Ştiol lake (graph 1-SAR, graph 2-SIRM, graph 3-Grain size, graph 4-Ti, graph 5-LOI/loss on ignition).

Thus, at Lake Ştiol, there is an increasing trend in the SAR from 1840 to 1965, followed by two clear episodes of high sediment accumulation: one around 1965 (from 0.04 to0.06 g cm^{-2} year^{-1}) and the second and more marked one after 2002 (from 0.06 to 0.09 g cm^{-2} year^{-1}) when the dam was built up. The general rise in SAR at this site corresponded most closely to an increase in particle size (Fig. 1.4.4).

Lake sediments and atmospheric pollution

The role of palaeolimnology in relation to the assessment of environmental pollution has been set out by Smol (2008), whereas Cohen (2003) details a wider range of applications of lake sediment-based research. Birks and Birks (2006) have reviewed the use of multiproxy studies in palaeolimnology, and Last and Smol (2001a, 2001b) and Smol et al. (2001a, 2001b) present relevant techniques employed both in the field and the laboratory. Indeed, palaeolimnology has been described as a substantial tool for monitoring environmental change providing an important longer-term temporal perspective and enhancing environmental assessment (e.g., Smol, 1992; Anderson and Battarbee, 1994; Anderson, 1995).

The Carpathian Mountains traverse Romania and hold around 270 glacial lakes in a region where there are considerable environmental concerns, but rather sparse environmental data. Nevertheless, relatively little has been published from this region on the alteration of their sediment characteristics due to recent human-induced environmental impacts despite a long tradition of palaeoecological study in the region (see Feurdean et al., 2007a,b).

Short lake sediment cores from lakes in the Romanian Carpathians have been analysed, both mineral magnetically and geochemically, providing an assessment of the potential of these mountain lakes' sediment records as a retrospective indicator of atmospheric pollution. Mineral magnetic characteristics suggest that recent sediments have been affected by atmospheric particulate pollution associated with fossil fuel combustion and vehicle emissions, although the properties may also reflect within-lake processes.

The sampled lakes were selected from two main areas: Rodna and Maramures Mts (6 sites) in the Northern Romanian Carpathians, and Făgăraș Mts (4 sites) in the Southern Carpathians. These areas represent the highest sections of the Carpathian Range in Romania. The lake sediment cores recovered varied in length from 12 to 35 cm, where the shortest cores are commonly those from the Rodna and Maramureș Mts. Key characteristics of the ten lakes sampled and their catchments are listed in Table 1.4.1 below.

One of the principal magnetic characteristics of their sediments is illustrated in Fig. 1.4.5 which shows some increase in the magnetic concentration parameter SIRM in the uppermost part of all their profiles. At the point in each core at which SIRM increases, there is also a shift in the parameters 'soft' and 'hard'. There is also a corresponding decrease in the SIRM/ARM ratio. These qualitative changes indicate that the apparent increase in the magnetic concentration of the sediments is also associated with a change in their magnetic grain size and mineralogy. Such features have been identified in other lake sediment profiles across Europe, and may indicate the influence of the atmospheric deposition of particulate pollution associated with fossil fuel combustion and vehicle emissions (e.g., Oldfield and Richardson, 1990; Renberg and Battarbee, 1990; Hutchinson, 1995; Korhola et al., 2002; Lotter et al., 2002).

Table 1.4.1. Summary table of catchment, lake and sediment core data. Catchment and lake areas were determined from 2005 aerial photography (except Stiol* where this was calculated after the enlargement of the lake by damming, see Mîndrescu et al., 2010). Lake depth and sediment core length were determined in the field

Site	Location	Elevation (m)	Catchment area (ha)	Lake area (ha)	Depth (max.) (m)	Catchment:lake ratio	Sediment max core length (m)
Northern sites							
Bila	47° 31′ 58″ N 24° 52′ 08″ E	1840	43.8	0.14	0.5	312.9	0.23
Buhăiescu-3	47° 35′ 14″ N 24° 38′ 48″ E	1825	62.9	0.09	0.5	698.9	0.12
Lala Mare	47° 31′ 41″ N 24° 54′ 04″ E	1810	16.1	0.70	1.6	23.0	0.18
Pietrosul	47° 35′ 54″ N 24° 38′ 52″ E	1835	54.4	0.41	2.3	132.7	0.12
Ştiol*	47° 34′ 30″ N 24° 48′ 55″ E	1671	156*	1.06*	5.0	147.2	0.18
Vinderel	47° 04′ 36″ N 24° 27′ 26″ E	1684	5.1	0.06	5.5	85.0	0.16
Southern sites							
Bâlea	45° 36′ 13″ N 24° 37′ 07″ E	2035	45.5	4.78	10.5	9.5	0.30
Călţun	45° 34′ 55″ N 24° 34′ 26″ E	2139	18.6	0.80	13.0	23.3	0.33
Capra	45° 36′ 03″ N 24° 37′ 46″ E	2249	29.7	1.87	8.6	15.9	0.35
Podragu Mare	45° 36′ 34″ N 24° 41′ 32″ E	2066	55.2	3.13	16.5	17.6	0.20

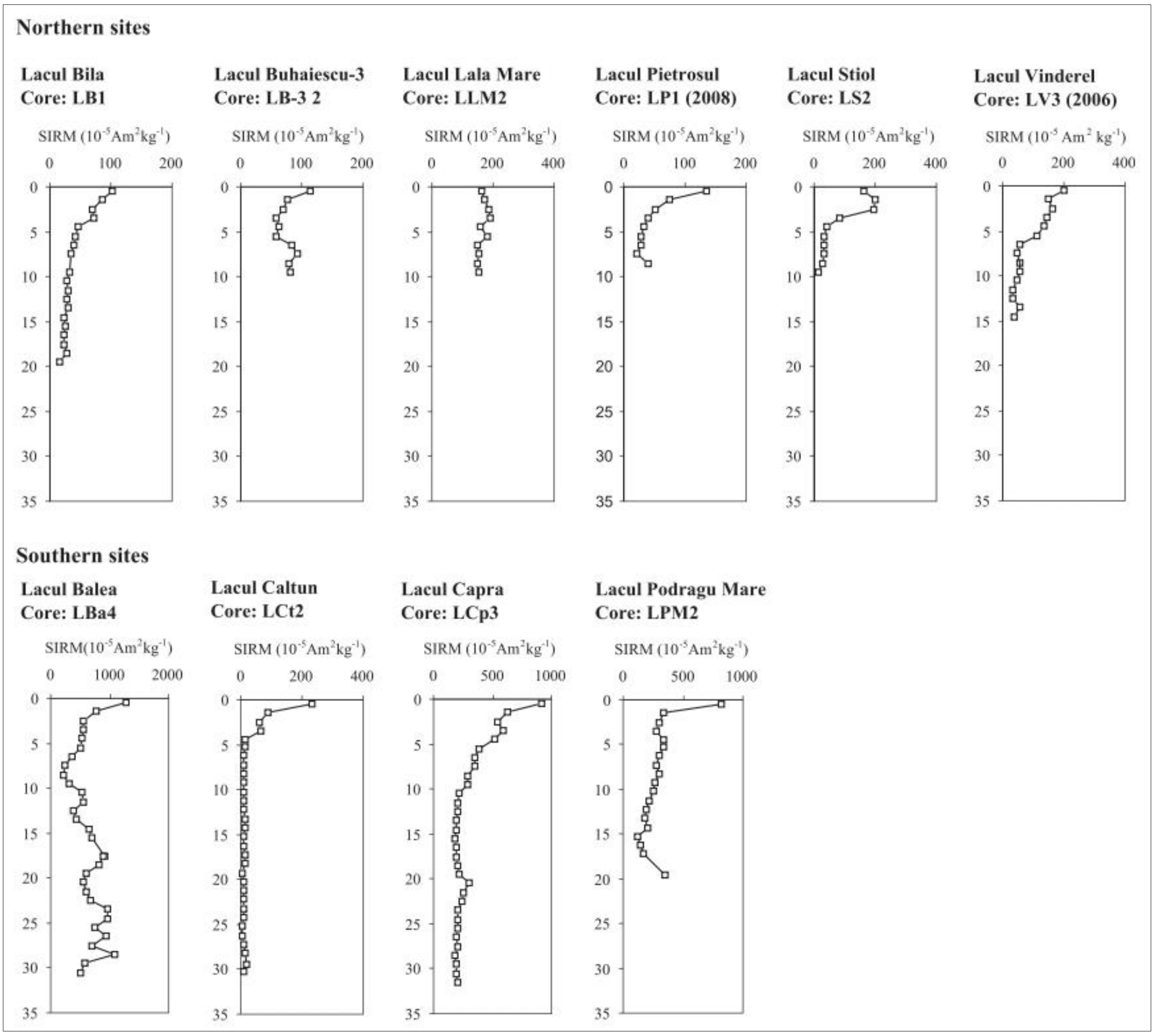


Fig. 1.4.5. Down-core SIRM profiles for the Bila, Buhăiescu 3, Lala Mare Pietrosu Ştiol (Rodna Mts), Vinderel (Maramureş Mts) Bâlea, Capra and Podragui Mare (Făgăraş Mts) lakes.

These sites therefore illustrate the potential of this technique to highlight lake basins whose characteristics and/or catchment history may make their sediments sub-optimal for sediment-based reconstruction of atmospheric pollution.

Also, the geochemical characteristics of sediments can provide excellent palaeoenvironmental records (Battarbee et al., 2002). Calculating sediment metal enrichment factors (EFs) is an approach that has been applied in a number of studies as a means of rapidly assessing the additional burden of trace metals present in sediments as a function of human activities such as atmospheric pollution (e.g., Dauvalter, 1994; Johansson et al., 1995; Rognerud and Fjeld, 2001; Tylmann et al., 2001). The approach relies upon the assumption that the undisturbed sediment surface reflects contemporary levels of contaminants and that deeper, older sediments characterise pristine, or at least, preindustrial conditions. The EF is the ratio of the concentration of an element at the surface of the sediment (present) to that at depth (background) and thereby takes into consideration the geogenic inputs (via runoff and/or atmosphere). Sediment core top and bottom concentrations for a range of selected trace metals likely to have been deposited as a result of pollutant emissions are given in Table 1.4.2.

Table 1.4.2. Selected trace metal concentrations (mg kg^{-1}) in the top and bottom layers of sediment cores and calculated enrichment factors (EFs)

Site; core	Depth (cm)	Co	Cr	Cu	Ni	Pb	Zn
Northern region							
Top							
Bila; LB 1	0.5	6.8	43.9	41.0	41.0	186.4	131.7
Buhăiescu 3; LB 3 2	0.5	4.7	30.4	29.1	24.9	116.2	148.4
Lala Mare; LLM 2	0.5	11.3	45.4	35.3	43.4	100.3	115.2
Pietrosul; LP 1(08)	0.5	12.0	23.4	38.6	25.3	140.1	129.5
Ştiol; LS 2	0.5	4.5	45.1	22.7	31.5	87.0	105.6
Vinderel; LV 3(06)	1.5	7.8	33.8	21.4	36.0	103.6	105.1
Mean		7.8	37.0	31.4	33.7	122.3	122.6
Bottom							
Bila; LB 1	19.5	6.1	47.4	20.4	38.2	140.2	119.1
Buhăiescu-3; LB-3 2	9.5	10.4	35.4	32.1	29.4	59.5	92.1
Lala Mare; LLM 2	9.5	13.9	50.4	40.8	43.6	97.1	105.6
Pietrosul; LP 1(08)	8.5	15.2	36.5	33.2	37.9	61.1	83.6
Ştiol; LS 2	9.5	13.9	92.2	52.3	57.4	79.2	95.6
Vinderel; LV3(06)	13.5	10.4	37.3	20.5	37.1	70.4	99.4
Mean		11.6	49.9	33.2	40.6	84.6	99.2
EF							
Bila; LB 1		1.1	0.9	2.0	1.1	1.3	1.1
Buhăiescu-3; LB-3 2		0.4	0.9	0.9	0.8	2.0	1.6
Lala Mare; LLM 2		0.8	0.9	0.9	1.0	1.0	1.1
Pietrosul; LP 1(08)		0.8	0.6	1.2	0.7	2.3	1.6
Ştiol; LS 2		0.3	0.5	0.4	0.5	1.1	1.1
Vinderel; LV 3(06)		0.8	0.9	1.0	1.0	1.5	1.1
Mean		0.7	0.8	1.1	0.9	1.5	1.3
Southern region							
Top							
Bâlea; LBa 4	0.5	30.2	172.3	91.1	143.8	278.8	308.5
Călţun; LCt 2	0.5	22.0	37.8	80.0	37.0	163.3	163.7
Capra; LCa 3	0.5	41.9	96.6	67.4	71.8	243.9	183.4
Podragu Mare; LPM 2	0.5	17.3	78.5	74.8	50.6	170.2	148.3
Mean		27.8	96.3	78.3	75.8	214.0	201.0
Bottom							
Bâlea; LBa 4	30.5	42.1	239.6	116.1	208.3	153.9	170.3
Călţun; LCt 2	31.25	23.3	38.4	56.3	40.8	85.6	126.4
Capra; LCa 3	30.5	47.0	144.0	104.7	94.7	95.9	87.2
Podragu Mare; LPM 2	18.25	15.0	73.1	48.1	46.0	64.0	86.2
Mean		31.8	123.8	81.3	97.4	99.9	117.5
EF							
Bâlea; LBa 4		0.7	0.7	0.8	0.7	1.8	1.8
Călţun; LCt 2		0.9	1.0	1.4	0.9	1.9	1.3
Capra; LCa 3		0.9	0.7	0.6	0.8	2.5	2.1
Podragu Mare; LPM 2		1.2	1.1	1.6	1.1	2.7	1.7
Mean		0.9	0.9	1.1	0.9	2.2	1.7

In the case of all trace metals, both the mean top and the mean bottom core sample concentrations are highest in the southern region (Table 1.4.2). This likely reflects the difference in the catchment geologies of the two areas mentioned above and follows a similar pattern to that for of mineral magnetic properties. In both regions, only Pb and Zn concentrations are higher at the top of the core than in the corresponding bottom sediments. In the Rodna and Maramures Mts, maximum sediment core top concentrations of Pb and Zn are 186.4 (lake Bila) and 148.4 mg kg (lake Buhăescu-3) respectively. In Făgăraș Mts they are higher at 278.8 and 308.5 mg kg^{-1} (both lake Bâlea) respectively. In the northern region the relative abundance of the trace metals reported is the same in both the mean surface and the mean bottom samples (Zn > Pb > Cr > Ni > Cu > Co), whereas in Făgăraș Mts these mean relative abundances differ from the former, and also between the surface (Pb > Zn > Cr > Cu > Ni > Co) and the bottom sediment samples (Cr > Zn > Pb > Ni > Cu > Co), which again may reflect the differing geologies of the two regions.

In conclusion, the use of mineral magnetic measurements and metal enrichment factors can be effective; while the former appear to indicate some regional scale variability in the apparent levels of atmospheric particulate deposition, the latter are relatively easy to determine, and also suggest, in the case of Pb and Zn at least, a similar pattern. The Southern Carpathians are generally closer to potential pollution sources in Romania. Overall, metal enrichment factors for contemporary sediments reveal that remote mountain lakes in this region appear to have been impacted by the long-range atmospheric transport of metallic pollutants. The results suggest that sites in the southern range are most impacted, although trace metal levels are relatively modest. Initial findings suggest that some sites have the potential to provide lake sediment-based pollution histories that will thereby contribute to a fuller, Europe-wide understanding of the impact of atmospheric pollutants in upland regions.

The earliest and most recent human impact

The *earliest human impact* in Romania appears within the palynological records around 8,000-7,000 cal y BP in the Central, Western and North-Western Romanian regions when the spatial heterogeneity of the landscape increased. However, in Eastern Romania the human presence is documented as late as ca. 4,000 cal y BP, which would suggest, when corroborated with archeological data, that the Eastern region was outside the major human movement tracks. This finding leaves room for more interpretation about how human settlements developed within the Romanian territory and how/whether this is related to climate (Fig. 1.5.2).

In the lowlands the human impact markedly altered burning trends from about 5,500 cal yr BP onward, whereas in the mountain regions its earliest influence was felt later, around 3,500 cal yr BP. It appears that prior to ca. 2,500 cal y BP the disturbances were mostly natural (Feurdean et al., 2010) and only after this date the human impact became more prominent. Recent research revealed a strong link between major land-use strategies of prehistoric societies (the use of fire as a tool to clear forests and extend alpine pastures) and changes in vegetation diversity (Feurdean et al., 2013a).

The most recent and alarming human impact on the environment was also traced in the Romanian Carpathians by means of multi-pollutant chemical and biological analyses (Begy et al., 2009, 2011; Rose et al., 2009). Thus, the past 250 years received special attention due to the significant changes occurring in lake ecosystems during this timeframe (e.g., acidification, high productivity) driven mainly by anthropogenic activities undertaken near or within the catchments. The Lacul Negru sediment record showed that the earliest atmospheric contamination occurred in 16th century with the inception of industrial activities, followed by an important increase in the 18th century, when the release of atmospheric pollutants was associated with coal combustion activities. Over the last ~300 years, the changes experienced by lake ecosystems are assigned to the enhanced human impact and subsequent land-use changes. Moreover, strong recent human impact has been locally highlighted in the eastern part of the Northern Carpathians based on the study of physical and geochemical properties of recent sediments at Iezer-Feredeu Lake (Mîndrescu et al., 2013).

Furthermore, ^{210}Pb and ^{137}Cs radioisotope analyses revealed that lake Sfânta Ana is experiencing an intense process of eutrophication (Begy et al., 2011). The reconstructed sedimentation rate revealed two distinct periods in the evolution of Lacu Roşu: ~1800-1989, characterized by a regular sedimentation rate when catchment deforestation was within a normal margin, and post-1989, when the high demand for wood led to increased woodfelling and triggered land-use changes and augmented sedimentation rates (Begy et al., 2009).

Recent sediment accumulation rates

Sediment accumulation rate (SAR) is a fundamental parameter that can facilitate characterisation of catchment and lake processes. Changes in SAR may also reflect the composition of flora and fauna assemblages as a result of changes in the catchment (Dearing et al., 2006). It is documented that the SAR has increased during the last 100–200 years in many lakes worldwide, reflecting intensification in land use and subsequent soil erosion. Furthermore, the use of fertilisers can lead to lake eutrophication and thereby an increase in the rate of sediment accumulation via autochthonous material (Dearing et al., 2006, 2012; Rose et al., 2011). A recent review of SAR in Western and Central Europe indicates that 71 % of the lakes assessed showed a higher recent SAR (post-1975) than during the pre-1850 period (Rose et al., 2011). It was therefore concluded that reference conditions, defined as conditions before significant anthropogenic impact, in the majority of these lakes had been altered. The same study also showed that lakes in lowlands have greater rates of sediment accumulation than those in upland areas (Rose et al., 2011). This was potentially related to a more significant modification of their catchments as a consequence of agricultural development. Mountain lakes, away from direct human impact, on the other hand, were found to be more sensitive to the effects of climate change (Catalan et al., 2002; Lami et al., 2000; Rose et al., 2011).

Despite the richness of the region in terms of lakes and peat deposits, assessment of recent changes in SARs in Romania is entirely derived from only two lakes located in the southern (a glacial lake) (Rose et al., 2009) and eastern (a natural barrage lake) Carpathians (Begy et al., 2009). In addition, Akinyemi et al. (2013) provide information on recent sediment characteristics and pollution trends in selected mountain lakes across the Romanian Carpathians.

We performed radiometric measurements (^{210}Pb, ^{241}Am and ^{137}Cs) and analysed sediment properties (organic content, mineral magnetism, grain size distribution and geochemical analyses) from six mountain lakes in the Romanian Carpathians and one from the lowlands of the Transylvanian Plain. The aims were to examine past changes and spatial variability in SARs and whether SARs have increased more recently.

The lakes in the Carpathians are located in three distinct areas within the country: in the north, in Rodna Mts (Lake Știol and Lake Buhăescu Mare) and Maramureș Mts (Lake Vinderel); in the south, in Făgăraș Mts (Lake Capra) and Retezat Mts (Lake Negru); and in the east, in Harghita Mts (Lake Sfânta Ana). The lowland lake (Lake Știucii) lies in the Transylvanian Plain, NW Romania (Fig. 1.4.6).

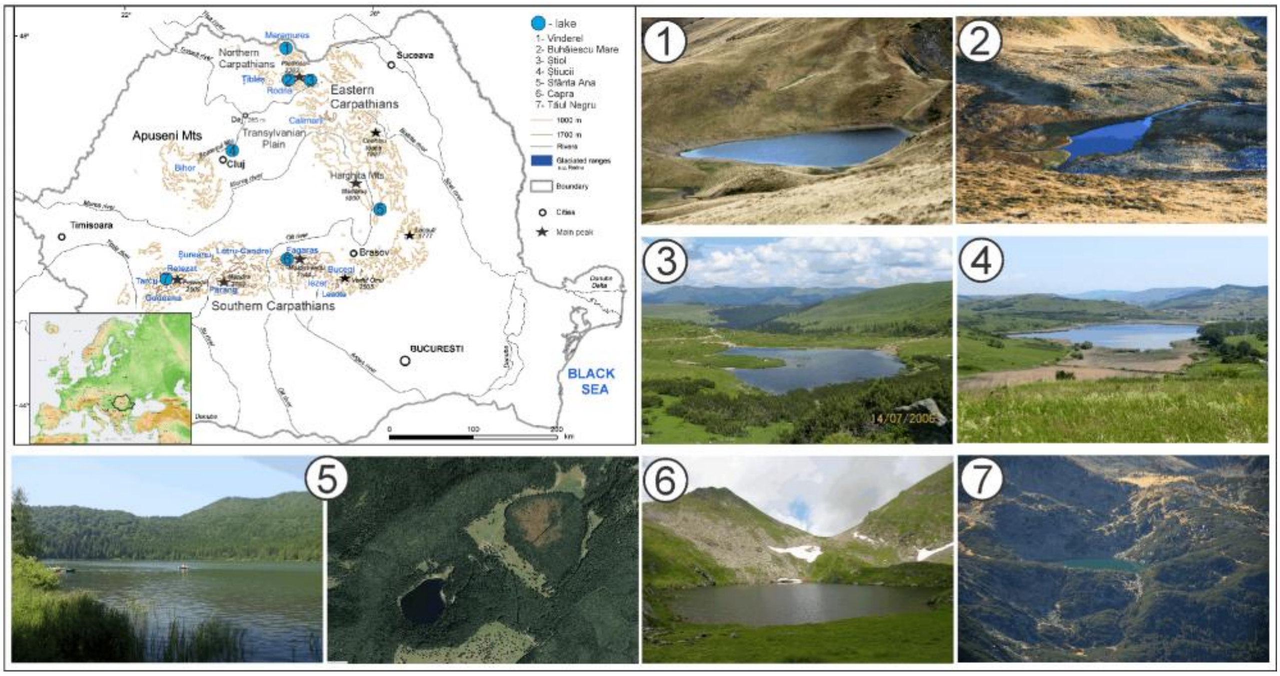


Fig. 1.4.6. a. Location of the investigated lakes. b. Photographs of lake: (1) Vinderel; (2) Buhăescu Mare; (3) Ştiol; (4) Ştiucii; (5) Lake Sfanta Ana; (6) Capra; (7) Lake Negru.

Laboratory analyses. To characterise the physical properties of the sediments (wet and dry bulk density), samples were weighed, dried at 40^{0}C and re-weighed (see Last and Smol, 2001). Saturation isothermal remanent magnetisation (SIRM) measurements were taken with a Molspin pulse discharge magnetiser. The resultant magnetic remanences were measured using a Molspin Minispin fluxgate magnetometer (Walden et al., 1999). The geochemical analyses were undertaken with a field portable Niton XL3t 900 XRF analyser mounted in a laboratory-based shield. The sediment samples were ground, and the powder pressed into cups fitted with a 6-lm-thick polyester film (Shuttleworth et al., 2014). NCS DC73308 was employed as a certified reference material (CRM). To assess the organic matter content, subsamples were dried at 105°C overnight, combusted for 5 h at 550^{0}C, and the resultant weight loss expressed as percentage loss of the dry weight (LOI; Heiri et al., 2001). The particle size distribution characteristics of the sediments were determined using a Horiba LA-950 Laser Scattering Particle Size Analyzer.

In order to determine the age of the sediments, samples were analysed for lead-210 (^{210}Pb), radon-226 (^{226}Ra), caesium-137 (^{137}Cs) and americium-241 (^{241}Am) by gamma spectroscopy (Appleby et al., 1986, 1992; Appleby, 2001). For Lake Ştiucii, Sfânta Ana, Vinderel, Tăul Negru and Capra, the radiometric analyses were performed using facilities at University College London (UCL), UK. Dried sediment samples were analysed by direct gamma assay in the Bloomsbury Environmental Isotope Facility (BEIF) at UCL, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector (Supplementary Material S1). For Lake Buhăescu Mare and Ştiol, measurements of radioisotope concentrations were taken at the Faculty of Environmental Science, University of Babes Bolyai Cluj, Romania, using an ORTEC DigiDart spectrometer with a HpGE detector, Gamma-X (GMX) type.

Age-depth models. Given the prevalence of nonlinear sediment accumulation rates, all our chronologies were constructed using the CRS model (Fig. 1.4.7).

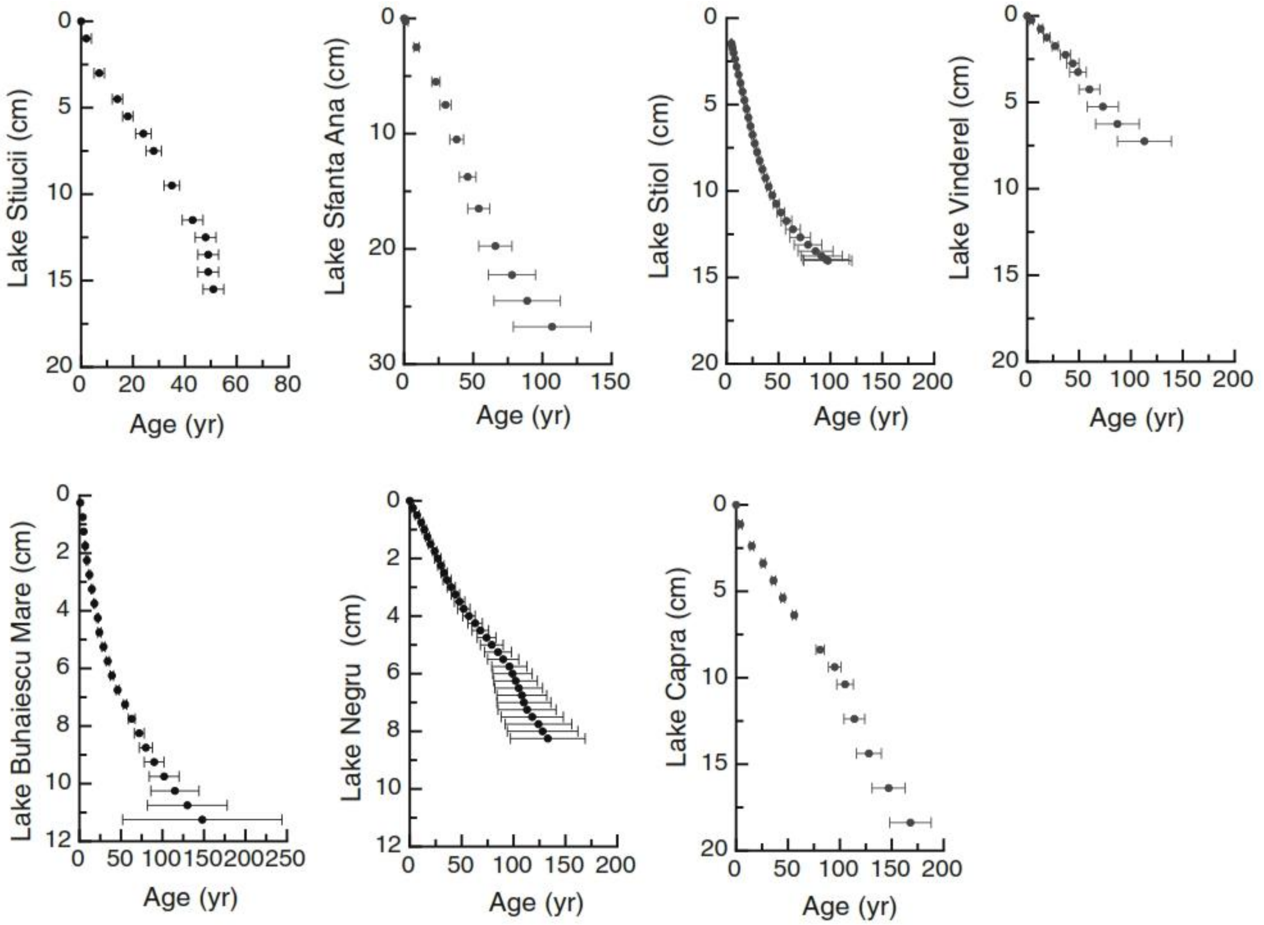


Fig. 1.4.7. Age-depth models (including the error bars) of the seven cores investigated employing CRS model ^{210}Pb dates.

Changes in the sediment accumulation rates and of sediment properties. At Lake Ştiucii, the SAR varied moderately during the period 1964 to 1988 (from 0.04 to 0.11 g cm^{-2} year^{-1}) and decreased from 1984 onwards. Ti and SIRM concentrations, as well as particle size values, largely followed similar trends to the SAR. Between 13.5 and 14.5 cm (≈1961–1963), there was a sharp peak in the sedimentation rate from 0.08 to 0.33 g cm^{-2} year^{-1} associated with a peak in SIRM. However, due to the unusual equilibrium of total ^{210}Pb activity with supporting

^{210}Pb, probably a result of a more impacted catchment, little confidence can be attached to the high sedimentation rates at depths below 13 cm. The increase in the SAR, ensued by decrease after 1984, is likely the result of intensive socialist agriculture which was implemented before 1989, and later replaced by subsistence agriculture during the 1990s, which is typical for a lowland lake located in an agricultural region of Romania.

At Lake Sfânta Ana, there was an overall increase in the SAR from 1900 to 1970 from 0.012 to 0.07 g cm^{-2} $year^{-1}$. Except for the Ti concentrations, there is little association between the increase in SAR and the SIRM and particle size values. SAR declined from 1970 to 2000, but re-increased at the sediment surface (2007) to about 0.06 g cm^{-2} $year^{-1}$. This may well be the result of deforestation (either natural by forest fire, or anthropogenic) which could have led to an increase in sedimentation rates after 1940. Albeit the SAR diminished as the forest developed within the catchment, it peaked again after mass tourism was boosted in the area of the lake and Mohos peatbog.

At Lake Știol, there is an increasing trend in the SAR from 1840 to 1965, followed by two clear episodes of high sediment accumulation: one around 1965 (from 0.04 to0.06 g cm^{-2} $year^{-1}$) and the second and more marked one after 2002 (from 0.06 to 0.09 g cm^{-2} $year^{-}1$) when dam was built up. The general rise in SAR at this site corresponded most closely to an increase particle size. Lake Stiol ranks among the lakes which experienced a continuous increase in sedimentation rates during the past 150 years, particularly after WWII, when traditional sheepherding intensified again and the road linking Bucovina and Maramures along Bistrita valley was built, thus granting easy access to this site but also generating significant impact on the area, which could explain the first peak in the SAR. The SAR peaked once more in 2002, after the dam was built to significantly increase the lake surface, and we believe that off road driving in the lake catchment will further contribute to increasing sedimentation rates (Fig. 1.4.8).

At Lake Vinderel, the SAR values are higher between 1920 and 1970 and declined markedly thereafter. Ti concentrations, median particle size and SIRM fluctuated strongly during most of this period, but there is a little co-variation among these parameters. The area where lake Vinderel is located was a fief of traditional pastoral agriculture from the late 19th century onward, reaching its peak intensity during the inter-war period, particularly due to the involvement of Jewish land renters. This resulted in the deforestation of Vinderel plateau in order to expand pasturelands, which were soon overcrowded with both sheep and cattle, further leading to overgrazing and pasture degradation (e.g., the growth of *Nardus stricta*). In turn, this resulted in the decline of sheepherding, as well as of the SAR recorded at Vinderel lake. During the past decade (mainly after 2007), EU subsidies encouraged local farmers to resume pastoral activities; however, these are now carried out using motor vehicles which often reach the lake area, thus contributing, along with the grazing itself, to the input of sediments to the lake, which is expected to increase.

Lake Buhăescu Mare shows a progressive increase in the SAR from 1870 to 1966, followed by clear rise from 1966 to the present from 0.02 to 0.08 g cm^{-2} $year^{-1}$. The SAR increase coincides well with a rise in Ti, SIRM and a coarsening of sediment particle size. Similar to Stiol, lake Buhăescu also recorded an increase in sedimentation, which could be linked to the pastoral activities carried out in the broad cirque hosting the lake. Despite its remore location, the site is reachable by off road motor vehicles (Fig. 1.4.8) due to an uncovered road built during the late 1990s.

Fig. 1.4.8. Off-road activities in the proximity of lakes Ştiol (left) and Buhăescu Mare (right).

At Lake Capra, the SAR varied greatly between 1860 and 1900 from 0.05 to 0.12 g cm^{-2} $year^{-1}$. However, SARs were relatively uniform (average rate of 0.03 g g cm^{-2} $year^{-1}$) in the last 100 years (1900–2007), with only a slight rise between 1990 and 2007. The high values in SAR are closely mirrored in the particle size values.

This type of variation could be explained, at least partially, by the fact that traditional pastoral activities were not continuos due to the high altitude of the site and small size of the cirque which could provide shelter for the sheepfold. Only after 1990, when the area became more attractive from a touristic standpoint and thus more frequented, the SAR increased slightly.

The age-depth model at Lake Negru suggests small fluctuations in the mean SAR over the period 1867–2009. The mean sedimentation rate was 0.007 g cm^{-2} $year^{-1}$ with slightly higher values between 1880 and 1900 (0.01 g cm^{-2} $year^{-1}$) and between 1970 and 1985 (0.009 g cm^{-2} $year^{-1}$), respectively. Due to its relative isolation, the site was protected from anthropogenic impact; furthermore, after it was included in the first national park in Romania (PNR), the site became accessible solely to researchers, excluding other activities. The data discussed in this subsection is illustrated in Fig. 14.9.

Sediment accumulation rates show an increase from basal (i.e. pre 1840) sediments towards the top of cores at only two sites. This trend contradicts wider findings from Western and Central European lakes, where sediment accumulation rates have predominantly increased over the last 150-year period.

Lowland and mid-elevations lakes were most markedly impacted by the socialist land use regime i.e. intensive land use with industrialised agriculture and deforestation. The higher elevation lakes from the southern Carpathians (n = 2) were more impacted by the intensification of summer pastoralist and shrub layer removal of the traditional period (1840–1920); whilst lakes from the northern Carpathians (n = 2) responded more strongly to the impact of the socialist and post- socialist land use regimes.

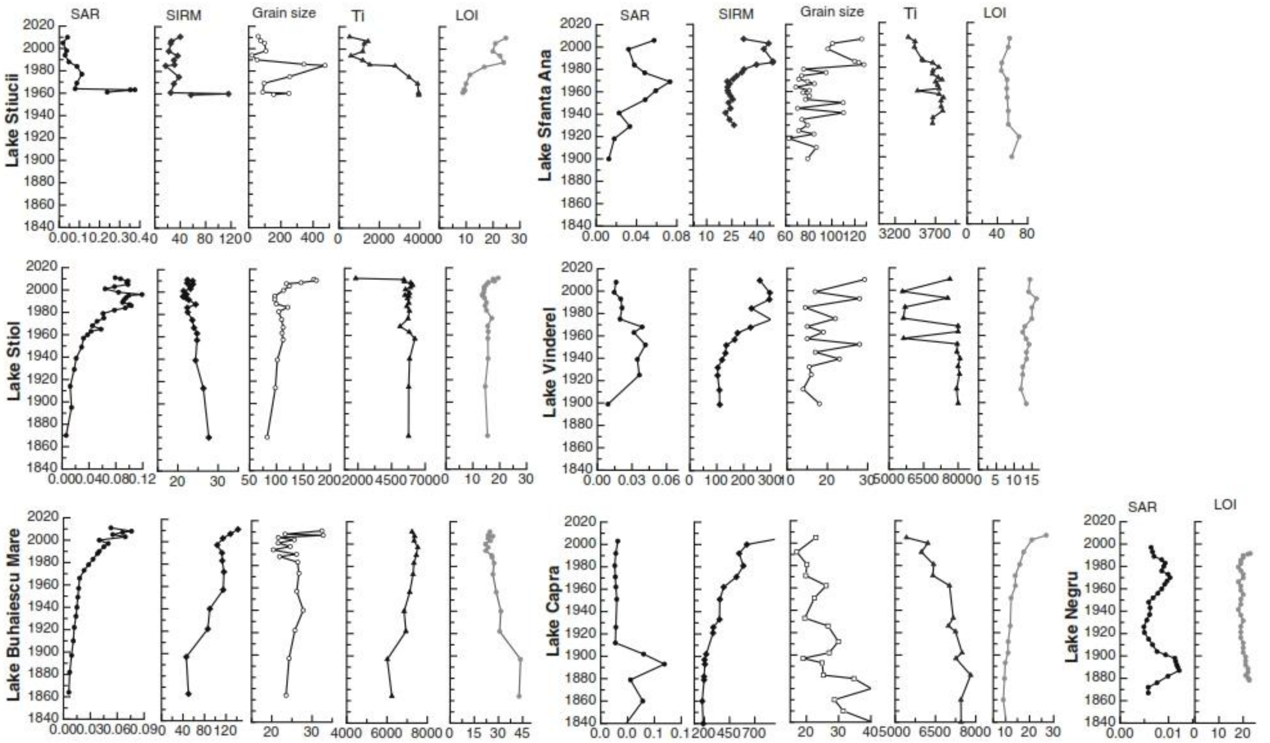


Fig. 1.4.9. Sediment accumulation rate (SAR) (g cm^{-2} year^{-1}), saturation isothermal remanent magnetisation (SIRM; 10^{-5} Am^{2} kg^{-1}), median grain size (micron), Ti content (mg kg^{-1}) and organic matter content (%) for Știol lake.

Our results can be combined with other sources of evidence (pollen, documentary records), highlighting the sustained impact of anthropogenic activities throughout the entire period considered and even in relatively remote mountain areas. This suggests that a temporal frame of 100–150 years is too short to register reference conditions of these lakes i.e. conditions before significant human impact. Therefore, a predominantly natural state may not have existed in these catchments for centuries. This is an important consideration if such reference conditions are anticipated as providing a 'baseline' against which environmental quality can be assessed.

1.5 Lake sediments as a record for climatic variability

Acting as sensitive and accurate barometers, lake and peat sediment records enable us to acquire an increasingly broader perspective on the mechanisms behind climatic and environmental changes. Over the past two decades the rising number and amount of data yielded by palaeolimnological studies for the CE Europe, in general, and Romania, in particular, allowed for the construction of a wide network of well-dated records which enabled comparison with the hallmark palaeoclimatic event stratigraphy of the North-Atlantic area and Western Europe. More specifically, the combined use of biological indicators with physical and geochemical data resulted in a multi-proxy approach for a variety of sites extending from the Transylvanian lowlands to the uplands of the Romanian Carpathians and spanning throughout the Holocene to the Pleniglacial. This section introduces a brief synthesis of the most outstanding results delivered by various investigations on Romanian lake and peat archives. Among these, lakes and peat bogs which came into existence during deglaciation, including both glacial lakes located in higher elevation mountain areas and lakes formed at lower elevations due to landslides subsequent to permafrost thaw are prevalent, and were preferred for such studies due to their long lifespans and location in mountain areas which have exhibited increased sensitivity to centennial and millennial-scale climate changes. The potential of lacustrine sediments for inferring past dynamics of climate and environmental conditions prompts us to highlight the necessity for expanding the spatio-temporal coverage of such studies in Romania in an attempt to create a relatively unitary perspective on regional palaeoenvironmental evolution.

An overview on lacustrine sites investigated to date in Romania

Palaeolimnological research focused thus far on 42 open lake and peat bog sites (Fig. 1.5.1 and Table 1.5.1) located throughout the Romanian territory which yielded a large amount of data regarding topics such as past climate changes, vegetation history and dynamics, past land use changes, pollution history and human impact, sedimentation rates etc.

Site elevation and latitudinal location

The locations of investigated sites range in terms of elevation from 240 m to 2250 m a.s.l., albeit the majority (29) are above 1000 m a.s.l. Around 70% are spread in the northern half of the Romanian territory, in the Northern Carpathians, Apuseni Mts and the northern Transylvanian Depression. This particular distribution of sites preferred for palaeolimnological studies is linked to the magnitude of the vegetational response which follows a S-N latitudinal and elevational trend (Feurdean et al., 2014). Extra-Carpathian lowlands (i.e. plains, plateaus and Subcarpathians <800 m a.s.l.) are particularly underrepresented in the growing network of investigated lacustrine and peat bog sites which is likely the effect of prevailing dry conditions during the Late Glacial at low altitudes

(Feurdean et al., 2007a). However, recent findings indicate that major climatic events are well expressed not only in the upland areas, as previously thought, but also in the lowland regions of Romania, where the magnitude of climate shifts is expected to be lower (Lascu et al., 2014).

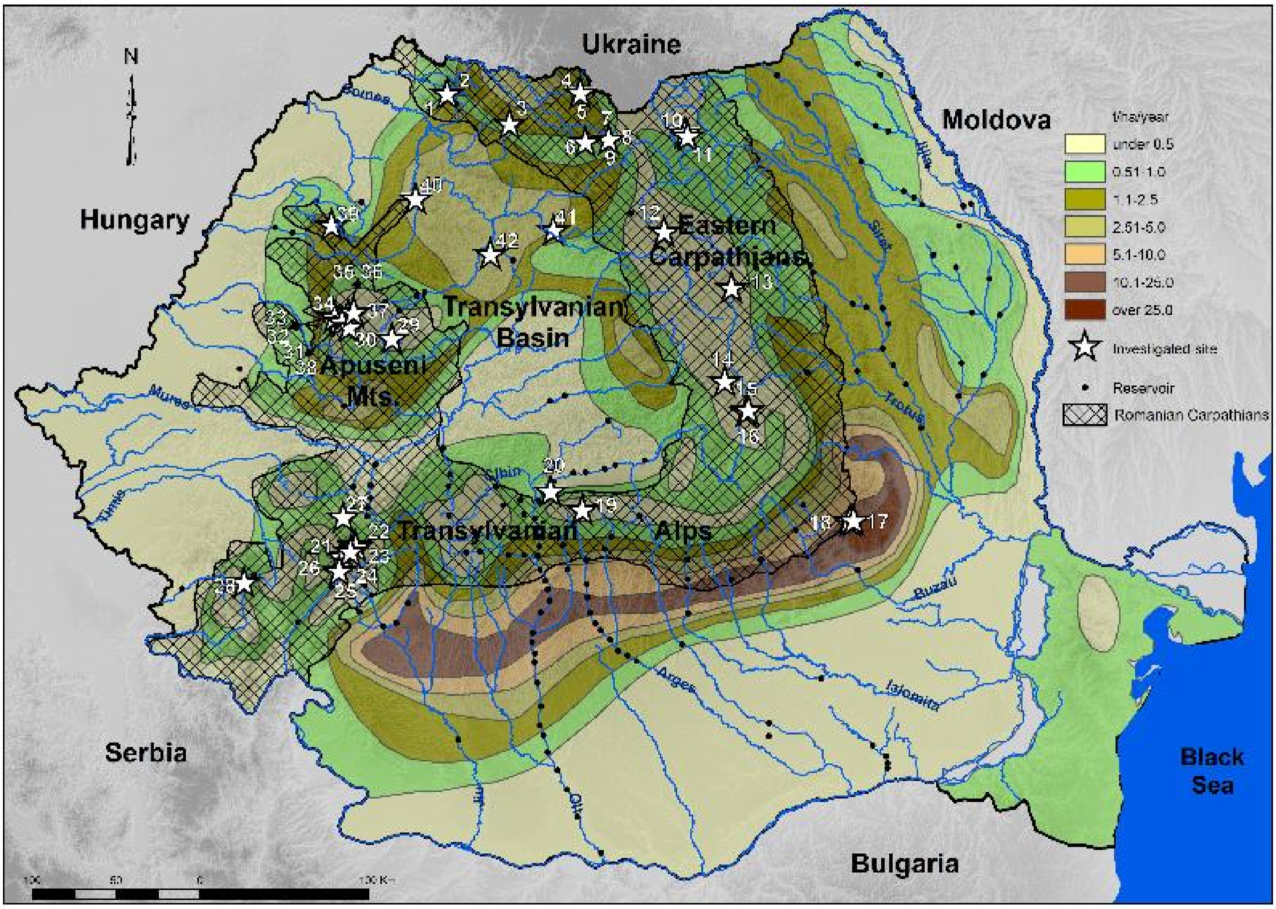


Fig. 1.5.1 Location of studied lake sites in relation to the specific sediment yield. The site numbers correspond to the ones listed in Table 8.5.1 (modified after Rădoane and Rădoane, 2005, Mociornița and Brateș, 1987, and Diaconu, 1971).

Site type and origin

Peat bogs were prevalent (ca. 60% of all investigated sediment archives) in terms of research interest due to the increased stability of peat bog deposition environment compared to lacustrine environments (i.e. absence of wind-induced disturbances, waves, bioturbation, sediment redeposition etc.), as well as the affinity of pollutants for organic fragments. However, not all proxies can be successfully applied to peat sediments.

In the majority of studied lakes the water depth is above 4 m, which according to Smol (2009) rank as suitable for palaleolimnological studies due to the absence of wind interference or bioturbation. Whereas investigated peat bogs formed mainly in karst sinkholes on limestone or in landslide basins, most of the open lakes are either glacial or landslide-dammed. Two sites are remnants of palaeolakes whereby the lacustrine sediments are buried under the topsoil horizon (i.e. Măgheruș and Turbuța).

As regards the type of parent rock hosting peat bogs and lakes, the sites from Apuseni Mts formed on limestone, while glacial lakes from Retezat Mts (S Carpathians) formed on granite and volcanic crater lakes and peat bogs on andesite. The sites from the Northern Carpathians occur either on volcanic breccia (Gutâi-Lăpuș Mts) or crystalline rocks (Rodna Mts), as is also the case with the lakes from Semenic and Poiana Ruscă Mts.

Sediment thickness and ages

The length of sedimentary sequences collected from Romanian lacustrine and peat bog sites ranges between 0.76 and 11.7 m, with the longest core extracted from crater lake Sfânta Ana. In over 2/3 of sites the thickness of sediment profile exceeds 3 m which is sufficient to ensure adequate resolution for Holocene climate reconstructions. With very few exceptions, the ages of investigated sites vary between 5.1 and 17.9 ka (Măgheruş). The oldest site documented thus far is Sfânta Ana (26 ka, Eastern Carpathians), whereas the youngest is landslide-dammed lake Iezer-Feredeu (1.035 ka, Northern Carpathians), albeit its 4 m-thick laminated sediment profile is comparable to older sedimentary archives. The sites from Apuseni Mts cover the Late Holocene, while sackung (Tăul dintre Brazi, Iezerul Călimani) and crater lakes and peat bogs (Sfânta Ana) and palaeolakes (Măgheruş, Turbuţa) span throughout the entire Holocene and the Late Glacial to various extents. Considering that in most instances the clay samples from the base of the sequences contain small amounts of pollen based on which the actual onset of sedimentation cannot be dated, the determined ages are likely underestimated.

An integrated late Pleniglacial - Holocene palaeoenvironmental perspective based on geochemical and biological lake sediment proxies

Understanding the mechanisms and impacts of past climate changes on the environment in terms of magnitude and temporal - spatial patterns has become a milestone in the context of the recent global projections (IPCC, 2014). The need for palaeoclimatic and palaeoenvironmental reconstructions covering a large period of time and particularly based on quantitative or at least semiquantitative information is strongly felt, especially in areas where such aspects have not been thoroughly investigated. In this respect, due to their pronounced sensitivity to climatic and environmental changes, lake and peat sediments are regarded as valuable archives as they record important information concerning processes and events manifested at various spatial and temporal scales.

One such region wherepalaeoclimatic data sets are particularly scarce is the Central-Eastern Europe. Here, several lacustrine and peat archives, some of which are located in the Romanian Carpathians, have become very valuable sources of information regarding the reconstruction of regional climatic and environmental history. Albeit Romania is a climatically sensitive area influenced by Atlantic, Mediterranean and Siberian air masses (Lascu et al., 2014), and therefore has the potential to record climatic shifts and test potential synchronicities with other sites across Europe, very few dated lacustrine sequences are available from this region. Overall, quantitative and semi-quantitative palaeoclimate reconstructions are extremely rare in Romania (Feurdean et al., 2012a, 2008b; Toth et al., 2012), whereas qualitative information is more abundant.

For the existing dated Romanian records the most widely employed proxies are biological, more specifically pollen and plant macrofossil analyses, with a special focus on the Late Glacial and Early Holocene periods where abrupt and short climatic events triggered important environmental changes (Magyari et al., 2013; Buczkó et al., 2012b; Tanţău et al., 2009; Feurdean et al., 2014). Nonetheless, even the main short term Holocene climatic shifts documented in the North Atlantic Area (Blockley et al., 2012) have been shown to impact on the Romanian territory (e.g. Feurdean and Willis, 2008b; Magyari et al., 2009b).

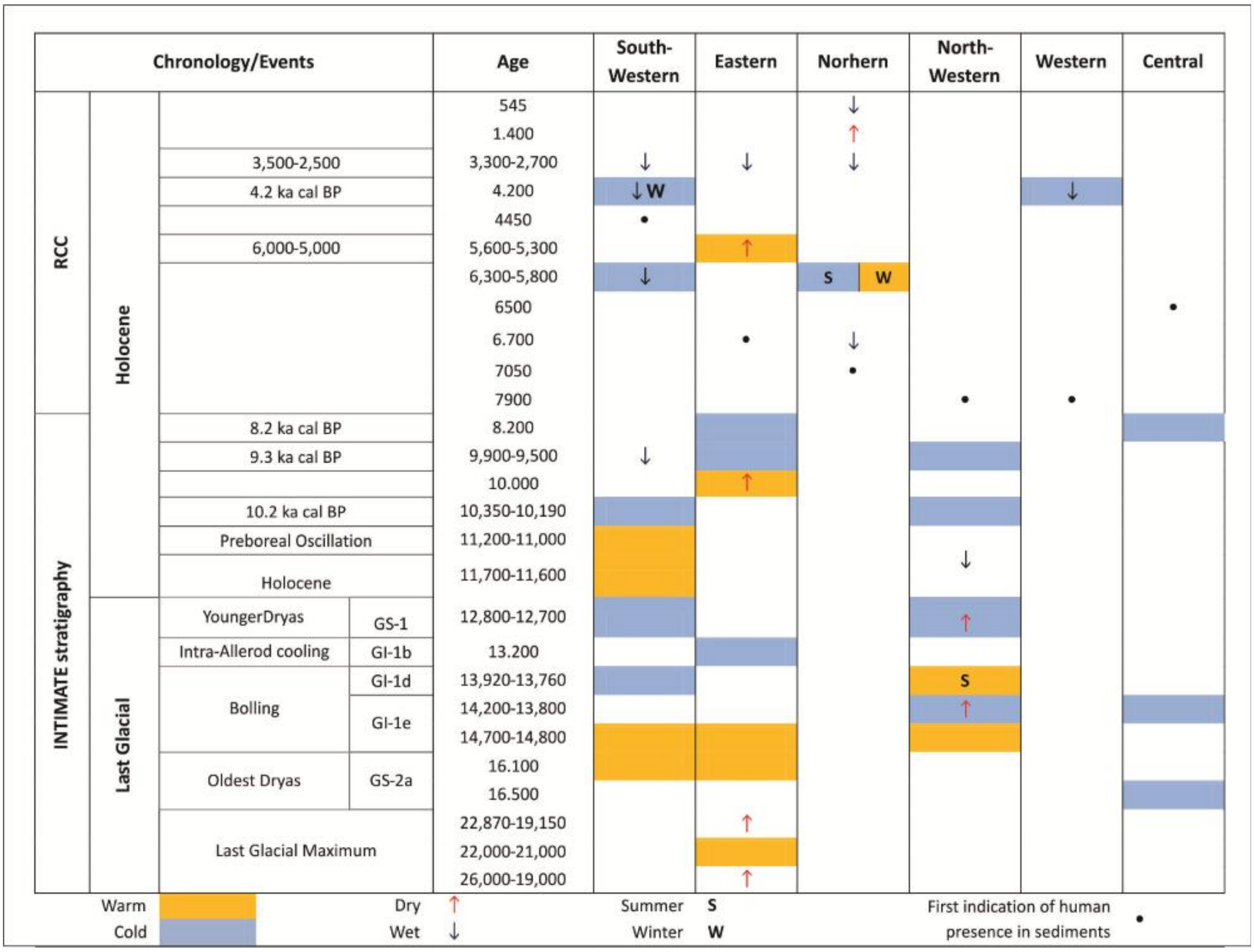


Fig. 1.5.2 Summary of inferred climatic changes between 26,000 and 550 cal y BP at reviewed sites from Romania.

We hereby showcase the most significant short-term climatic events recorded in lake and peat sedimentary archives on the Romanian territory within the framework of a regional comparison (Fig. 1.5.2). These climatic oscillations are further related to the Intimate event stratigraphy (Blockey et al., 2012) from 26,000 to 8,000 cal y BP, whereas the period 8,000 cal BP to present is roughly related to the regional climatic changes documented by Mayewski et al. (2004) and Magny et al. (2004). Among the reviewed sites the longest timeframe covered by a lacustrine sedimentary sequence was reconstructed in Eastern Romania at lake Sfânta Ana (946 m a.s.l.), extending back to the Pleniglacial (26,000 cal y BP). Palaeoclimatic reconstructions based mainly on pollen analyses are abundant in NW and Western Romania, both in terms of number and consistency, whereas in the SW Romanian Carpathians the proxies employed for lacustrine sediment investigations are rather diverse.

Sensitivity to climatic signals

Within the investigated studies, mid-elevation sites (730-1100 m a.s.l) were found to be the most sensitive to climate change during the Late Glacial and Early Holocene (Feurdean et al., 2012b). Less prominent climatic shifts were recorded only at mid-altitude sites (Feurdean et al., 2007b; Magyari et al., 2013), which might be explained by the fact that at higher elevations the terrain was covered by ice until warming condition were established (Early Holocene) which imprinted a prolonged cooling effect on the surrounding environment. Furthermore, lowlands are generally underrepresented on the map of Romanian palaeoclimate reconstructions. Although climate changes are expected to be recorded at a lower magnitude at lowland sites (Feurdean et al., 2014), palaeoclimatic archives located in the Transylvanian Basin (i.e. lakes Măgheruş, Avrig, Turbuţa, Ştiucii) recorded prominent climatic events which occurred in the North Atlantic area and propagated towards the Central-Eastern Europe.

26 to 19 ka cal BP. During the Late Glacial Maximum (26,000-19,000 cal y BP) the geochemical proxies employed for the oldest lacustrine sequence in Romania (lake Sfânta Ana) located in the Eastern Romanian Carpathians indicate a general low lake productivity accompanied by an increase in the aeolian input (Magyari et al., 2014a). This suggests enhanced climatic aridity, limited vegetation cover, unconsolidated soils and high wind speed (Kasse et al., 2002). Two short climatic fluctuations, from 23,500 to 23,000 cal y BP, and 22,000 to 21,000, respectively, were associated with the millenial-scale stadial/interstadial climatic fluctuations in marine isotope stage 2: GI-2.1-GI-2.2. From 22,870 to 19,150 cal y BP enhanced regional continentality and persistent drought were inferred from tree diversity and increased fire activity (Magyari et al., 2014a).

18 to 12 ka cal BP. During this interval the northerly shift in the summer westerly jet from the Mediterranean Sea region (Strandberg et al., 2011, Huntley et al., 2013 cited by Magyari et al., 2014a) coupled with increased summer insolation (Berger and Loutre, 1991 cited by Magyari et al., 2014a) impacted the ecosystems in two phases: the first interval (19 to 16.1 ka) was dominated by changes in summer insolation, whereas during the second one (16.1 to 12 ka) warming and precipitation increase prevailed. However, these changes manifested to various extents throughout the Carpathians, while the lowlands were shown to exhibit lower sensitivity. Thus, in Southern Transylvania a clear response of the vegetation to the Oldest Dryas cold phase - 16.65 kyr cal BP was documented (Avrig record - Tanţău et al., 2006), whereas in Northern Transylvania (Măgheruş record - Lascu et al., 2014) the physical and chemical proxies indicate warmer and wetter conditions during Bølling-Allerød (or Greenland Interstadial 1, GI-1) followed by the cooler and drier Late Glacial Stadial (Younger Dryas/Greenland Stadial 1, GS-1).

In the SW Carpathians the contribution of winter precipitation inferred from diatom silica oxygen isotope variations ($\delta^{18}O_{DIAT}$) was generally higher during the Late Glacial (until 12.3 kyr cal BP) (Buczko et al., 2012a,b; Magyari et al., 2013). The prolonged cold and most likely wet conditions sustained in-wash processes, inhibited lake productivity and provided suitable conditions for steppe-tundra vegetation development (Korponai et al., 2011). In the Eastern Carpathians, from 18,000 to 16,100 cal y BP, the presence of warmer climate species indicates an enhanced effect of summer insolation on vegetation composition (Magyari et al., 2014a). At 16,100 cal y BP increased lake productivity and high levels of clastic input suggest a coupled effect of warm and highly moist conditions.

A detailed qualitative reconstruction of Late Quaternary climate and environment in the western sector of the Northern Carpathians based on multi-proxy analyses (Feurdean and Bennike, 2004) showed that prior to 14.7 kyr cal BP (the Plenniglacial), cold and dry conditions prevailed, ensued by a short phase with more stable environmental conditions. A pollen-based quantitative temperature reconstruction (Feurdean et al., 2008b) showed a 2°C increase in annual temperatures, which reached 4°C at 14.8 kyr cal BP. This event is equivalent to the GS-2/GI-1e transition in the Greenland ice core isotope record, which shows an increase in temperature amplitude (Blockley et al., 2012). During this period, in the Northern, Eastern and Southwestern Carpathians, the temperature increase was documented in winter temperatures, whereas summer temperatures remained unchanged.

In the SW Carpathians an episode of slight warming occurred around 14,920 cal y BP, inferred exclusively from geochemical proxies, which was related to the GI-1e event in the NGRIP (Braun et al., 2013). The transition from cold to warm conditions, i.e. Oldest Dryas/Bølling, is marked here at 14,700 cal y BP by an increase in chironomid-inferred mean July air temperature by 2.8°C (Tóth et al., 2012), while geochemical proxies (Braun et al., 2013), macrofossils, and stomata (Magyari et al., 2011, Korponai et al., 2011) show a delay of almost 500 years, at ~14250 cal yr BP. The warming period - Bølling (GI-1e) – was documented in the Eastern Caphatians in the lake Sfanta Ana record at around 14,700 cal y BP in the shape of a pronounced increase in temperature which resulted in vegetation growth and catchment slope stability.

In the western part of the Northern Carpathians a cooler and drier climatic phase was documented from around 14.1 to 13.8 kyr cal BP followed by an increase in air temperature and moisture availability. In the SW Carpathians from 13,920 to 13,760 cal yr BP the geochemical proxies point towards a weak cold episode, probably matching the GI-1d short-event from NGRIP, followed by short-term warmer conditions between 13,760 and 12,950 cal y BP (Buczkó et al., 2009a, 2012a,b). During Bølling/Allerød interstadial the chironomid-reconstructed air temperatures of the warmest month are placed around 8.1-8.7°C (for comparison, present day temperature is 11.2°C), lower compared to other records across Europe (Tóth et al., 2012). This was explained by stronger oceanic influences in the Southern Carpathians coupled with a down-slope cooling effect coming from the perennial ice-covered peaks, which might have affected the warm season (Tóth et al., 2012).

In the western sector of the Northern Romanian Carpathians, between 13.8 and 12.7 kyr cal BP an increase in summer temperature close to present day values (13-17°C) was noticed. However, winter and annual temperatures (-6 to -12°C and 0.5 to 6°C respectively) as well as annual precipitation (550-700 mm) were lower (Feurdean et al., 2008b). Higher summer temperatures are also indicated by enhanced fire activity in the area (Feurdean et al., 2012a). This LG warming is also evident in the Southern Carpathians, and related to the previous observations, it indicates the prevalence of stronger inter-seasonal variability and enhanced continental conditions (Feurdean et al., 2008b; Braun et al., 2013; Buczko et al., 2009a, 2012a,b; Magyari et al., 2011).

In the Eastern Carphatians around 13,200 cal y BP the geochemical proxies reveal a lake level drop which appears to reflect the intra-Allerød cooling event (GI-1b). In the Luci pollen record (Harghita Mts) the climatic shifts (14,700 and 13,200 cal y BP) are weakly expressed, albeit this site appears to have been more sensitive to the changes which occurred during the Allerød (13,800 cal y BP) (Tanţău et al., 2014).

The magnitude of climate changes for the 14.7 to 8 ka cal BP interval was much lower compared to the more oceanic Western Europe (Feurdean et al., 2014); the onset of the LG cold intervals was accompanied by marked decrease in precipitation values and most likely increased continentality; low fire activity characterized the LG; short climatic fluctuations around 13.9, 13.6 and 13.2 ka cal BP were generally reflected in vegetation composition changes (Tanţău et al., 2006, 2014; Feurdean et al., 2007a,b, 2012a,b; Magyari et al., 2013).

12.8 to 11.7 ka cal. BP. The decline in temperatures during **Younger Dryas** (12.8-11.7 ka cal BP) was recorded across the entire Romanian Carpathian Region and manifested more strongly during winter. The marked decrease in precipitation associated to the cooling indicates a progressive transition towards more continental or seasonally variable climatic conditions (Feurdean et al., 2014).

In the SW Carpathians abrupt climate shifts occurred throughout the Late Glacial and at the onset of the Holocene (Iepure et al., 2011; Korponai et al., 2011). However, a strong regional vegetation response was recorded during the YD cooling at 12.8 kyr cal BP, which involved deforestation and spread of steppe-tundra and snowbed vegetation (Magyari et al., 2011). Although the chironomid-inferred temperatures do not show a marked decrease at the onset of the Younger Dryas (less than 1°C), the diatom-based reconstructions suggest that the cooling associated with YD mainly occurred during the winter season. The ecosystem changes recorded in the Southern Carpathians during Younger Dryas were most likely caused by strong seasonal changes which implied longer and likely colder winters with slightly altered July temperatures and increased precipitation (Iepure et al., 2011; Buczko et al., 2012a; Magyari et al., 2013; Tóth et al., 2012). Similarly, recurrent cold, dry YD conditions (12.9 - 11.5 kyr cal BP) were also recorded in the western part of the Northern Carpathians whereby the onset of Younger Dryas was characterized by a 2°C increase in mean summer temperature (pollen-based reconstruction) and a marked decrease of ca. 9°C in mean winter temperature, concomitant with a 250 mm decrease in annual precipitation (Feurdean et al., 2008b). Diminished peat surface moisture and lake levels in the former area (Feurdean et al., 2013b; Schnitchen et al., 2003, 2006), SW Carpathians (Magyari et al., 2009b; Buczko et al., 2012a,b), along with the diatom/chironomid-inferred cold conditions in the SW Carpathians (Buczko et al., 2012a; Magyari et al., 2013; Tóth et al., 2012) and the augmenting landscape openness in Southern (Tanţău et al., 2006) and Northern Transylvania (Feurdean et al., 2007a,b), as well as in the western sector of the Northern Carpathians (Björkman et al., 2002, 2003) and Eastern Carpathians (Tanţău, 2006; Tanţău et al., 2003a) also support these findings.

Between 12450 and 11400 cal yr BP, in the SW Carpathians a decrease in the duration of the winter ice-cover season was inferred (Buczkó et al., 2009a, 2012a,b; Braun et al., 2013) which is synchronous with the warming phase detected in the Eastern Carpathians at ~12500 cal yr BP (Magyari et al., 2014a).

Farther north, pollen-related findings showed that glaciation was not as severe in Călimani Mts compared to Retezat Mts (Fărcaş et al., 1999). The regional persistence of broad-leaved temperate forest (at 46°N) during the LGM, coupled with charcoal data suggest a continuous, regional and extra-local presence of wood biomass and its frequent burning, likely as a result of increased continentality, with relative warm and dry summers.

11.7 to 8 ka cal. BP. Similar to other regions in Europe, climate warming at the YD - Holocene transition resulted in enhanced vegetation competition and diversity. This major and abrupt climate shift triggered a visible response in vegetation at both lowland and upland sites (Fărcaş et al., 1999; Björkman et al., 2002, 2003; Tanţău et al., 2003 a,c, 2006; Feurdean, 2005; Fărcaș et al., 2006; Tanțău, 2006; Feurdean et al., 2007a,b), which demonstrates that all elevations were comparably vulnerable. During the Early Holocene (11.7 to 8 ka cal BP) high summer insolation led to an increase in summer temperature and thus influenced seasonality. Biomass burning reached maximum values due to fire-prone conditions and biomass availability.

In the Eastern Carpathians the YD - Holocene transition (11 700 cal y BP) appeared most evident at Luci and Bisoca peat bogs (Harghita Mts and Buzaului Subcarpathians, respectively), where vegetation reconstructions from peat sediments reveals the role of the YD cooling conditions in limiting the vegetation development; the fast replacement of open vegetation by forests at the LG/Holocene transition was interpreted as a response to the Early Holocene warming (Tanţău et al., 2009, 2014). At lowland sites, after the YD cold event the Avrig sediment record indicates that vegetation responded rather slowly to the Early Holocene warming.

In the SW Carpathians the onset of the Holocene warming is marked in geochemical proxies, at ~11,600 cal y BP. Evolution of July temperatures is reflected in the chironomid record by a two steps increase during from 11,500 to 10,830 cal yr BP, first by 0.6°C and second, by 2.7°C.

During this period the palaeoenvironmental records from the western sector of the Northern Carpathians revealed moister conditions; overall, the pollen-based quantitative reconstruction of winter, summer and annual temperatures, as well as precipitation (Feurdean et al., 2008c) enabled the identification of two main climatic intervals: i) 11.7 - 11.2 kyr cal BP – characterized by less stable climate with a decrease in seasonality and reduction in continentality; ii) 11.2 - 8.3 kyr cal BP – during which generally stable climatic conditions prevailed, albeit it was interrupted by minor fluctuations occurring around 10.2 kyr cal BP (i.e. a drop of 100 mm in precipitation amount) and 8350 - 8000 cal yr BP (a decrease by ~1.5-2 °C in mean annual temperatures and 200 mm reduction in precipitation). This last cooling event appears to reflect the centennial-scale cold phase 8.2 ka event also documented in other regions.

Charcoal records revealed lower fire activity between 12 and 10.7 kyr cal BP in the lowland of northern Transylvania due to a shortage in fuel availability against the background of arid and strongly seasonal climatic conditions, i.e. higher summer temperature (4°C above current mean temperature) and lower precipitation (by 33%) compared to the present (Feurdean et al., 2013b).

In the SW Carpathians the warming tendency (Magyari et al., 2011; Braun et al., 2013) was interrupted by a short-lived cold event, between 11.2 and 11 kyr cal BP, which determined an increase in the duration of ice-cover (Buczkó et al., 2012b) and a drop in July temperatures by ~1°C (Toth et al., 2012). The event was associated with the Preboreal Oscillation which occurred at ~11,250 cal yr BP as defined in the GRIP $\delta^{18}O$ isotope record (Rasmussen et al., 2006). Between 10.6 and 10.3 kyr cal BP, the chironomid record coupled with the presence of fir pollen grains suggested that summer mean temperatures were ~2.8°C higher than present temperatures (Toth et al., 2012; Magyari et al., 2013). A short-term cooling was detected at 10.350-10.190 cal yr BP, when mean summer temperatures decreased by ~1°C (Tóth et al., 2012) and the water table dropped suddenly (Magyari et al., 2013). This event was also reported in other parts of the Carpathians between 10,000-10,500 cal yr BP (e.g., Tămaş et al., 2005; Feurdean et al., 2008b; Tanţău et al., 2009, 2014) and lowland Transylvania (Feurdean et al., 2007a), Western Europe (Lang et al., 2010) and most likely corresponds with the 10.2 ka event identified in Greenland ice cores (Björck et al., 2001).

Between 9900 and 9500 cal BP, higher lake levels accompanied by decreasing lake productivity and changes in sediment geochemistry, vegetation and fossil organisms (Buczko et al., 2012a; Magyari et al., 2009b, 2011; Soróczki-Pintér et al., 2014), appear to reflect the shift towards drier conditions from ~9200 cal yr BP. This is also evident in the Eastern Carpathians (Tanţău et al., 2009, 2014) and can be further linked with the 9.3 ka widespread climatic anomaly which might have been triggered by meltwater input into the North Atlantic.

The 8.2 ka cooling anomaly detected in the Greenland ice core isotope record, characterized by lower temperatures, minima in ice accumulation rates and windy conditions (Alley et al., 1997; Wiersma and Renssen, 2006; Renssen et al., 2001 cited by Buczkó et al., 2012b) was also recorded in the Eastern (Tanţău et al., 2009, 2014) and Southern Carpathians, but manifested weakly by a slow rise in the lake level and increased storminess between 8400 and 8200 cal yr BP (Buczkó et al., 2012a; Magyari et al., 2009a,b). In other regions of the Carpathians this particular timeframe was either showcased by the lowest water levels at Lake Sfanta Ana (Magyari et al., 2009c), decreased mire surface wetness and dry summer conditions with cold winters (Schnitchen et al., 2006; Feurdean et al., 2008a,c), or was not reflected at all in other temperature-proxy records such as speleothems (Tămaş et al., 2005; Constantin et al., 2007). Some small change towards a drier climate was noticed around the same timing in lowland Transylvania (Turbuta peat bog) (Feurdean et al., 2007a).

8.2 to 3 ka cal BP. Between 8000 and 3000 cal yr BP, in the western sector of the Northern Carpathians, coldest month and annual temperatures were lower compared to current conditions, whereas summer temperatures and precipitation showed increased values, comparable to the present; however, more stable conditions prevailed compared to the Early Holocene, but were interrupted by a number of short-term climate oscillations (Schnitchen et al., 2006; Feurdean et al., 2008c). A dry event is identified around 6,740 cal yBP in Tăul Mare Bardău (Maramureş Mts) sediment record (Cristea et al., 2014). In the lowlands, a cooler and wetter climate was inferred between 7100 and 3300 cal yr BP which favored woodland extension and reduced biomass burning (Feurdean et al., 2012a).

In the SW Carpathians diatom records reflect a short-lived event between 6300 and 5800 cal yr BP, characterized by summer cooling, a decrease in winter ice-cover season and an augmenting size of the water body, probably as a result of cooler and moister conditions (Buczkó et al., 2013; Magyari et al., 2009a,b). The event is synchronous with a short climatic change recorded in the SE Europe and the Northern Mediterranean Region known as 6000-5000 cal yr BP cold anomaly (Mayewski et al., 2004) characterized by cooler summers and warmer winters (Cheddadi et al., 1996 cited by Tanţău et al., 2011a). This anomaly was also identified, albeit with an even greater amplitude, in the Eastern Carpathians, at lake Sfânta Ana (Buczko et al., 2012a) and Poiana Ştiol peat bog (Tanţău et al., 2004, 2011a), in Buzău Subcarpathians (Tanţău et al., 2009) and Southern Transylvania - Făgăraş Depression (Tanţău et al., 2006; Tanţău, 2011b).

Furthermore, at 4200 cal yr BP a significant decrease in $\delta^{14}O_{DIAT}$ signals another climatic change, characterized by increased winter precipitation and/or cooler winters (Magyari et al., 2013), which was aligned to the 4200-3800 RCC (Mayewski et al., 2004). This event was also detected in Apuseni Mts whereby the pollen record revealed a short term abrupt cooling and wet event which started around 5500 cal yr BP, reaching maximum at 4200 cal yr BP (Feurdean and Willis, 2008b). It was also recorded in the stalagmite oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes (Onac et al., 2002), tree-ring records (Kern and Popa, 2007) and supported by proxy-based evidence (pollen and testate amoebae) in NW Romania (Schnitchen et al., 2006).

3 ka cal. BP to Present. In the Northern Carpathians the last 3000 cal yr BP were characterized by warm winters (0-1°C mean temperature of the coldest month) and elevated annual temperatures (7-8 °C); precipitation decreased by about 100 mm.

After 3,200 cal y BP, diatom assemblages reflect a sudden increase in water level in the SW Carpathians which culminated around 2,800 cal y BP (Buczkó et al., 2012b; Magyari et al., 2013). This shift towards wetter conditions is also reflected in the Eastern Carpathians at lake Sfânta Ana (whereby it is part of a major environmental change which occurred between 3300 and 2700 cal yr BP, Buczko et al., 2012b), the Northern Carpathians (Cristea et al., 2014), speleothem $\delta^{18}O$ (showing gradual decrease) and other proxies in the Carpathians (Magyari et al., 2013; Schnitchen et al., 2006 etc). In the eastern part of the Northern Carpathians (flysch mountains), a succession of different environmental conditions spanning the last 4000 years is reflected in sedimentation changes and limnogeological evolution documented for Lake Bolătău (Nemeth et al., 2014).

A dry event occurred at 1,430 cal yr BP in the Northern Carpathians, ensued by another wet event at 545 cal yr BP, strongly related to a decrease/increase in precipitation availability

(Cristea et al., 2014). Based on pollen stratigraphy from Iaz peat bog, cold and dry conditions were inferred in NW Transylvania between 1600 and 1300 cal yr BP (Grindean et al., 2014), followed by warmer conditions between 1300 and 1100 cal yr BP (Grindean et al., 2014; Feurdean et al., 2012a).

During the last 2,500 years, in lake Buhăescu Mare (Rodna Mts) and Tăul Mare Bardău peat bog (Maramureș Mts) the warm-cold oscillations known as RWP, DACP, MWP and LIA were also detected by multi-proxy analyses (Cristea et al., 2014; Geantă et al., 2014). Little Ice Age cold event was also traced in the lowlands in Avrig record (Tanţău et al., 2011b) at ca. 600-700 cal yr BP. Over the past millennia, drier conditions may be inferred in the Eastern Carpathians from lake eutrophication and gradual shallowing and in NW Romania from the testate amoebae record (Schnitchen et al., 2003, 2006).

Conclusions

Albeit palaeolimnological research is a new field of scientific investigation in Romania (no more than ca. 15 years), it has already produced a network of sites located at different elevations, in diverse physical environments and undergoing various degrees of anthropogenic influence, which has the potential to reveal local and regional differences in the environmental response to climate fluctuations and anthropogenic stressors. To date investigations focused mainly on lacustrine and peat bog sites older than 5ka located above 1000 m a.s.l. in the northern half of the Romanian territory (Northern Carpathians and Apuseni Mts). The mean thickness of investigated sedimentary sequences is commonly above 3 m, but in a small number of instances the sediment profiles were as thick as 10 to 12 m. Sedimentation hiatuses occur in a well-marked number of cases. Lacustrine deposits accumulated during variable timeframes ranging typically from 5 to 15 ka, although in exceptional cases the absolute ages of lake sediments are as high as 19 to 26 ka, spanning throughout the Holocene and Late Glacial to the Late Pleniglacial. Based on this data the sedimentation rates for natural lakes and peat bogs have been estimated, which range within a rather broad interval, although they are not nearly as high as rates of accumulation in man-made reservoirs.

As regards the climatic and palaeoenvironmental data inferred from various multi-proxy analyses applied to sedimentary records from Romanian lakes and peat bogs, biological and geochemical records along with historical and archaeological data and the use of model-data comparison demonstrate that during the Late Pleniglacial - Late Glacial and the early Holocene the climate was mainly driven by natural forces, whereas during the second part of the Holocene it was influenced by mixed natural-anthropogenic factors. During the Holocene a strongly divergent pattern in biomass burning in the lowlands as opposed to the highlands suggest that forests in the Romanian Carpathians were cleared much later than in the rest of Europe (Feurdean et al., 2012a). Further on, as we approach the present times, particularly over the last millennium, human activities appear to shape the environment to an ever increasing extent.

Despite chronological uncertainties, the scarcity in quantitative information and the variety of investigation methods employed, the reconstruction is relatively unitary throughout the

Romanian territory. However, new high resolution data is required to fill in gaps (particularly for uncharted areas such as the lowlands) along with novel integrated interpretations of existing information, for building more accurate climatic and environmental prediction models, and ultimately for implementing sustainable local management.

This chapter also includes elements from the following publications:

Akinyemi OF, Hutchinson SM, Mîndrescu M, Rothwell JJ (2013) Lake sediment records of atmospheric pollution in the Romanian Carpathians. Quaternary International 293:105-113

Fărcaş S, Tanţău I, Mîndrescu M, Hurdu B (2013) Holocene vegetation history in the Maramureș mountains (Northern Romanian Carpathians). Quaternary International 293:92-104

Geantă A, Gałka M, Tanţău I, Hutchinson SM, Mîndrescu M, Feurdean A (2014) High mountain region of the Northern Romanian Carpathians responded sensitively to Holocene climate and land use changes: A multi-proxy analysis. The Holocene 24:944-956

Hutchinson SM, Akinyemi FO, Mîndrescu M, Begy R, Feurdean A (2015) Recent sediment accumulation rates in contrasting lakes in the Carpathians (Romania): impacts of shifts in socio-economic regime. Regional Environmental Change. doi: 10.1007/s10113-015-0764-7

Mîndrescu M, Cristea AI, Hutchinson SM, Florescu G, Feurdean A (2013) Interdisciplinary investigations of the first reported laminated lacustrine sediments in Romania. Quaternary International 293:219-230

Mîndrescu M, Cristea IA, Hutchinson SM (2010b) Bathymetric and sedimentological changes of glacial lake Ştiol, Rodna Masiff. Carpathian Journal of Earth and Environmental Sciences 5(1):57-65

Table 1.5.1 Lacustrine sites investigated in Romania dated based on absolute date measurements (^{14}C, ^{210}Pb etc)

No	Site name	Geographic location	General information (elevation, area, maximum water depth, thickness of sediment sequence, age yrs cal BP)	Type of investigated site	Estimated age (yrs cal BP)	SR[3] (mm/yr)	Proxies	References
1	Preluca Ţiganului	Eastern Carpathians - Gutâiului Mts western slope 47°48’83’’ N 23°31’ 91’’ E	Elev. = 830 m a.s.l. Site area = 2.374 ha CA[1] = 29 ha St[2] = 10 m (hiatus) Age = 14.400 at 9.88 m	Peat bog. Located in rock slope failure (sackung) Rock type= volcanic breccia	LG - H: 0 - 14400	0.69	Lithostratigraphy, pollen, plant macrofossil, mineral magnetic analyses (SIRM), organic matter content via LOI, charcoal, petrographic analyses (clay mineralogy and grain size measurement)	Wohlfarth et al. 2001 Björkman et al. 2002, 2003 Feurdean and Bennike 2004 Feurdean 2005 Feurdean and Astalos 2005 Feurdean et al. 2007a, b, 2008
2	Steregoiu	Eastern Carpathians - Gutâiului Mts slope 47°48’48’’ N 23°32’41’’E	Elev. = 930 m a.s.l. Site area = 0.59 ha CA = 12.55 ha St = 5.92(hiatus) Age = 14.000 at 5.30 m	Peat bog Located in rock slope failure Rock type = volcanic breccia	LG - H: 0 - 14000	0.38	Lithostratigraphy, pollen, plant macrofossils	Björkman et al. 2002 Fărcaş et al. 2006 Feurdean and Bennike 2004 Feurdean and Astalos 2005 Feurdean et al. 2007, 2008
3	Văratec (Fenyves-tetö)	Eastern Carpathians - Lăpuşului Mts 47°39’ 43.63’’N 24°02’21.77 ’’E	Elev. = 1340 m asl Site area = 1.2 ha CA = 2.84 ha St = 4.0 (hiatus) Age = 9102 at 3.81 m	Peat bog Located in rock slope failure Rock type = volcanic breccia	H: 0- approx. 9790 (older but no 14C dates)	0.42	Lithostratigraphy, geochemistry, testate amoebae, humification	Schnitchen et al. 2003; 2006
4	Tăul Mare Bardău	Eastern Carpathians - Maramureş Mts 47°50’08.89’’ N 24°35’ 42.62’’ E	Elev. = 1615 m a.s.l. Site area = 0.84 ha CA = 5.34 ha St = 3.80m Age =7 030 at 3.79 m	Peat bog Located in glacial cirque Rock type = conglomerates	H: 0-7030	0.54	Lithostratigraphy, pollen, carbon isotopic composition of bulk peat, sedimentation rates (SR) using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am	Fărcaş et al. 2013 Cristea et al. 2014 Hutchinson et al. 2015
5	Cristina	Eastern Carpathians - Maramureş Mts 47°50’09.08’’ N 24°37’08.18’’ E	Elev. = 1573 m a.s.l. Area = 0.12 ha CA = 21.05 ha St = 3.01 m Age = 8000 at 3.01 m	Peat bog with pool Located in glacial cirque Sampled in peat Rock type = conglomerates	H: 2300-8000	0.38	Lithostratigraphy, pollen	Fărcaş et al. 2013

6	Buhăescu Mare	Eastern Carpathians - Rodna Mts, northern slope 47°34’21.51’’N 23°38’31.12’’E	Elev. = 1918 m a.s.l. Pool area = 0.1 ha Peat bog area = 1.44 ha CA = 15.75 St = 1.25 m (hiatus) Water depth = 0.5 m Age = 9928 at 0.86 m	Peat bog with pool Located in glacial cirque Sampled in pool area Rock type = crystalline schist	H: 0-10000	0.09	Lithostratigraphy, pollen, stomata, plant macrofossils, magnetic susceptibility, charcoal, organic carbon content (LOI), elemental geochemistry, grain size, sedimentation rates (SR) using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am	Geantă et al. 2014 Hutchinson et al. 2015
7	Gărgălău	Eastern Carpathians - Rodna Mts, northern slope 47^0 34′ 25.65″ 24^0 48′ 10.23″	Elev.= 1812 m a.s.l. Site area = 1.62 ha CA = 16.21ha St = 1.50 m Age = 11200 at 1.50 m	Peat bog Located in glacial cirques Rock type= crystalline schist	H: 160-11200	0.13	Pollen and spore analysis, AMS radiocarbon dates	Tanţău et al. 2014
8	Ştiol[4]	Eastern Carpathians - Rodna Mts, northern slope 47° 34’ 30’’ N 24° 48’ 55’’ E	Elev. = 1670 m a.s.l. Site area = 0.059 ha (lake) CA = 153 ha St = 1.30 m Water depth = 2 m Age= 100 at 0.14 m	Glacial lake Located in glacial cirque Rock type = crystalline schist	H: 0-130	1.40	Sedimentation rates (SR) based on mineral magnetic properties and ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am, pollution history	Hutchinson et al. 2015 Mindrescu et al. 2010b Akinyemi et al. 2013
9	Poiana Ştiol	Eastern Carpathians - Rodna Mts, northern slope 47°35’14’’N 24°48’99’’E	Elev. = 1540 m a.s.l. St = 3.20 m Site area = 0.6 ha CA = 10 ha Age = 10.380 at 2.93 m	Peat bog Located in a cirque floor sinkhole Rock type = crystalline limestone	H: 0-11000	0.28	Lithostratigraphy, pollen	Tanţău et al. 2011a Tanţău and Fărcaş 2004 Tanţău 2006 Fărcaş et al. 2006
10	Bolătău - Feredeu	Eastern Carpathians - Feredeului Mts 47° 37’ 21’’N 25°25’54’’E	Elev. = 1137 m a.s.l Site area = 0. 23 ha CA = 29.57 St = 4.01 m Water depth = 5.4 Age = 4419 at 3.06 m	Lake Landslide-dammed, located on the slope near the wathershed Rock type = flysch	H: 68007000	0.69	AMS radiocarbon, 137Cs dates and isotopic geochemistry	Mindrescu et al. 2015 (submitted) Németh et al. 2014 Mîndrescu et al. 2013

11	Iezer - Feredeu	Eastern Carpathians - Feredeului Mts 47°36' 13''N 25°26'58''E	Elev. = 920 m a.s.l. Site area = 0.75ha CA = 355ha St = 4.11 m Water depth = 4.47m Age = 1035 at 3.86 m	Lake Landslide-dammed located on the bottom of valley Rock type = flysch	H: 0-> 1035-1176 cal AD	3.73	Cladocera, elemental geochemistry, lithostratigraphy, magnetic properties, grain size	Mîndrescu et al. 2013, 2010a, c
12	Iezerul Călimani	Eastern Carpathians - Călimani Mts 47°19'40'N 25°16'25''E.	Elev. = 1650 m a.s.l St = 5.0 m Site area = 0,255 ha Water depth = 0.7m Age = 14800 at 4.60 m	Lake with peat bog Located in rock slope failure (enhanced by nivation) Rock type = volcanic breccia	LG - H: 0-17730	0.31	Lithostratigraphy, pollen	Fărcaş et al. 1999, 2002, 2003, 2006 Feurdean et al. 2007b
13	Lacu Roşu	Eastern Carpathians - Hăghimaş Mts 46^0 47'0''N 25^0 47'0''E	Elev. = 983 m a.s.l. Site area = 11.65ha CA = 3880 ha St ≈ 3 m Water depth = 9.6m Age = 160 at 0.60 m	Lake Landslide-dammed located on the bottom of valley Rock type = limestone	H: 0-150?	11.70	Estimation of sedimentation rate, 210Pb and 137Cs, geochemistry	Begy et al. 2009, 2014 Pandi 2004
14	Luci	Eastern Carpathians - Harghita Mts 46°17'52.46''N 25°43'03.24''E	Elev. = 1080 m a.s.l. Site area = 120 ha CA = 1065 ha St = 7.50 m (hiatus) Age = 14700 at 7.22 m	Peat bog Located in former volcanic crater Rock type = andesite	LG - H: 0-14900	0.49	Lithostratigraphy, pollen,	Tanţău et al. 2003c, 2014 Tanţău 2006 Fărcaş et al. 2006 Feurdean et al. 2007b
15	Sfânta Ana	Eastern Carpathians - Harghita Mts 46°07'35'' N 25°53'18''E	Elev. = 950 m a.s.l. St = 11.7 m (2010) Water depth = 6 m (2000) Site area = 19.7 ha (2000) CA = 202ha Age = 26056.5 at 10.62 m	Lake Located in whole volcanic crater Fed exclusively by meltwater and runoff Rock type = andesite	LG - H: 0-27000 (assumed to be older, ~40k)	0.04	Lithostratigraphy, pollen, macrofossil, diatom, cladocera, geochemistry, testate amoebae, cysts, sedimentation rates (SR) using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am	Magyari et al. 2006, 2009c, 2014a,b Buczkó and Magyari 2007 Hutchinson et al. 2015 Begy et al. 2011
16	Mohoş	Eastern Carpathians - Harghita Mts 46°08'.52''N 25°54'13.26''E	Elev. = 1040 m a.s.l. Site area = 80 ha St = 10.65 m CA = 230 ha Age = 9750 at 10.05 m	Peat bog with Sphagnum Located in a former volcanic crater Rock type = andesite	LG - H: 0-13890	0.10	Lithostratigraphy, pollen	Tanţău et al. 2003a,b, 2006 Tanţău 2006 Fărcaş et al. 2003, 2006 Feurdean et al. 2007b

17	Lacul Negru - Bisoca	Curvature Subcarpathians, Buzău sector 45°32'58.98''N 26°40'07.54''E	Elev. = 910 m a.s.l. Site area = 2 ha CA = 10 ha St = 7.0 m (hiatus) Age = 11060 at 6.66 m	Peat bog with Sphagnum Located in a landslide basin near watershed Rock type = molasse	H: 0-11000	0.60	Lithostratigraphy, pollen	Tanţău et al. 2003a Tanţău 2006 Fărcaş et al. 2006
18	Lacul cu Muşchi - Bisoca	Curvature Subcarpathians, Buzău sector 45°33'02.36''N 26°40'21.89''E	Elev. = 930 m a.s.l. Site area = 0.6 ha CA = 4.5ha	Peat bog with Sphagnum Located in a landslide basin near watershed Rock type = molasse	Not specified	-	Lithostratigraphy, pollen	Tanţău et al. 2003a Tanţău 2006
19	Avrig 1 Avrig 2 (2 cores)	Transylvanian Basin - Făgăraş Depression 45°43''N 24°23''E	Elev. = 400 m a.s.l. St Avrig 1 = 8.06 m St Avrig 2 = 11.9 m Site area = 10 ha Age Avrig 1 = 13880 at 7.2 m	Peat bog with Sphagnum Located on fluvial terrace of river Olt Rock type = platform deposits	Avrig 1: LG - H: 0-17200 Avrig 2: H: 0-4800	0.52	Lithostratigraphy, pollen	Tanţău et al. 2006, 2011b Feurdean et al. 2007b
20	Capra	Transylvanian Alps - Făgăraş Mts, southern slope 45°36'04.75'' N 24°37'44.11'' E	Elev. = 2249 m a.s.l. Site area = 1.88 ha CA = 29.7ha Water depth = 13.1 m St = 0.6 m Age=170 at 0.185 m	Lake Located in glacial cirque Rock type = crystalline schist	H: 1840-2008AD	1.09	Sedimentation rates (SR) using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am, pollution history	Hutchinson et al. 2015 Akinyemi et al. 2013
21	Galeş	Transylvanian Alps - Retezat Mts, northern slope 45°23'09.69''N 22°54'38.51''E	Elev. = 1973 m a.s.l. Site area = 3.68 ha CA = 177.5 ha Water depth = 20 m St = 3.28	Lake Located in glacial cirque Rock type = granite Age = 13540 at 2.80 m	LG - H: 0-15124	0.30	Pollen, macrofossils, conifer stomata, diatoms, Cladocera, chironomids, chrysophyte stomatocyst	Buczkó et al. 2013 Magyari et al. 2009a,b Soróczki-Pintér et al. 2014
22	Tăul dintre Brazi	Transylvanian Alps - Retezat Mts, northern slope 45°23'49.58''N 22°54'11.43''E	Elev. = 1730 m a.s.l. Site area = 0.11 ha CA = 5.28 ha Water depth = 1.1 m St = 4.9 m Age = 13620 at 5.78 m	Lake Located on the bottom of a glacial valley Rock type = granite	LG - H: 0-15750	0.21	Lithostratigraphy, elemental geochemistry, organic matter content via LOI, pollen, macrofossils, conifer stomata, diatoms, ostracode, chironomids, ancient DNA	Magyari et al. 2009a,b, 2011, 2013 Buczkó et al. 2009a, 2012b Tóth et al. 2012 Iepure et al. 2011

23	Bucura	Transylvanian Alps - Retezat Mts, southern slope 45°21'38.58''N 22°52'34.15''E	Elev. = 2040 m a.s.l. Site area = 10 ha CA = 201.4 ha Water depth = 17.5	Lake Located in a complex glacial cirque Rock type = granite	Not published	-	Pollen, macrofossils, cladocera, chironomids	Buczkó et al. 2013
24	Lia	Transylvanian Alps - Retezat Mts, southern slope 45°21'08.73''N 22°52'44.24''E	Elev. = 1910 m a.s.l Site area = 1.3 ha CA = 431.9 Water depth = 4.3 m St = 7.62 Age = 14200 at 7.62	Lake Located in glacial cirque Rock type = granite	LG - H: 14200	0.54	Diatoms (siliceous algae), pollen, macrofossils, cladocera, chironomids	Buczkó et al. 2013
25	Tăul Negru	Transylvanian Alps- Retezat Mts, northern slope 45°21'34.24''N 22°49'44.46''E	Elev. = 2005m Site area = 4.6 ha Water depth = 24.8 m St = 0.43 m Age = 140 at 0.095 m	Lake Located in glacial cirque Rock type = granite	H: 1860-2000	0.68	Sedimentation rates (SR) using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am, atmospheric contamination and ecological changes	Hutchinson et al. 2015 Rose et al. 2009
26	Tăul Zănoguţii	Transylvanian Alps - Retezat Mts, western slope 45°20'03.35''N 22°48'18.02''E	Elev. = 1855 m a.s.l. St = 4.80 (5.65) m (hiatus) CA = 54.1 Site area = 0.21 ha Age = 11140 at 4.70 m	Lake Located in glacial cirque Rock type = granites	LG - H: 0-14800	0.42	Lithostratigraphy, pollen, diatoms, green algae	Fărcaş et al. 1999, 2003, 2006 Feurdean et al. 2007b
27	Semenic (Zănoaga Roșie)	Western Carpathians - Banat Mts Semenic range 45°08'23''N 21°59'00''E	Elev. = 1400 m a.s.l. St = 1.6 m	Peat bog Located in rock slope failure (on summit) Rock type = crystalline schist	LG - H: 0-7620	0.21	Lithostratigraphy, pollen, plant macrofossil	Rösch and Fischer 2000 Fărcaş et al. 2003, 2005, 2006
28	Peşteana	Western Carpathians - Banat Mts Poiana Ruscă range 45°32'37.42''N 22°48'28.62''E	Elev. = 508 m a.s.l. Site area = 1.5 ha CA = 6.5 ha St = 5.10/ max. 5.80 m (hiatus)	Peat bog with pool Located in a landslide basin Rock type = crystalline schist	LG - H: ca. 0-17000	0.30	Lithostratigraphy, pollen, testate amoebae	Fărcaş et al. 2006

29	Căpăţâna	Western Carpathians - Apuseni Mts 46°30'20.88''N 23° 09'5.53''E	Elev. = 1220 m a.s.l. St = 5.35 m	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: ca. 0-7000	0.76	Lithostratigraphy, pollen, testate amoebae	Fărcaş et al. 2003, 2006
30	Molhaşul Mare	Western Carpathians - Apuseni Mts 46°35'24''N 22°45'51''E	Elev. = 1224 m a.s.l. Site area = 8 ha St = 5.7 m	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: 0-5700	1.00	Lithostratigraphy, pollen, charcoal	Feurdean and Willis 2008a, b Feurdean et al. 2009
31	Călineasa	Western Carpathians - Apuseni Mts 46°33'03,550''N 22°47'26,94''E	Elev. = 1360 m a.s.l. Site area = 1 ha St = 2.24 m	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: 0-5100	0.44	Lithostratigraphy, pollen, charcoal, magnetic susceptibility, LOI	Feurdean and Willis 2008b
32	Padiş - Sondori	Western Carpathians - Apuseni Mts 46°35'44,86''N 22°44'00,96''E	Elev. = 1290 m a.s.l. Site area = 1 ha St = 0.76 m	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: 0-6000	0.13	Lithostratigraphy, pollen, charcoal	Feurdean and Willis 2008b Feurdean et al. 2009
33	Padiş	Western Carpathians - Apuseni Mts 46°35'53.2''N 22°43'58.4''E	Elev. = 1240 m a.s.l. St = 0.9 m	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: ca. 0-5300	0.17	Lithostratigraphy, pollen, magnetic susceptibility, LOI	Bodnariuc et al. 2002 Jalut et al. 2003 Fărcaş et al. 2003, 2006
34	Bergerie	Western Carpathians - Apuseni Mts 46°37'23.1''N 22°40'56.4''E	Elev. = 1400 m a.s.l. St = 2.3 m	Peat bog with Sphagnum, infilled sinkhole Located on plateau Rock type = limestone	H: ca. 0-7900	0.29	Lithostratigraphy, pollen	Bodnariuc et al. 2002 Jalut et al. 2003 Fărcaş et al. 2006
35	Ic Ponor I (core 1)	Western Carpathians - Apuseni Mts 46°37'46''N 22°48'24''E	Elev. = 1040 m a.s.l. St = 2.95 m (hiatus) Area = 7 ha	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: ca. 0-10100	0.29	Lithostratigraphy, pollen	Bodnariuc et al. 2002 Jalut et al. 2003 Fărcaş et al. 2003, 2006
36	Ic Ponor II (core 2)	Western Carpathians - Apuseni Mts 46°37'46''N 22°48'24''E	Elev. = 1020 m a.s.l. St = 1.65 m (hiatus)	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: ca. 0-9900	0.16	Lithostratigraphy, pollen	Bodnariuc et al. 2002 Jalut et al. 2003 Fărcaş et al. 2003, 2006

37	Pietrele Onachii	Western Carpathians - Apuseni Mts 46°38’33’’N 22°50’43’’E	Elev. = 1055 m a.s.l. Site area = 3.5 ha St= 1.85 m	Forested peat bog, infilled sinkhole located on plateau Rock type=limestone	H: 0-5500	0.34	Lithostratigraphy, pollen, charcoal	Feurdean and Willis 2008b
38	Cimetière	Western Carpathians - Apuseni Mts Coordinates not specified	Elev. = 1280 m a.s.l. St =1.30 m	Peat bog, infilled sinkhole Located on plateau Rock type = limestone	H: 0-8800	0.15	Lithostratigraphy, pollen	Bodnariuc et al. 2002 Jalut et al. 2003
39	Mlaştina de la Iaz	Western Carpathians - Apuseni Mts 47°06’30″N 22°39’40″E	Elev. = 300 m Site area = 0.35 ha St = 5.40m (hiatus) Age = 7000 at 5.20 m	Peat bog (forested) Located into a landslide basin Rock type = crystalline schist	H: 0-7000 (8380 maximum but not used)	0.74	Lithostratigraphy and pollen	Grindean et al. 2014
40	Turbuța	Transylvanian Basin, northwestern part 47°15’ 26.5’’N 23°18’42.9’’E	Elev. = 275 m a.s.l. Site area = 1.5 ha St = 1.9 m (hiatus)	Paleolake landslide dammed Rock type = sedimentary platform deposits	LG - H: 5000-13100	0.14	Lithostratigraphy, pollen, micro-charcoal, total carbon analyses	Feurdean et al. 2007a
41	Măgheruş	Transylvanian Basin, northern part, in Măgheruș Valley 24°23'47.21"E 47°05'56.43"N	Elev. = 345 m a.s.l. Site area = 0.6 CA = 1939 ha St = 1.39 Age= 15495 at 1.265 m	Paleolake landslide-dammed Located on valley bottom Rock type = sedimentary platform deposits	LG: 11000-17000 (max. 17894)	0.08	Radiocarbon dating, mineral magnetic analyses, loss on ignition, organic macrofossils (sclerotia of Cenococcum geophillum)	Lascu et al. 2014
42	Lake Stiucii	Transylvanian Basin, northern part 46°58’044 N 23°54’106 E	Elev. = 239 m a.s.l. Study area = 38 ha St = 7.27 m	Lake Mixed origin: salt karst and landslide-dammed Rock type = sedimentary platform deposits	H: 0-12000	0.61	Lithostratigraphy, pollen, micro & macrocharcoal, organic matter content via LOI, magnetic susceptibility, elemental geochemistry; sedimentation rates (SR) using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am	Hutchinson et al. 2015 Feurdean et al. 2015

[1] Catchment area [2] Sediment thickness [3] Sedimentation rate (estimation) [4] Data corresponds to old glacial lake prior to human intervention

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Chapter 2

Glacial cirques and their climatic implications

Rationale

Glacial cirques have long been used as evidence of former climates (e.g. Porter, 1977, and references in Evans, 2008). Earlier work in the Carpathians (e.g. de Martonne, 1900; Pawlowski, 1936) was based on rather poor maps, but since 1989 air photos and former military maps have become available, together with modern surveys. Hence a resurvey of cirques in Romania by Mîndrescu (2006) permits more accurate measurement of cirque form and altitude, and provides a comprehensive inventory: cirques have been defined, delimited and measured in ways consistent with those applied by Evans and Cox (1995) in Britain and by Evans (1994) in British Columbia. Our aim in this chaper was to use information on the altitude, aspect and spatial distribution of cirques across the whole of Romania and glacial deposits analysis to make several inferences concerning glacial palaeoclimates in the Late Pleistocene. In particular, we discuss the implications of both regional and local variations for *palaeowind directions, precipitation patterns, palaeodeglaciation level and snowline (cirque floor level).* The mountain glaciation of Romania in the Late Pleistocene was extensive, and remarkable for the dominance of cirque development. A number of glacial troughs were developed, but only three glaciers were longer than 10 km (Urdea, 2004), and these pre-dated the Last Glacial Maximum (LGM). The style of glaciation was thus marginal, more like that of individual Appennine, Balkan or Iberian ranges than that of the Alps or Pyrenees (in contradiction to Velcea, 1973). The glacial cirques and troughs provide evidence of former cirque and valley glaciers and thus of climate during a number of glacial maxima, as their erosion is believed to require tens or hundreds of thousands of years. The altitudes of cirque floors and of the palaeoglaciation level, and the aspects (azimuths, downslope directions) of cirques, may be strongly affected by former wind directions, as well as by temperature and solar radiation conditions (Evans, 1977; Mîndrescu, 2004).

2.1 Historical background

The study of glaciation in the Romanian mountains was started by Tietze (1878) and its history is summarized in Urdea and Reuther (2009), but only a small proportion of the literature deals quantitatively with glacial cirques. The pioneer was de Martonne (1900) who, faced with poor quality maps, personally surveyed two Parâng cirques in detail. He later covered the whole eastern part of the Parâng, plus the Soarbele cirque in the Godeanu Mountains (de Martonne, 1906: an impressively accurate map). De Martonne (1900) measured the maximum, minimum and mean floor altitudes for 16 cirques, plus their floor areas, mean floor gradients, aspect, and number and minimum altitude of lakes.

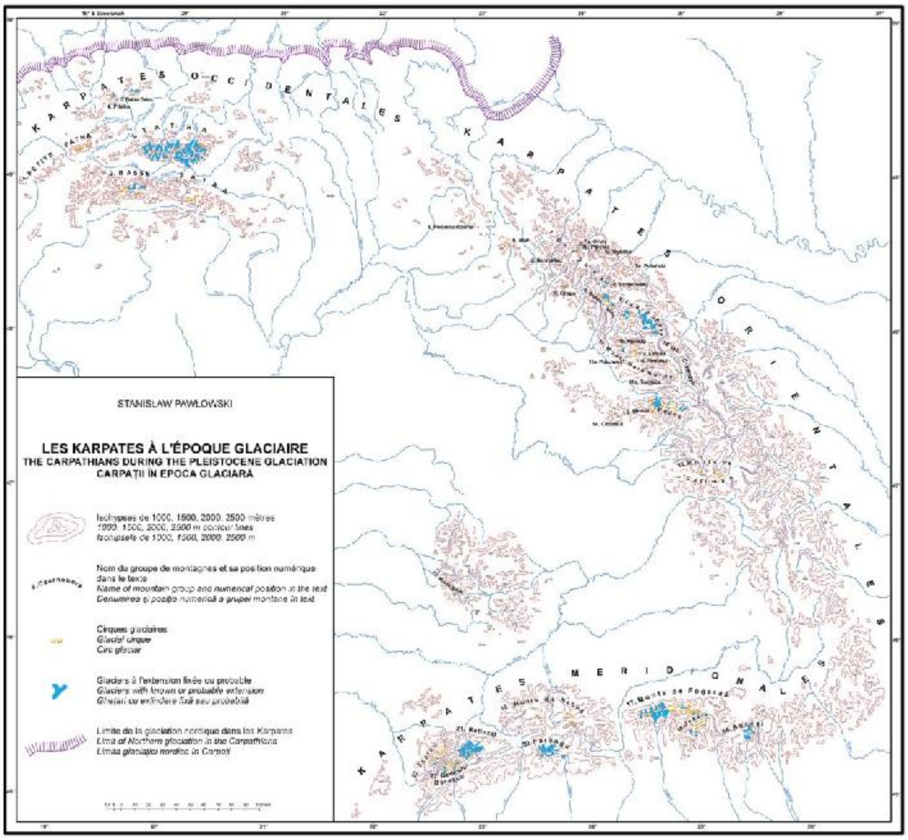

Fig. 2.1.1. The Carpathians during the Pleistocene glaciation (redrawn after Pawłowski, 1936).

All the cirques contained roches moutonnées, and three had clear striations. In much of the Carpathians, however, weak rocks such as flysch and schist preserve few striations, and weathering of coarse-grained granites and gneisses produces rough surfaces, eliminating most striations (de Martonne, 1901). De Martonne (1901, 1907) noted the influence of geological structure, distinguished large cirques from small hanging cirques, and produced a compromise between 'glacialist' and 'antiglacialist' interpretations. Further cirque mapping was performed by Szilády (1907) for the Rodna Mountains. Sawicki (1912) suggested former snowlines, and Pawłowski (1936) mapped snowlines throughout the Carpathians and defined glacial features asymmetry (Fig. 2.1.1).

Under the 1947–1989 communist regime, many regional geomorphology monographs were published, often containing morphological maps of mountains with cirques. Table 2.1.1 lists these (marked *), and/or the most recent research papers.

Table 2.1.1 Romanian mountain ranges (20 glaciated): highest summits in each range (in metres), ordered from north to south, then to west; and modern works on glaciated ranges. *indicates monographs. Note that figures from different sources sometimes vary by a few metres

Range name	Summit height (m)	Reference
Maramureş	1956	Sîrcu (1963)
Ţibleş	1853	Mac et al. (1990)
Rodna	2303	Sîrcu (1978)*
Călimani	2100	Naum (1970); Kern et al. (2006)
Siriu (Mălaia)	1662	Orghidan (1932); Naum (1957)
Bucegi	2505	Micalevich-Velcea (1961)*
Leaota	2133	Sultana (1976)*, Murătoreanu (2009)*
Iezer	2470	Nedelcu (1967), Szepesi (2007)*
Făgăraş	2544	Florea (1998)*
Cindrel	2244	Niculescu (1969)
Lotru	2242	Ancuţa (2005)
Latoriţei	2055	Călin (1987)
Căpăţânii	2130	de Martonne (1907)
Parâng	2518	Iancu (1970)*, Marinescu (2008)
Şureanu	2130	Trufaş (1962), Niculescu (1969)
Retezat	2509	Urdea (2000)*
Godeanu	2291	Niculescu (1965)*
Ţarcu	2192	Niculescu (1990), Gruia (1998)
Muntele Mic	1802	Niculescu (1990)
Bihor/Apuseni	1848	Berindei (1971)

Published classifications of cirques included Niculescu's (1965, 1969, 1990) four fold division into simple, elongated and complex cirques, and 'complexes of (adjacent) cirques'. He attributed steps within cirques and glacial troughs to geological factors: others have related them to preglacial features. Sîrcu (1964) discussed the limited glaciations of most of the Eastern Carpathians. During recent decades Romanian glacial geomorphology regained contact with the Western literature, and quantitative evaluation of glacial features using geomorphometric methods was introduced. The application of absolute dating methods began to establish a chronology of multiple glaciations and readvances, with initial results in the Retezat (Reuther et al., 2004, 2007; Urdea et al., 2011) and Rodna (Gheorghiu, 2011; László et al., 2013) Mountains. These have demonstrated that some cirques were last occupied in the Younger Dryas. New glacial features continue to be discovered (Mîndrescu, 2002, 2009a; Urdea et al., 2011), demonstrating that glaciation was more widespread than previously considered.

2.2 Distribution of glacial cirques

At 45-48^{0}N latitude, the Romanian Carpathians occupy a central position within the temperate climate zone. They provide evidence of Quaternary climates in an important transitional region between cool temperate and Mediterranean climates. They are also placed between the oceanic climates of Western Europe and the arid regions of interior Asia (Fig 2.2.1). It is believed that the oceanic climates are most responsive to climate change in the North Atlantic, and Central Asia is the least responsive. For climatic studies, the Carpathians are thus a key region that would have recorded changes in patterns of atmospheric circulation and their consequences for precipitation gradients.

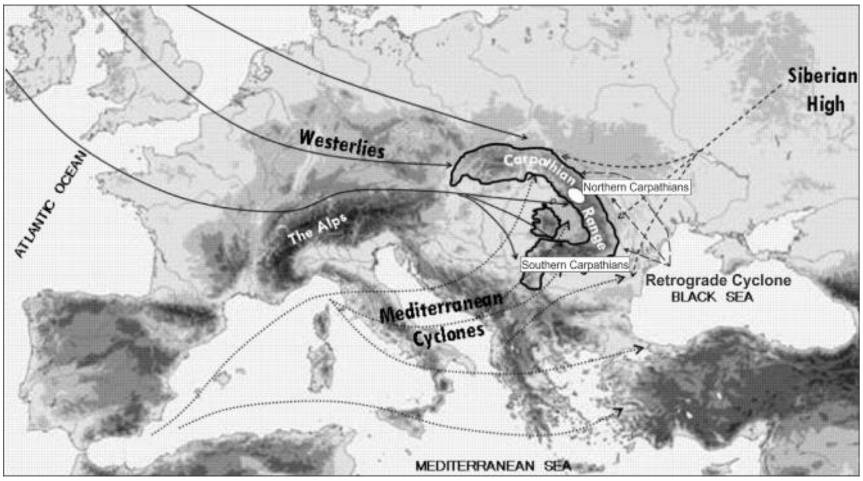

Fig. 2.2.1. Relief map of Europe with location of the Carpathians (contour line) and its contact between oceanic, continental, Mediterranean and Black Sea air masses.

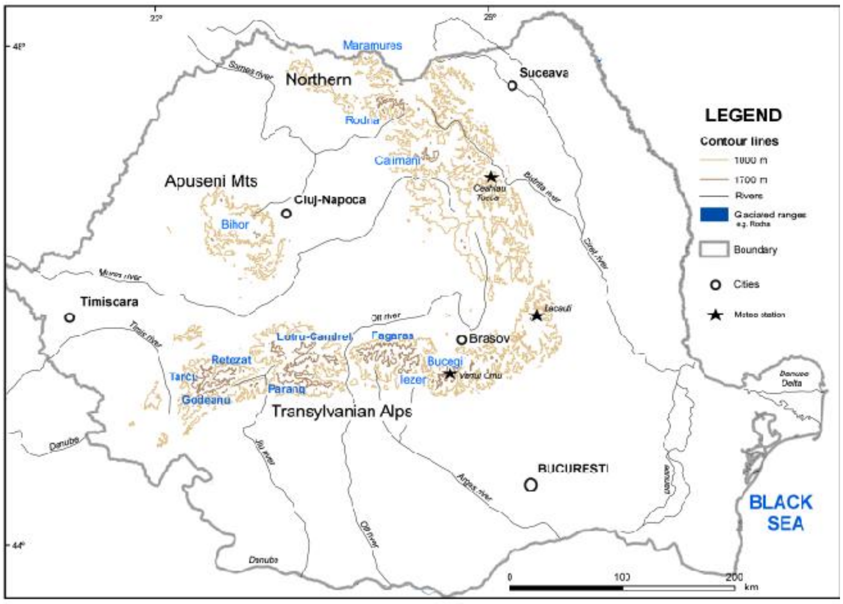

Fig. 2.2.2. Romania, showing high ground, with names (in blue, on-line) of the main mountain ranges with cirques, as used here for the 12 range groups.

In modern Romania precipitation comes largely from the west, and thus the western part of the Transylvanian Alps (the Retezat, Godeanu and Ţarcu Mountains), and the Bihor or Apuseni Mountains in western Transylvania, receive more rain and snow than the eastern mountains. From regional cirque distributions and local cirque aspects it appears that a similar situation applied during Late Pleistocene glacial phases, with the main moisture-bearing winds coming from north of west (Urdea and Reuther, 2009; Mîndrescu et al., 2010).

Romania contains many mountain ranges with summit altitudes between 1800 and 2544 m, high enough to support small glaciers during glacial periods of the Late Pleistocene. Romania has no present-day glaciers or permanent snow patches; the latest snow patches are found within cirques in the Rodna (Buhăiescu Mare) and Maramureş (Pop Ivan, Ukraine) Mountains, but none of them survive to August.

All of the many separate mountain ranges rising above 2000 m altitude, however, supported glaciers in the Late Pleistocene (Table 2.1.1), whereas no ranges below 1600 m did so. There were numerous valley glaciers (one in Retezat was 18 km long: Urdea, 2004), but most were cirque glaciers.

The numerous former glaciers developed a large number of cirques: we recognise 631 glacial cirques in Romania and the adjacent Ukrainian Maramureş as the range straddles the international border (Figs 2.2.1 and 2.2.3).

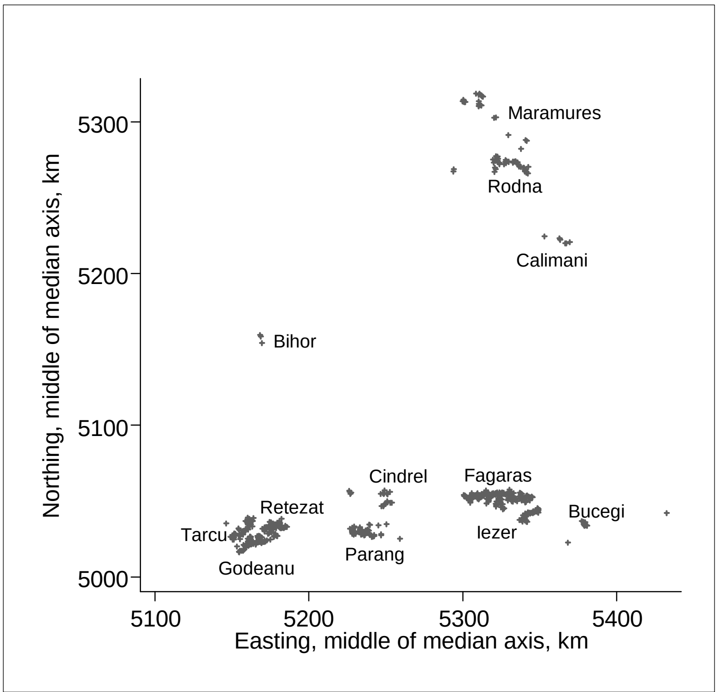

Fig. 2.2.3. Spatial distribution of glacial cirques of Romania, with names of the main ranges.

Most cirques are eroded into schists, granites, or gneisses, which permitted fairly uniform cirque erosion. Structural influences were stronger on the massive conglomerates of the Bucegi Range (Fig. 2.2.4).

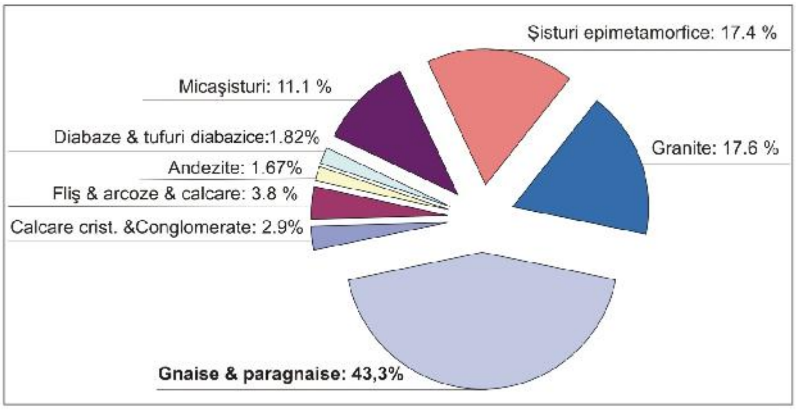

Fig. 2.2.4. Distribution of glacial cirques from the Romanian Carpathians according to lithology (summarized version) (M. Mîndrescu).

Glaciation was heaviest and most azimuthally symmetrical in the Transylvanian Alps (Southern Carpathians), with 547 cirques in all. This applies especially to the Făgăraş Mountains because of their high altitude and the length of the main ridge (above 2000m altitude), and to the Retezat Mountains because they receive more precipitation than ranges farther east. Taking the area above 1800m as that most exposed to glaciation, the Făgăraş, with 238 km^2 and the Retezat with 116km^2 are well ahead of the other ranges, which each have less than 75 km2.

The second centre of glaciation was in the north (the Rodna, Maramureş and Călimani Ranges), where regionally lower temperatures compensated for lower altitudes and 81 cirques formed. Finally, the Bihor Range of the Apuseni Mountains, a lower massif sometimes termed the Western Carpathians in Romania, was just high enough to support glaciers producing three cirques.

Thus glaciation was most extensive in the higher and wetter mountain ranges, and these developed the greatest numbers of cirques. First come the Făgăraş Mountains with 206 cirques: they have 238 km^2 above 1800 m and the highest summit is 2544 m altitude. Second, the Retezat (Fig. 2.2.5) reaches 2509 m and has 84 cirques. It is followed by the Godeanu (2291 m, 69 cirques) and Ţarcu (2192 m, 58 cirques) Ranges, whose western location compensates for lower altitude. The Parâng (2518 m; 51 cirques) and Iezer (2470 m; 38 cirques) Ranges, despite their altitudes, are relatively small and sheltered from winds from north of west.

Although the Bucegi Mountains reach 2505 m, the high area is restricted and only 11 cirques formed. Despite their low altitudes (1848, 1658 and 1530 m) three summits in the Bihor Mountains, exposed to winds from west and northwest, support cirques on leeward slopes. This strongly suggests that, as today, snowfall during glacial periods must have been greater in the Bihor Mountains and the westernmost Transylvanian Alps than at similar altitudes elsewhere in Romania.

With 547 cirques, the Transylvanian Alps (the South Carpathians) were clearly the main centre of glaciation in Romania.

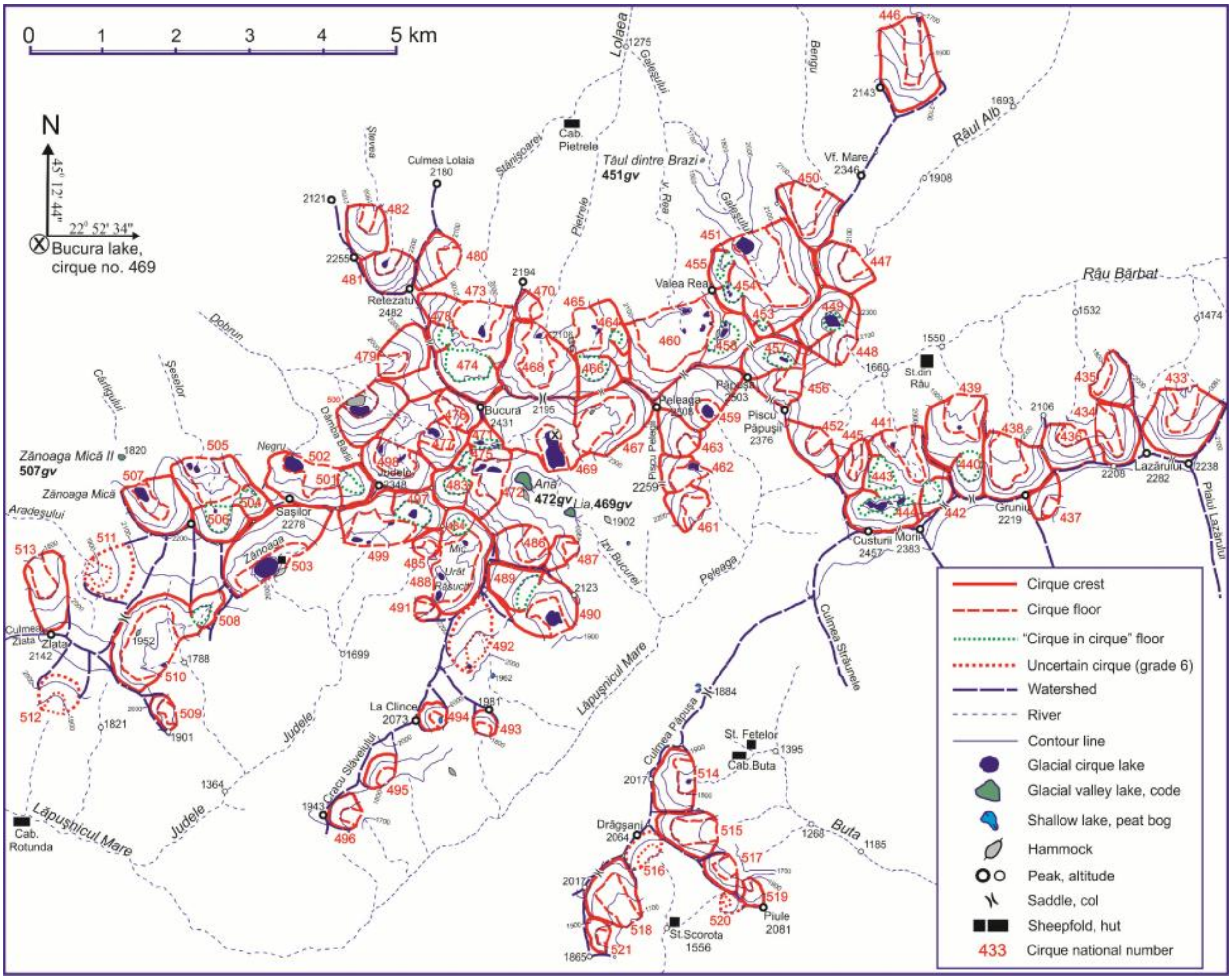

Fig. 2.2.5. Maps of cirque outlines and floors for Retezat.

In the north of Romania, regionally lower temperatures compensated for lower altitudes, giving a second centre of glaciation with 81 cirques. Most of these (45) are in the Rodna Mountain Range (summits up to 2303 m: Fig. 2.2.6), but 27 are on separate mountains with summits of 1713 - 1957 m altitude in Maramureş, and 7 are in the Călimani Mountains (1989 and 2100 m). South of these, a large section of the relatively dry Eastern Carpathians with summits up to 1907 m lacks glacial cirques.

Altogether, 20 mountain ranges in Romania, named in Table 2.1.1, have one or more glacial cirques.

For most statistical analyses it is necessary to merge those ranges with few cirques with adjacent ranges, giving 12 range groups (regions). Thus Ţibleş (2 cirques) is assigned to Rodna region, Ciucaş-Siriu and Leaota (1 each) to Bucegi, Căpăţânii (1) and Latoriţa (4) to Parâng, and Muntele Mic (1) to Ţarcu, while Lotru (10), Cindrel (8) and Şureanu (4) are combined as Lotru-Cindrel region.

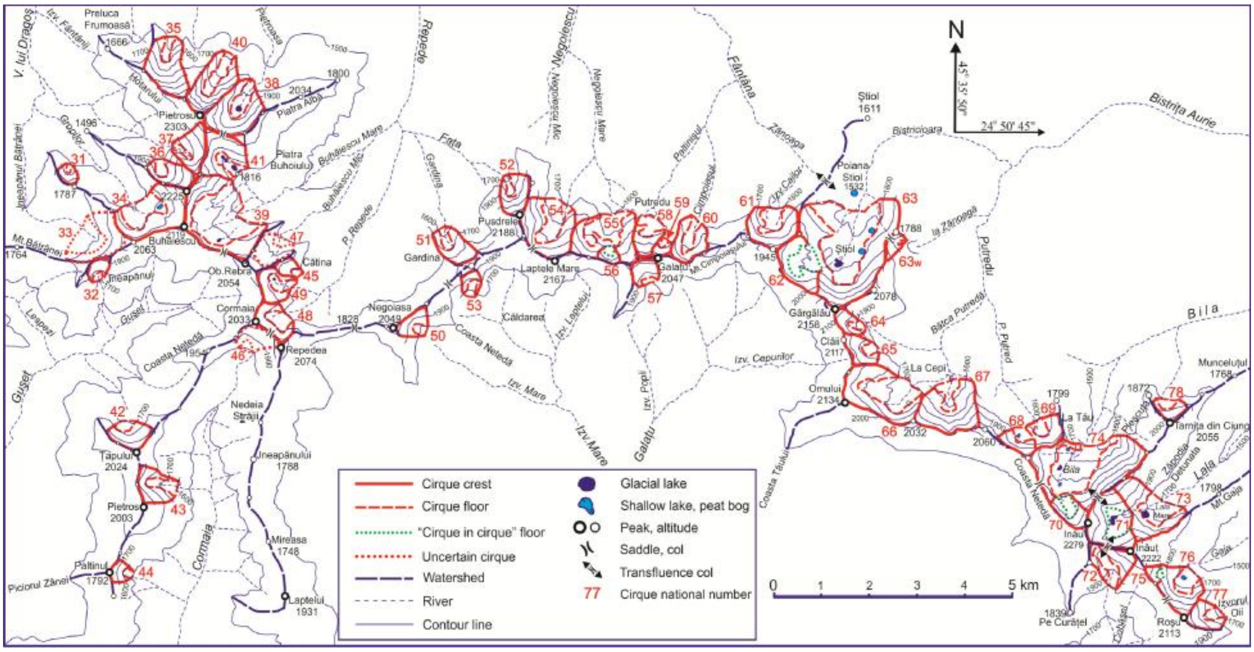

Fig. 2.2.6. Maps of cirque outlines and floors for Rodna.

Overall, the distribution of glacial cirques in Romania can be summarized as follows:

- Cirques of all grades are abundant in Romania.
- They are lower in the north and west of the Romanian Carpathians.
- A clear tendency to face eastward is superimposed on the general poleward aspect, & is strongest in the western Transylvanian Alps.
- This demonstrates important winds from the west during times of cirque formation, but less so in Northern Romania.
- Cirque development would be active around glacial maxima.
- Cirques lengthen and widen more than they deepen with size, confirming the allometric development seen elsewhere.

2.3 Cirque size

The average of the Romanian cirque (of the 631) is *654 m long and 718 m wide*, with a height range of 318 m, an axial amplitude of 272 m, and a maximum headwall height of 209 m. Respective medians are 596, 650, 300, 260, and 198 m, and standard deviations (SD) are 276, 320, 116, 99 and 89 metres. Mean area is 43.7 ha (SD 39.4), floor area is 12.1 ha (SD 12.6 ha), and perimeter averages 2413 m (SD 1036 m): medians are 32.2 ha, 8.4 ha and 2212 m. Mean and median values are useful only if an inventory is complete, as here. They would be greater if poor or marginal (doubtful) cirques were excluded.

As is clear from the high ratios of standard deviation to mean, frequency distributions of all these size variables are positively skewed. All medians are below corresponding means: skewness is between 1.00 and 1.88 for all linear variables, and 2.7 and 4.03 for the two areal ones. This implies several problems for statistical analysis: for example, a few high values have the greatest influence (leverage) on correlations and regressions. The best way to adapt such analyses is to apply transformations that give symmetrical frequency distributions: these usually provide even scatter around regression lines (Evans, 1979; 1983). Logarithmic transformation of all size variables has the desired effect: skewness is reduced to between – 0.09 and +0.20, excepting – 0.35 for cirque floor altitude range. This implies good fits to the log-normal (log-Gaussian, multiplicative) model (Limpert et al., 2001), as is common for size variables where there is considerable variance and negative values are impossible (Evans, 2010). Logarithmic scales are therefore used in further analyses of these variables.

As in cirque studies elsewhere, linear measures vary over one decimal order of magnitude, from approximately 200 m to 2 km in width and length and from 100 to 900 m in height range. This produces low logarithmic standard deviations, roughly 0.18 for horizontal and 0.16 for vertical dimensions: logarithmic ranges are 1.0 (i.e., ten-fold) (Fig. 2.3.1). Correspondingly, cirque area varies over two orders and has a logarithmic standard deviation of 0.33 (range 2.0). *Romanian cirques are scale-specific, with a limited range of sizes*.

It is useful to have a single linear measure of cirque size (e. g. allometry). To cover all three orthogonal dimensions, length, width and amplitude are selected. They are multiplied together and the cube root is taken so that a linear measure in metres is obtained: this 'Size' averages 495 m (SD 178 m) and is more amenable to statistical analysis than are volume measures.

Fig. 2.3.1 shows how all these size variables (horizontal, vertical and combined) have smooth, unimodal frequency (or probability) distributions, symmetrical on a logarithmic scale and with limited variability: most values fall within ± 0.2 logarithms of their median. Romanian cirques form a single population, with no obvious division into sub-populations on grounds of size.

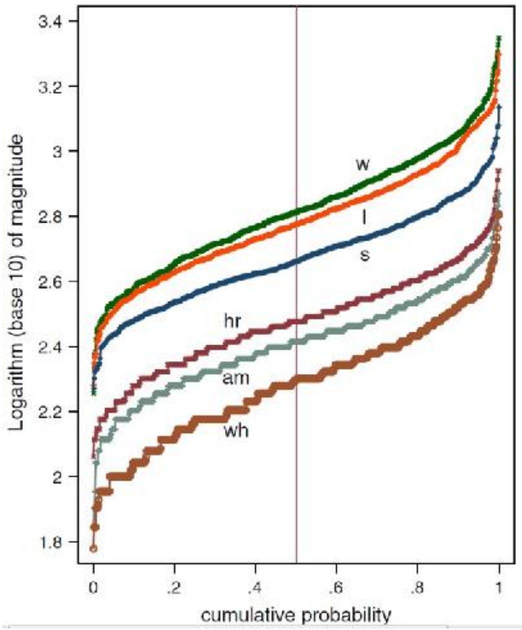

Fig. 2.3.1. Log-normal size distributions of horizontal measures (w = width, l = length), vertical measures (hr = height range, am = amplitude, wh = wall height) and a combined measure (s = size) of cirque size. The vertical line is drawn at the median.

All size variables are strongly interrelated: product-moment correlations of logarithms, all positive, are considered. Cirque perimeter varies so closely with cirque area, r = 0.994 for logarithms, that it does not require separate consideration; likewise floor perimeter, which correlates 0.983 with floor area. Cirque area correlates 0.955 with Size, 0.910 with length, 0.929 with width and 0.897 with floor area. Length correlates 0.715 with width, and amplitude correlates 0.738 and 0.465 with these two. Height range correlates 0.881 with amplitude and all its correlations are stronger, for example 0.609 with width.

All size variables increase with crest and summit altitudes, e.g. log (size) correlates +0.35 with maximum crest altitude. Lowest altitude correlates negatively with size variables, because the higher it is, the more possible amplitude is restricted: these correlations, however, are weaker than the positive correlations between size and crest altitudes.

By region, the largest cirques are in Rodna: median length 742 m, width 729 m and amplitude 310 m. It is followed by Făgăraş in vertical dimensions, but by Bucegi in horizontal: in fact, median width (734 m) is slightly greater for Bucegi although means are much greater for Rodna (816 cf. 727 m for length and 868 cf. 780 m for width). With both smaller and larger cirques than Bucegi, Rodna has a much higher standard deviation. Maramureş and Călimani have the smallest cirques in width and length, but Bihor and Ţarcu have the smallest in vertical dimensions. Dividing the regions into the 20 ranges, Rodna cirques remain easily the largest while Maramureş, Călimani, Bihor and Ţarcu cirques are the smallest except for some ranges with few cirques. The five ranges with only one or two cirques might be expected to have small cirques because of their marginal glaciation, but in fact they are very varied, with the cirques in Căpăţânii and Siriu being larger than average, Leaota near-average, and Ţibleş and Muntele Mic among the smallest. Muntele Mic has easily the smallest range average, but not the smallest cirque – its one cirque is at the 8^{th}percentile.

2.4. Cirques shape: gradient and closure

From the cirque definition, we have certain expectations of a well-developed cirque. Distinction from fluvial valley-heads increases as floors increase in relative size and become flatter, as headwall gradients increase, and headwalls become more arcuate or rounded. The latter is the most difficult to express quantitatively. Plan closure should also increase as cirques develop, although even fluvial valley-heads may have plan closures approaching 180º. (Plan closure is useful in comparing cirques, but of little use in discriminating cirques from other features.)

In contrast to size variables, the shape variables measured here have fairly symmetrical distributions on the initial measurement scales, and only '*Cols*' requires transformation. Mean values of minimum and maximum gradient are 8° and 51°, and mean axial (overall) gradient is 24°. Standard deviations are 5°, 9°and 6° respectively. Plan closure averages 137° (SD 40°) (Fig. 2.4.1) and profile closure, 43° (SD 11°). All of these frequency distributions are unskewed (skewness 0 to 0.33) and can be approximated by normal (Gaussian) frequency distributions. Fig. 2.4.2 shows the symmetry of frequency (probability) distributions for the four gradient variables, and for profile closure which shows greater variation. The distribution of minimum gradient is limited by zero, as bathymetric data have not been considered: the reversed slopes in lake basins would ideally be measured as negative down-valley gradients.

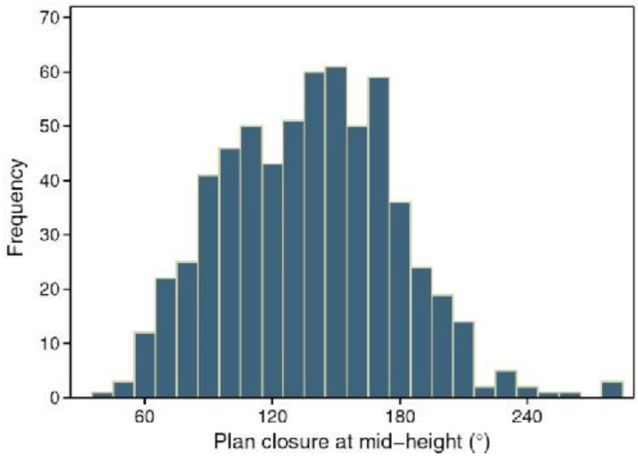

Fig. 2.4.1. Histogram of Plan closure. The mean is 137°, standard deviation 40.5°, skewness 0.23.

Compared with the limited data available elsewhere (Table 2.4.1), Romanian cirques have high plan closure, comparable to the British Columbian cirques andwell above those in Britain. Minimum gradient lies between those for Britain and British Columbia, as does the ratio of length to height range. Romania's lowmaximumgradients are attributed to limitations of the 1: 25,000 contour maps used. The average ratio of length to height range is

2.10, corresponding to 25.5°. This is smaller (steeper) than for British and Bohemian cirques (in low-relief areas) and very similar to Kamchatka, but larger (gentler) than for the High Tatra, Maritime Alps, Pyrenees and British Columbia high-relief areas (Table 2.4.1). Hamann and Embleton (1988) found an average of 2.72 for 138 well-developed cirques in central Austria.

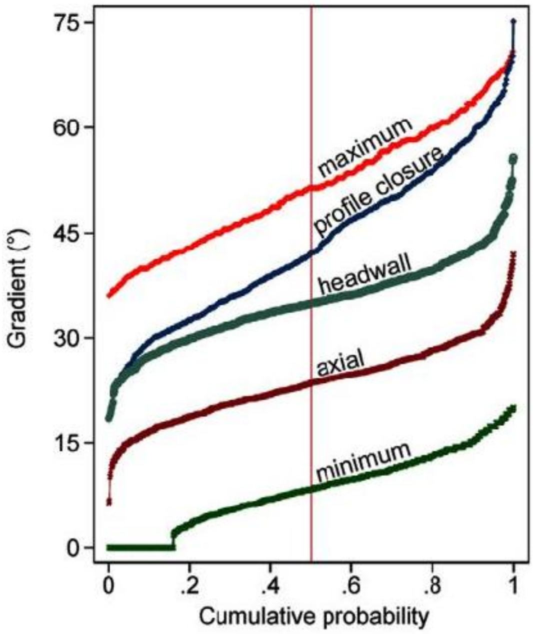

Fig. 2.4.2. Normal (Gaussian) distributions of gradient variables and Profile closure. Maximum gradient is measured over 50 m vertically, minimum over 10 m. Headwall gradient is measured at the highest part of the headwall, and axial gradient is arctan (amplitude/length). Profile closure is the difference between maximum and minimum gradient.

Table 2.4.1. International comparisons of means of size and shape variables. N.Z. = New Zealand. Note: Gordon (1977) gives amplitude, somewhat less than height range; also his gradients are not extrema. Richter's (2006) definitions of length and width produce slightly higher values than our definitions

Region	Number	Length (m)	Width (m)	Height range (m)	Plan closure (°)	Max grad (°)	Min grad (°)	Length/height range	Source
Romania	631	654	718	318	137	51.6	8.3	2.10	This paper
High Tatra	116	570	550	311				1.87	Křížek and Mida (2013)
Bohemia	27	788	700	272				2.96	Křížek et al. (2012)
Maritime Alps	432	672	663	355				1.93	Federici and Spagnolo (2004)
C. Pyrenees	206	519	691	364				1.49	García-Ruiz et al. (2000)
SW. Asturias	70	487	594	255				1.95	Ruiz-Fernández et al. (2009)
Wales	260	667	772	269	116	60.4	5.0	2.56	Evans (2006b)
English Lake D.	158	620	680	276	120	63.4	7.5	2.24	Evans and Cox (1995)
Kintail-Affric-Cannich, Scotland	231	625	586	(276)	103	44.6	10.1	(2.21)	Gordon (1977) (simple cirques)
Cayoosh	198	798	749	403	134	65.6	10.3	1.96	Evans, unpublished
Bendor	222	785	759	419	128	60.3	8.9	1.89	Evans, unpublished
Kamchatka	3520	868	992	421				2.12	Barr and Spagnolo (2013)
Fiordland, N.Z.	1296	855	882	463				1.90	Richter (2006)
Westland, N.Z.	480	1069	961	580				1.93	Richter (2006)
Ben Ohau Ra., N.Z.	90	489	536	216				2.40	Brook et al. (2006)

Most cirques have no cols (over 30 m deep) along their crest: 36% have one, 4.6% have two, and 0.8% have three cols. After square root transformation, number of cols (mean 0.44, SD 0.53) has a skewness of +0.5. Width / length ratio varies from 0.46 to 3.1, with a mean of 1.14, SD 0.37 and skewness 1.03.

The new variable *Floor closure*, floor perimeter related to threshold length, has a mean of 76° and SD 10°; its skewness is only −0.5. *Floor area ratio*, Floor area divided by cirque area, averages 28% (SD 10%) and ranges from 8 to 71%. The 10 and 90 percentiles are 16 and 41%. The frequency distribution is well-behaved, with a small positive skew (0.54), and there are no unusually low values (Fig. 2.4.3). Neither variable requires transformation of measurement scale. The four cirques with floors occupying over 57% of their area may be regarded as unusually floor-dominated: they are Buhăiescu Mare (Rodna), Şucu cu Lac (Ţarcu), Pe Custură (Făgăraş), and Custura Mică (Retezat). Their *Grades* (see below) are 1, 2, 2 and 4 respectively.

Two are inner cirques and two are valley-head cirques with thresholds; all but the latter are well-defined.

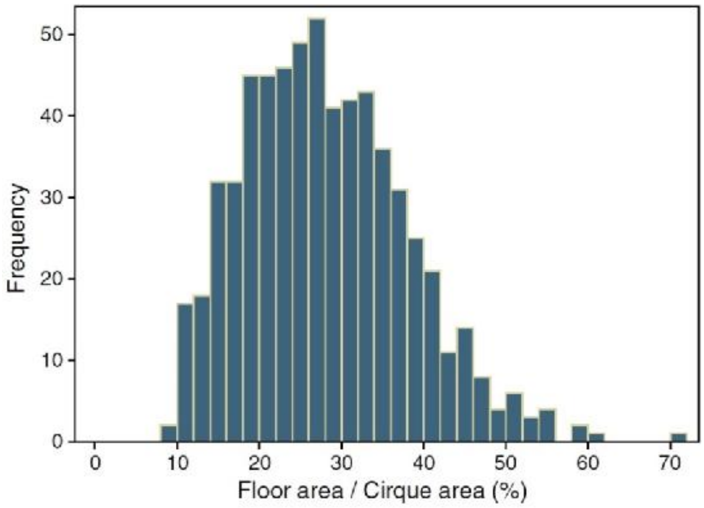

Fig. 2.4.3. Histogram of Floor area ratio. The mean is 28%, standard deviation 10%, skewness 0.54.

Correlations between these variables are not strong, except where inbuilt by definition: profile closure is the difference between minimum and maximum gradient and correlates +0.90 with the latter and – 0.69 with the former (which has less variance). The correlation between minimum and maximum gradient, however, is only – 0.29, and they correlate – 0.47 and + 0.37 respectively with plan closure (Fig. 2.4.4).

We therefore focus on maximum and minimum gradient, and their correlations, considered separately rather than as combined in profile closure. Minimum gradient tends to have stronger correlations with other *shape* variables than does maximum gradient. This may be because, being measured over a greater horizontal distance, it is more reliable, whereas maximum gradient contains greater measurement error.

Overall axial gradient averages between 20 and 26° in all twelve regions, being flattest in Bihor and Lotru-Cindrel and steepest in Maramureş, Călimani and Făgăraş. 90% of cirques are between 15 and 33º. This is approximately the gradient of former glaciers filling the cirque (glaciers are more likely to rise to the crest at the centre than at the highest part of the crest), and is appropriate for rotational flow (Lewis, 1960). Axial gradient is controlled mainly by length of floor and, thus, correlates most with minimum gradient (+ 0.56) but only +0.16 with maximum gradient. It correlates + 0.43 with Grade (see below) and – 0.36 with plan closure.

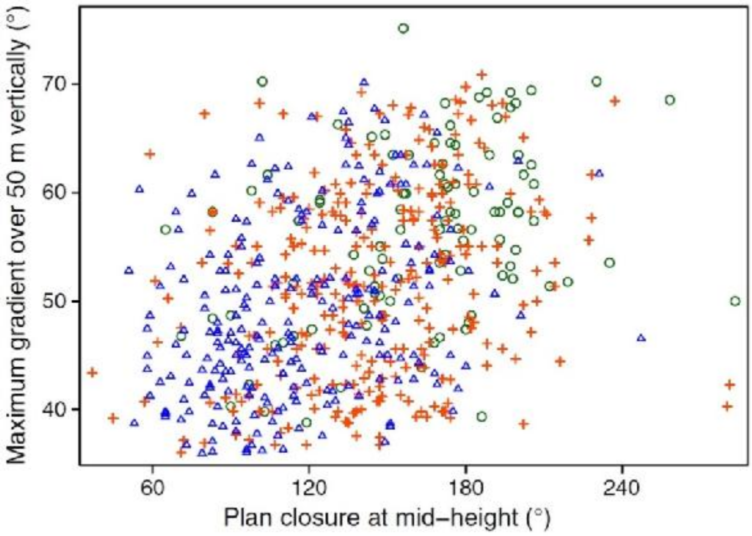

Fig. 2.4.4. The weak relations between plan closure, maximum and minimum gradient. Triangles: minimum gradient ≥ 10°; crosses: below 10° but N0°; circles: 0°.

Two new shape variables correlate very weakly with those above. Floor area ratio correlates –0.26 with both axial and minimum gradient. Floor closure correlates +0.34 with plan closure, which is logical but weak, and –0.33 with width/length ratio: cirques wider relative to their length have poorer floor closure. Apart from this, and a correlation of +0.28 with (square root of) cols, width/length has no other shape correlation stronger than |0.12|. 'Cols' has similarly weak correlations with plan closure (+ 0.29), minimum gradient and Grade. With n = 631, however, even these weak correlations are highly significant (p = 0.0001 for r = 0.16). Width/length is a simple, widely used measure of cirque shape, but it has only slight relationships (linear or parabolic) to measures of cirque development.

Relations to altitude are strongest for maximum crest altitude, which correlates +0.33 with plan closure, +0.45 with maximum gradient and -0.24 with minimum gradient. All of the altitude variables correlate with similar signs: on average, higher cirques are better developed in these respects.

Regionally, cirques in Călimani are much poorer than elsewhere, with easily the worst plan and profile closure, Grade and maximum gradient, as well as the lowest relative floor area and number of cols and the highest minimum gradient. Bihor generally scores poorly, except for floor area and floor closure, and Maramureş, Iezer and Ţarcu also have poor scores. Maximum gradient is highest for Făgăraş, Retezat and Parâng, while minimum gradient is lowest for Retezat, Parâng and Lotru-Cindrel. The three latter have the highest overall Grade and all four together with Bucegi have the highest plan closures (mean > 140°). Cols are most frequent in Rodna, Retezat and Făgăraş and floors are proportionately larger in Ţarcu and Retezat.

Relation between shape and size

There are systematic relations between cirque shape and size (Table 2.4.2). Maximum gradient increases, and minimum gradient decreases, with increase of any of the size variables. Maximum gradient relates more to vertical dimensions, especially height range and wall height, while minimum gradient relates to Floor area and other planimetric dimensions (width a little more than length). Plan closure also increases with each size measure, especially area and width. Axial gradient declines for longer cirques (as length is in the definition of axial gradient, this could be regarded as inbuilt, a ratio correlation: Evans and Jones, 1981), but it declines also for wider cirques. Its strongest correlation is with Floor area. Floor area ratio declines as wall height increases, as headwalls become more extensive relative to floors: its increase with *Floor area* is another inbuilt ratio correlation. Floor closure correlates (increases) primarily with length.

Table 2.4.2. Correlations (x100) of eight size variables with five shape or gradient variables

	Max. gradient	Min. gradient	Axial gradient	Plan closure	Width/length	Floor ratio	Floor closure
log (Length)	23	−47	−50	48	−31	−05	37
log (Width)	22	−53	−44	52	43	01	10
log (Area)	25	−55	−50	56	09	−01	24
log (Floor area)	23	61	57	49	12	42	15
log (Size)	31	−44	−30	49	−05	−11	29
log (Amplitude)	38	−10	21	25	−31	−26	31
log (Height range)	43	−20	05	38	−11	−28	30
log (Wall height)	43	−23	09	34	01	−40	14

Again comparing with similar variables for Wales (Evans, 2006b), all the maximum gradient correlations are weaker: scatter of maximum gradient may be greater because of a somewhat poorer quality of contouring on the Romanian maps. *Axial gradient* and width/length correlate more weakly with vertical dimensions than in Wales, but correlations of plan closure and width/length ratio with width are stronger.

2.5 Cirques allometry

Many landforms develop allometrically, that is they change shape as size increases. In all but the most dynamic situations this can be tested only by considering variation with size at a given time, i.e. static allometry, as was proposed for cirques originally for a small population (15) in Colorado. It is now possible to test this for several cirque populations, each much bigger than in Olyphant's (1977) original study. Logarithmic plots of horizontal and vertical dimensions against overall size are presented. They show that, as size increases, cirque length increases faster than vertical dimensions. This is confirmed wherever the 95% confidence intervals on exponents do not overlap – which is consistent across regions.

It is useful to quantify the variation of cirque dimensions with overall size using the *concepts of allometry*, as applied by Olyphant (1981) and Evans (2006b). If each dimension changes with size at the same rate, the variation is said to be isometric: small cirques and large ones have the same shape. If one or more dimensions change at a significantly different rate, shape varies with size and the variation is allometric. Cirque headwalls retreat as they are eroded, and cirque floors are lowered, hence it is reasonable to regard larger (longer, wider and deeper) cirques as further along a developmental path.

As cirque development takes many thousands of years, and the form of these erosional features at earlier times is lost to us, we have no alternative to using size as a surrogate for relative age. This substitution of space for time is not without risks (Thornes and Brunsden, 1977); strictly speaking, we are analyzing static allometry, and inferring that this has relevance to development over time. Brook et al. (2006) analysed cirque development in an exceptional situation where, along an uplift gradient, it is reasonable to substitute space for time: cirques enlarged in all three dimensions (least in width) and became more concave in both profile and plan. The basic concepts of allometry have been developed in biology (biometrics) (Thompson, 1942). Comments pertinent to geomorphology may be found in Cox (1977) and Church and Mark (1980).

The size measure used is obtained by multiplying three orthogonal dimensions (length, width and vertical amplitude) together, and taking the cube root so that a number in metres is obtained. As all cirque dimensions have positively skewed frequency distributions, and range over about one decimal order of magnitude, a logarithmic transformation facilitates their statistical analysis; it tends to give more linear relationships with an even scatter of data points providing homoscedasticity.

More importantly, however, development is concerned with rates of change, and for this logarithmic scales are natural and necessary. In an isometric situation, the exponent relating the logarithm of each dimension to that of overall size should be 1.0. Note that when logarithmic (power) regressions are used, the exponents of length, width and amplitude sum exactly to 3; if one exponent exceeds 1, another must be smaller.

The large data set for Romanian cirques provides clear-cut results (Table 2.5.1; Fig. 2.5.1). Length has an exponent of 1.095 ± 0.032: the lower 95% confidence limit of 1.064 is well above 1.0, so length has a significantly greater-than-average rate of increase with size. The width exponent is 1.043 ± 0.051, just about consistent with isometric behaviour. However, amplitude has an exponent of 0.861 ± 0.046: amplitude increases with size, but significantly more slowly than length and width. Exponents for height range and wall height are very similar to those for amplitude, and well below 1.0. Fig. 2.5.1 shows that these differences are subtle, yet visible; with a set of 631 cirques, the difference between amplitude and length exponents is highly significant (the 95% confidence bands are a long way from overlapping).

Table 2.5.1. Confidence intervals on size exponents for logarithmic (power) regressions of size variables on overall cirque size. There are 293 cirques in Western, 206 in Făgăraş and 132 in East and Northern (including Ukrainian Maramureş). For height range and wall height, only the regression for all 631 is given

Exponents for-	Exponent	Confidence limits	r^2	RMA exponent
Length				
Western	1.130	1.085–1.176	0.893	
Făgăraş	1.062	1.001–1.124	0.850	
East & Northern	1.100	1.039–1.161	0.907	
Romania	1.095	1.064–1.127	0.881	1.167
Width				
Western	1.015	0.939–1.091	0.702	
Făgăraş	1.094	1.008–1.180	0.752	
East & Northern	1.061	0.947–1.174	0.722	
Romania	1.043	0.993–1.094	0.721	1.228
Amplitude				
Western	0.854	0.787–0.921	0.683	
Făgăraş	0.844	0.763–0.925	0.671	
East & Northern	0.839	0.741–0.938	0.684	
Romania	0.861	0.815–0.907	0.681	1.044
Other				
Height range	0.871	0.829–0.914	0.717	
Wall height	0.852	0.785–0.919	0.496	

As in previous work, e.g. Evans (2010), non-overlapping confidence intervals have been taken as a simple test confirming significant difference. This is correct and widely used, but the test is weak and quite conservative: for example if the standard errors differ by less than twofold, as here, an apparent 0.05 significance level is actually about 0.01 (Schenker and Gentleman, 2001). Thus where confidence intervals overlap, it is worth applying the standard test: but the difference between length and width exponents still fails to reach significance at the 0.05 level.

It is feasible to subdivide the data, so long as a reasonable number of cirques remain in each division. We might expect the results to be fairly consistent between different spatial divisions of Romania. With 206 cirques, the Făgăraş Mountains can be analysed on their own, leaving ranges to their east (Iezer, Bucegi and the Eastern Carpathians, north to the Ukrainian border) to be analysed together, likewise those to the west (Retezat, Ţarcu, Godeanu, Parâng, Lotru and Bihor). Table 2.5.1 and Fig. 2.5.1 show that in all three divisions the length exponent is the greatest and the amplitude exponent is the smallest. Moreover, although confidence intervals for length and width exponents overlap, the amplitude exponents are always significantly smaller than both; results are consistent between these three divisions. Confidence intervals are wider than for the whole data set, and in each of the three regional divisions the difference between length and width exponents again fails to reach significance by the standard test.

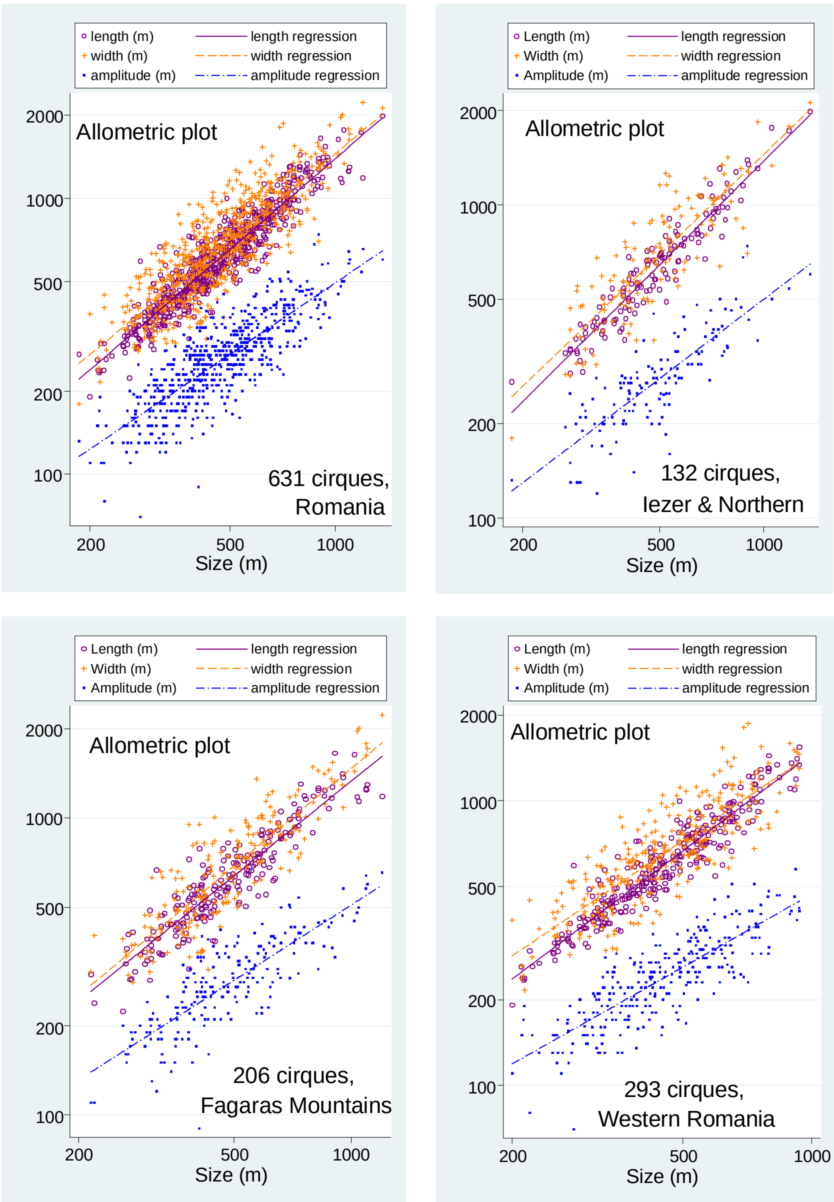

Fig. 2.5.1. Allometric plots; (upper left) Romania, (upper right) Northern and Eastern (Iezer, Bucegi), (bottom left) Făgăraş, (bottom right) Western

Although the length exponent is greater than the width exponent in two divisions and in the whole data set, the reverse is the case for the Făgăraş Mountains (Figs. 2.5.1 and 2.5.2). This may be because the width/length ratio for Făgăraş is positively skewed (1.35, more than for the other 11 regions) and although the mean is near average the median ratio of 1.03 is the smallest. Given the large overlaps between confidence intervals (Table 2.5.1), little reliance can be placed on this difference. The overall pattern shown in Fig. 2.5.2, however, is conclusive: length exponents significantly exceed 1.0 whereas amplitude and height range exponents are very significantly below 1.0. Width exponents are probably above 1.0. Thus allometry is strongly confirmed for Romania as a whole, and for these three divisions.

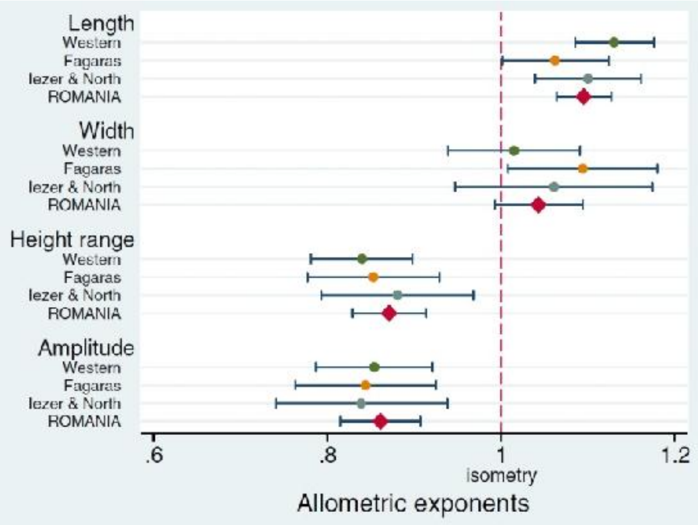

Fig. 2.5.2. Confidence limits (95%) on regression coefficients (allometric exponents) for Romania and three divisions. If 95% confidence limits do not overlap, coefficients are significantly different at approximately the 1% level. Note the contrast between length and width, and height range and amplitude.

A further general point is that the r^2 values, measuring goodness of fit of the regressions, are always smallest for amplitude and greatest for length, perhaps because amplitude has the lowest variance and thus less weight in the combined variable Size.

As in Wales (Evans, 2006b), exponents are similar for different types of cirque and for cirques on different rock types in Romania. Exclusion of 'outer' cirques or 'inner' cirques, to avoid 'double counting' of their shared areas slightly weakens the contrasts but length exponents (1.101 and 1.097) remain significantly above 1.0, and amplitude exponents (0.891 and 0.840) significantly below. Length exponents significantly exceed 1.0 for valley-side cirques and for valley-head cirques with and without thresholds (1.114, 1.111 and 1.134, respectively).

From exclusion of 'poor' and 'marginal' cirques likewise are weaker but consistent, with exponents of 1.079 for length and 0.899 for amplitude (n = 527 cirques). For the eight grouped geologies, we exclude andesite (n = 10) because of extremely wide confidence limits: exponents then range from 1.038 to 1.169 for length, 0.848 to 1.207 for width and 0.678 to 0.962 for amplitude. Results for different Grades and for major regions are generally consistent, but with wide confidence intervals and anomalous results only for 'poor' cirques and the Pârang–Lotru–Cindrel combined region.

Following the suggestion by Cox (1977) that functional forms other than power functions might be useful in allometric analyses, further tests using geometric mean regression were applied (Warton et al., 2006). Clearly there is measurement error in x as well as in y: if we give y and x equal status, calculation of the geometric mean regression (the 'standard deviation line' or 'reduced major axis') is appropriate. This will always be steeper (Δy/Δx) than the regression of y on x, which minimises the error variance in y, without allowing for any error in x, and gentler than the regression of x on y, which minimizes the error variance in x, without allowing for any error in y. All three relationships, calculated by least squares, pass through the logarithmic mean in both x and y. With geometric mean regression there is no constraint on the exponent sum, which will be greater where scatter is greater (where r^2 is lower) (Evans, 2010).

This alternative approach is applied to test the robustness of conclusions on the relative size of coefficients. The confidence limits are provided by a bootstrap command. The geometric line is steeper than the normal regression, but the difference is not great so long as r^2 is high, as in Romania. Thus there is little effect on the comparisons between length, width and amplitude exponents. It can be stated conclusively that, in Romania, the increase with overall cirque size of length is significantly and very generally greater than that of vertical amplitude, consistently confirming cirque allometry. Width exponents are intermediate, but significantly greater than amplitude exponents in all three divisions of Romania (Table 2.5.1; Fig. 2.5.2). Evans (2010) found similar relations between exponents in Britain, British Columbia, northern Scandinavia, the Maritime Alps and the Pyrenees. Gordon (1977) found similar variations in cirque shape with size in northwest Scotland, as did Richter (2006) in New Zealand; in northwest Spain also, Ruiz-Fernández et al. (2009) found that headwall recession was faster than cirque deepening.

2.6 Cirques grade

The subjective attribute *Grade* takes whole-number values from 1 (classic, best-developed) to 5 (poorest), so the numbers provide a negative measure of development. Fig. 2.6.1 illustrates an example for each of these classes**.** Câlcescu, with a major lake and a floor embraced by a clear headwall is 'classic'. Bila has an excellent, steep headwall and a good but outsloping floor, so it is 'well-defined'. Jupania Superior has a simple form with a sloping floor and a moderately steep headwall, so it is a 'definite' cirque. Leaota is graded as 'poor' because of its shallow incision and Ţibleș no. 30 is 'marginal' because with a gentle headwall and rounded crest, its glacial origin is debatable. The final photo illustrates the Bila 'cirque within a cirque', with clearly separate floors.

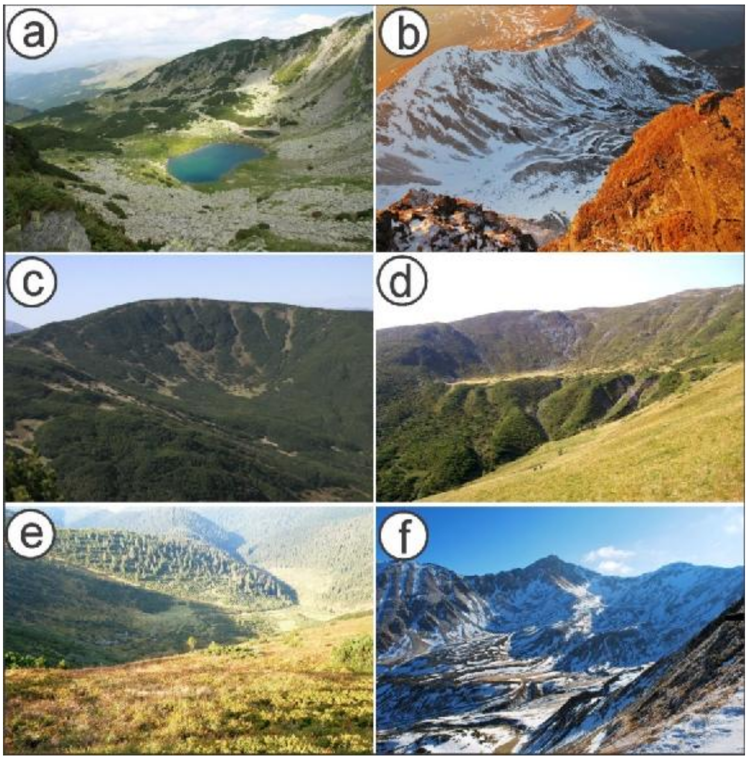

Fig. 2.6.1. Examples illustrating each cirque grade. (a) Grade 1: Câlcescu, no. 401, Parâng Mountains. (b) Grade 2: Bila, no. 74, Rodna Mountains. (c) Grade 3: Jupania Superior, no. 26, Maramureş. (d) Grade 4: Leaota, no. 100, on Leaota Mountain (Photo: George Muratoreanu). (e) Grade 5: cirque no. 30, in Ţibleş Mountains. (f) Nested cirques: Bila inner and outer, nos. 70 and 74, Rodna Mountains.

In the different environment of the Swedish mountains, Vilborg (1984) used a five-fold grading, but his N:4 and N:5 types are probably not cirques in our terms. His description of N:1 matches our 'classic', and his N:2 and N:3 forms correspond to our remaining five grades. Note, however, that we consider even grade 4 and grade 5 cirques to involve the action of glaciers (near their sources): they are not 'nivation cirques'.

Although Grade is on an ordinal measurement scale, some useful results are nevertheless obtained by treating it, liberally, as on an interval scale (i.e. assuming equal separation of adjacent points along the scale). Grade then averages 2.67 (SD 0.96). It correlates quite strongly with minimum gradient (r = + 0.76), moderately with plan closure (– 0.51) and somewhat with maximum gradient (– 0.38). Allowing this liberal treatment, Grade can be predicted from these three as:

$$\text{Grade} = 2.77 + 0.1183\ (\text{max gradient}) - 0.0147\ (\text{min gradient}) - 0.11763\ (\text{plan closure})$$
$$R^2 = 62\%$$

Together with *Grade*, these three variables define the overall quality (degree of development) of a cirque. Other shape and size variables add less than 1% to the prediction of Grade, although width on its own can account for 26%. Width, length and area (cirque or floor) have moderate correlations with Grade, but vertical dimensions have very weak correlations. This contrast arises from correlations of -0.47 to -0.61 between minimum gradient and horizontal size variables, and correlations of 0.48 to 0.56 between plan closure and horizontal size variables, compared with only -0.10 to -0.23 and 0.25 to 0.38 respectively with vertical dimensions (Table 2.4.2). Maximum gradient correlates more with vertical dimensions than with horizontal. Lake, Type and Floor area ratio have significant but weak correlations with Grade. Inclusion of Lake with the three quantitative variables increase R^2 to 64%, beyond which neither Type nor Geology nor Floor area ratio nor Cols improves R^2 significantly. Thus there is a good agreement between subjective and objective measures of cirque development.

Returning to profile closure, this correlates –0.64 with Grade and 0.49 with plan closure, so these three are the core measures of cirque development. Number of cols (after square root transformation) correlates weakly, around |0.26|, with these three and with minimum gradient: better-developed cirques are more likely to have cols.

Fig. 2.6.2 shows the greater variation of mean length and width with Grade, than of the three vertical dimensions. The differences between grade 4 and grade 5, however, are negligible except for width. Fig. 2.6.2 shows the rise in minimum gradient, and the decline in maximum and in profile closure, toward poorer grades. The smoothest variation is the rise in axial gradient. Again the differences between grades 4 and 5 are small, the greatest being the smaller proportion of cirque area covered by floor. This proportion is unusual in varying little from grade 1 to grade 4.

Median values for different grades confirm the above relationships. Maximum gradient varies from 58.7° for classic to 44.2° for marginal; minimum gradient, from 0° to 16°; and plan closure, from 173° to 94°. The trends are monotone over the five grades, and in the expected directions.

In relation to altitude, all grades cover a wide range, but the average altitudes increase consistently for higher-grade cirques. Maximum crest altitude for classic cirques averages 2346 m, 268 m higher than for marginal cirques. Floor altitude, at 2015 m, averages 158 m higher than for marginal. The correlations are respectively -0.34 and -0.18. As higher-grade cirques are larger in all dimensions (Fig. 2.6.2a), this increase probably reflects the increase in size with crest altitude (r = +0.35).

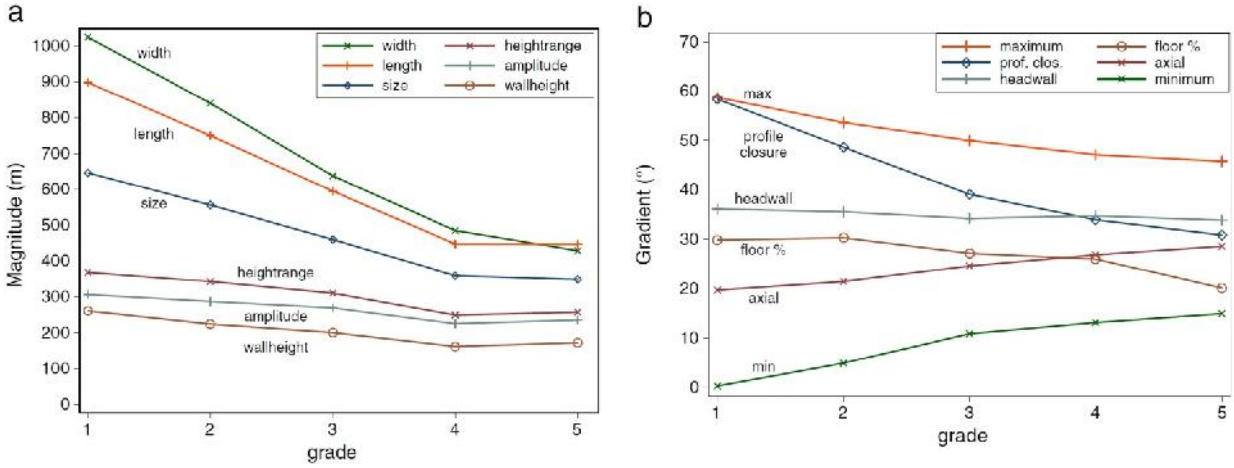

Fig. 2.6.2. Mean values for each grade, of (a) size variables and (b) gradients, profile closure (°) and Floor area ratio (%). Grade 1 is 'classic', whereas grade 5 is 'marginal', i.e. doubtful.

Most of the high-grade cirques are in the Transylvanian Alps, especially the Retezat and Parâng ranges with respectively 17 and 12 classic cirques (Fig. 2.6.3). Although the Lotru-Cindrel are lower, they have mainly well-defined cirques (Fig. 2.6.3b) because they have extensive surfaces above cirque crests, providing drifting snow to increase mass turnover in their cirques.

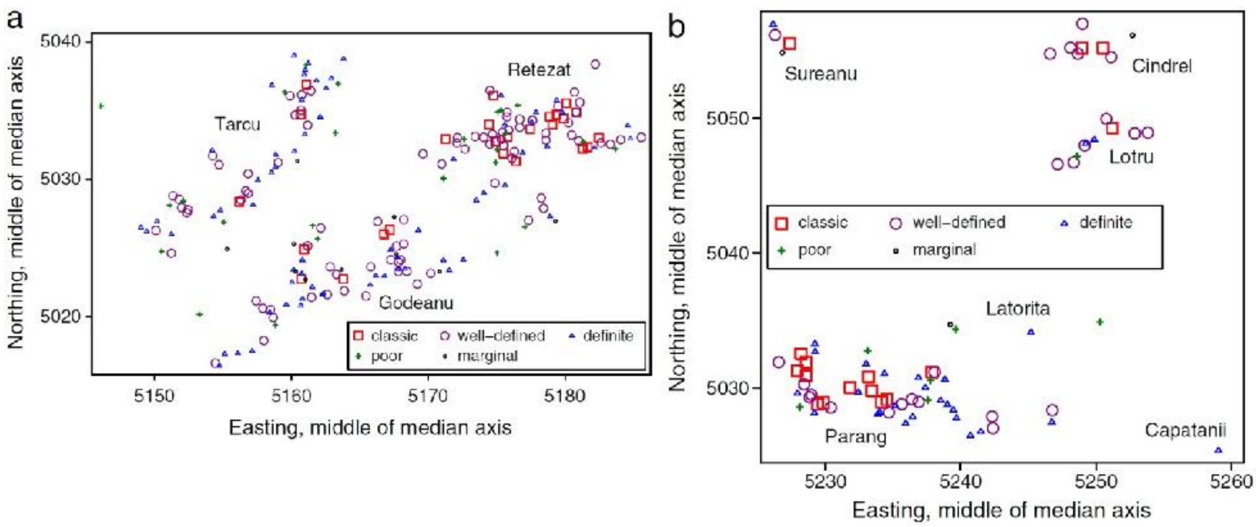

Fig. 2.6.3. Maps of cirques classified by Grade, in (a) Retezat,Ţarcu and Godeanu, and (b) Paring–Latoriţei–Căpăţânii and Lotru–Cindrel–Şureanu. The scale (same for eastings and northings) is given by axes labelled at 10 km intervals.

With only 27 in the lowest grade ('marginal'), the distribution of cirques between grades is less even than in Wales and the English Lake District. This may reflect small differences between the subjective thresholds. There are 62 classic, 216well-defined, 249 definite and 76 poor cirques.

2.7 Glaciation level during the Late Pleistocene

Cirque altitudes

Cirques are found in 19 mountain ranges (Table 2.7.1), but for statistical analyses those with few cirques are grouped with neighbours in the 12 range groups shown in Figs 2.7.1&2.2.3 and Table 2.7.2 (Bihor is too far from other ranges with cirques to be grouped with any.) Further analyses were performed on six major regions. For the whole cirque dataset, average modal floor altitude is 1938m and average maximum crest altitude is 2217 m. Most cirques (82%) have thresholds between 1650 and 2110m altitude and 83% are on mountains 2000–2470m high. 86% of lakes in cirques are between 1800 and 2200m altitude.

Table 2.7.1. Altitudes (m) of mountains with and without glacial cirques, and the inferred palaeoglaciation level (PGL). Mountain ranges are ordered from north, south to Ciucaş, and then to the west, ending with Bihor/Vlădeasa

Range	Lowest with	Highest without	Interpolated PGL
Maramureş	1713, 1775	1763, 1811	1765
Tibleş	1839	1829	1830
Rodna W	1787, 1792	1931, 2034	1900?
Rodna E	1930, 1945	1856, 2002	1900
Călimani	1897, 1958	2031, 2050	2000
Bistriţei	—	1758, 1859	>1850
Ceahlau	—	1907, 1900	>1900
Buzău–Vrancei	—	1785, 1777	>1780
Ciucaş–Siriu	1662	1883, 1954	1800?
Baiu	—	1900, 1923	>1920
Bucegi	2404, 2421	2401, 2481	2410
Iezer	2170, 2163	2093, 2142	2150
Făgăraş E	2130, 2132	2044, 2084	2100
Făgăraş C	2157, 2170	2172, 2258	2170
Făgăraş W	1750, 2193	2129, 2162	2170?
Cindrel	2047, 2129	2007, 2035	2040
Lotru	1992, 2070	2080, 2171	2070
Latoriţei	2049, 2053	1978, 2038	2040
Căpăţânii	2125	1954, 2108	2120
Parâng	2061, 2084	2074, 2184	2080
Şureanu	2000, 2056	2009, 2130	2050
Vâlcan	—	1946, 1868	>1940
Retezat	1943, 1977	1852, 2180	1940
Godeanu	1872, 1891	2000, 2030	1950
Ţarcu	1860, 1910	1924, 1995	1930
Muntele Mic	1801	1675	1800
Vladeasa	—	1826, 1836	>1830
Bihor	1530, 1658	1597, 1774	1710

For the whole of Romania, cirque floor modal altitudes rise to the east and south:

floor altitude = 4494 + 0.931 *east* – 1.471 *north* R^2=42%

where east = grid easting in km and north = grid northing in km (Romanian UTM grid)

In the *Northern major region*, with 81 cirques,

floor altitude = 5946 + 1.313 *east* – 2.129 *north* R^2=34%

Recalculating without the term for easting (which is insignificant, at P = 0.05), cirque floors rise southward at 2.87 m km^{-1}, over a north-south distance of 99 km within the area with cirques. Floor altitudes average 1591 m in Maramureş, 1749 m in the Rodna Mountains, and 1804 m in the Călimani.

In the *Transylvanian Alps*, with 547 cirques,

floor altitude = –4076 + 0.650 *east* + 0.523 *north* R^2=14%

Recalculating without the term for northing (which is insignificant), cirque floors rise eastward at 0.714 m km^{-1}, over a 286 km distance. Cirque floors in the Făgăraş average 2034 m altitude; those farther west average 1925 m.

Table 2.7.2. Vector statistics and significance tests for wall and axis aspect, by range group

Group	Obs	Wall aspect (highest part)				Rayleigh	Kuiper	**Median axis aspect**			
		Mean	Strength	95%	Limits			**Mean**	**Strength**	**95%**	**Limits**
		°	%	°	°	probabilities		°	%	°	°
Maramureş	27	44.3	62.7	21.5	67.1	0.000	0.000	**50.7**	**76.6**	**36.1**	**65.3**
Rodna	47	34.5	44.2	8.7	60.2	0.000	0.000	**41.1**	**54.7**	**21.0**	**61.3**
Călimani	7	15.5	73.7	334.8	56.1	0.016	0.014	**8.7**	**69.1**	**320.8**	**56.6**
Bucegi	13	4.2	9.8	—	—	0.887	0.844	**36.3**	**24.3**	**—**	**—**
Iezer	38	26.7	39.9	355.2	58.1	0.002	0.007	**26.7**	**38.3**	**348.4**	**65.0**
Făgăraş	206	59.4	18.6	28.7	90.1	0.001	0.005	**70.3**	**21.5**	**43.8**	**96.9**
Lotru–Cindrel	22	67.8	42.5	19.4	116.2	0.017	0.016	**82.3**	**37.0**	**21.6**	**143.0**
Parâng	56	72.1	43.8	47.4	96.7	0.000	0.000	**68.2**	**45.3**	**45.4**	**90.9**
Retezat	84	60.1	20.8	15.2	105.1	0.026	0.063	**46.4**	**22.9**	**359.6**	**93.1**
Godeanu	69	105.8	33.1	76.1	135.5	0.000	0.003	**114.1**	**30.5**	**81.0**	**147.2**
Ţarcu	59	69.7	42.4	44.8	94.6	0.000	0.000	**76.5**	**45.9**	**53.9**	**99.2**
Bihor	3	77.8	72.4	—	—	0.223	0.253	**66.8**	**71.4**	**—**	**—**
Total	*631*	*60.2*	*29.1*	*49.5*	*70.9*	*0.000*	*0.000*	***63.0***	***31.4***	***52.7***	***73.3***

95% confidence limits on the vector mean are given as northwest-most followed by southeast-most. The Rayleigh significance test gives the probability of results at least as extreme as those obtained, if the population is azimuthally uniform, tested against the alternative of one favoured mode. The Kuiper test is against any deviation from uniformity. Note that results for axis aspect (right, bold) are close to those for wall aspect, falling into two clear sets: more northward (the first five) and more eastward (the last seven).

To form 'range groups', Rodna includes Ţibles¸ (2 cirques) and Suhard; Bucegi includes Siriu (1) and Leaota (1); Lotru–Cindrel includes Şureanu (4) as well as Lotru (10) and Cindrel (8); Parâng includes Latoriței (4) and Căpățânii (1); Ţarcu includes Muntele Mic (1).

Trends were calculated also for different cirque aspects in the Transylvanian Alps. These were consistent, but the eastward rise of cirque floors was less (0.365 m km^{-1}) for the north-facing quadrant than for others. Trends for smaller divisions, i.e. within ranges, tend to be statistically insignificant. Thus it is best to regard the overall south-eastward rise of cirque floors in Romania as the resultant of two components: an eastward rise of 204 m along the Transylvanian Alps, related to diminishing precipitation; and a southward rise of 283 m in Northern Romania, due partly to rising temperatures but also to diminishing precipitation.

Cirques are thus lowest in the north and west of Romania. Maramureş has floor altitudes more than 200 m lower than the western ranges of the Transylvanian Alps, and the three cirques in the Bihor Mountains are lower still, due to their position on the west side of northern Romania. Considering means for 12 range groups, Fig. 2.7.1 shows floor altitudes rising southward from Maramureş to Bucegi, and rising westward through the Transylvanian Alps from Bucegi to Ţarcu. There are also contrasts between ranges on the north side of the Transylvanian Alps and those on the south side: cirques in Lotru and Cindrel (including Şureanu) are over 100 m lower than those further south, in Parâng. Floors in Retezat are higher than in neighbouring ranges, but here we should note the correlation between floor altitudes and crest and mountain altitudes. The large numbers of high summits in Retezat and Făgăraş produce more high floors, giving higher standard deviations of modal floor altitude. If instead we take the 5 percentile (from lowest) of floor altitude, Retezat has a value of 1760 m, transitional between 1640 for Godeanu (to the west) and 1820 for Parâng (to the east). Moreover, Făgăraş at 1830 m is lower than Iezer at 1870 m. This is suggestive of a moisture source from north of west.

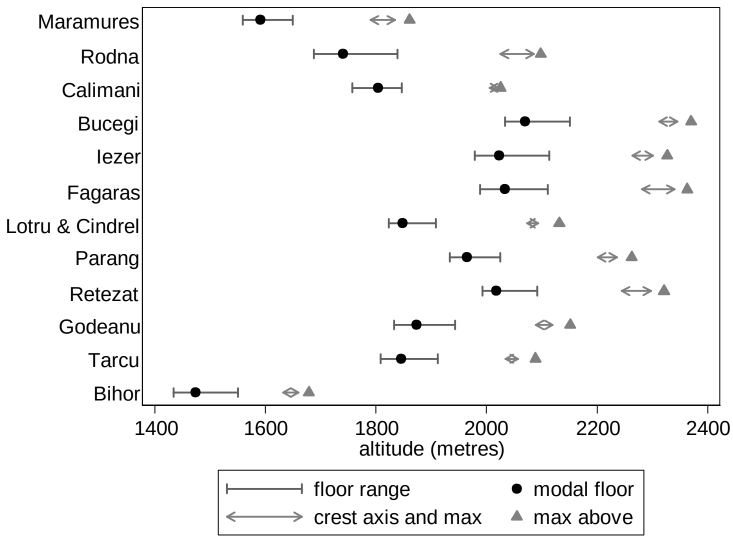

Fig. 2.7.1. Mean values of floor and crest altitudes, and maximum altitude above, for cirques in the 12 mountain range groups in Romania. Floor altitudes are lowest (per cirque), highest and modal (most representative); crest altitudes are maximum, and at the median axis. Range groups are ordered from north, to southeast (Bucegi), to west.

In more detail, Fig. 2.7.2 shows the statistical distribution of individual values of floor and maximum crest altitudes, for major regions. These are intermediate between Gaussian (giving a transposed sigmoidal plot) and rectangular (giving a linear plot as in 'Northern').

There are two low outliers, which are discussed below. Iezer-Bucegi and Făgăraş are similar, Parâng-Lotru-Cindrel cirques are considerably lower, Retezat-Godeanu has lower cirques at the low end, and Northern region cirques are considerably lower. The difference between floor and crest altitudes is a measure of vertical cirque dimension, greatest for Făgăraş. For comparison, Urdea (2004) gives the lowest Pleistocene snowlines as around 1550 m in the Rodna Mountains and 1670 m in the Transylvanian Alps. These are rather low, at the 10 and 3 percentiles of cirque floor altitudes respectively.

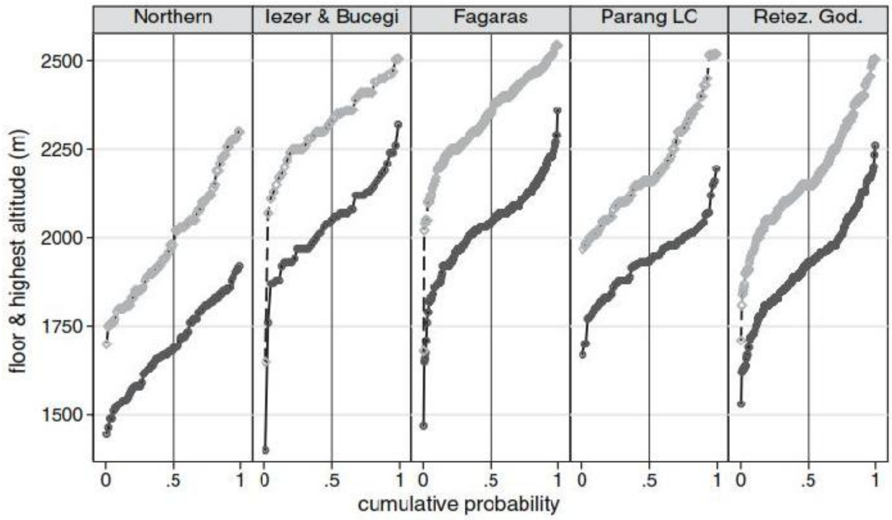

Fig. 2.7.2. Quantile plots (Cox 2005) showing the cumulative distributions of modal floor altitude and maximum crest altitude for five major regions (not Bihor, as it has only 3 cirques). Medians can be read off from intersections with the .5 line.

The elevation of glacial cirques allows for the approximate delineation of the snowline, for which we used the averaged minimum elevation of cirques. The cirque floor line is positioned rather close to the snowline during glaciation, usually no more than 100 below.

In the Eastern Carpathians (Fig. 2.7.3) this line (blue) starts at 1600m in Cernahora Mts and reaches 1850m in Leaota Mts. All glaciated mountain ranges peak at least 200 m above the cirque floor line, whereas non-glaciated areas peak either below the cirque floor line (e.g. Lăcăuți, Penteleu), near (e.g. Saca in Gurghiu Mts, Mădăraș in Harghita Mts) or 100 m above it, at most (e.g. Ciucaș, Baiu Mts); the sole exception is Bistrița Mts (nearly 200 m above the cirque floor line) which is rain shadowed by Călimani and Ceahlău Mts. Most likely, the latter mountain range hosted plateau glaciers which leave little trace compared to cirque glaciers.

In fact, the cirque floor line follows a less than linear trajectory (red dash) in terms of elevation: Cernahora (1600m) - Maramureș (1490m) - Rodna (1580m) - Călimani (1770m) - Leaota (1850m) - Iezer Păpușa (1880m).

However, if only alpine cirques and inner cirques from Rodna and Călimani Mts are considered (which point towards the existence of a subsequent generation of glaciers), the resulting cirque floor line (blue dash) starts at 1800m in Cernahora Mts and reaches 2050m in Leaota Mts, which leaves just Rodna, Călimani, northern Maramureş (Pop Ivan and Farcău) and Cernahora Mts above it.

Furthermore, the line joining the elevations at which Younger Dryas glacial deposits are found (green) rises markedly between Cernahora (1400m - Breskul area) and Rodna Mts (1800m - Pietrosu peak), after which point if follows rather closely the gradients of the cirque floor lines from both phases up to Făgăraș Mts (2064m, at Capra - V. Doamnei). The average gradient of the cirque floor lines is 78m/100m, whereas the mean gradient of the dated glacial deposits line (south of Rodna Mts) is ca. 85m/100m. The two values are rather close, therefore the elevation of cirques and the ages of glacial deposits are arguably in agreement.

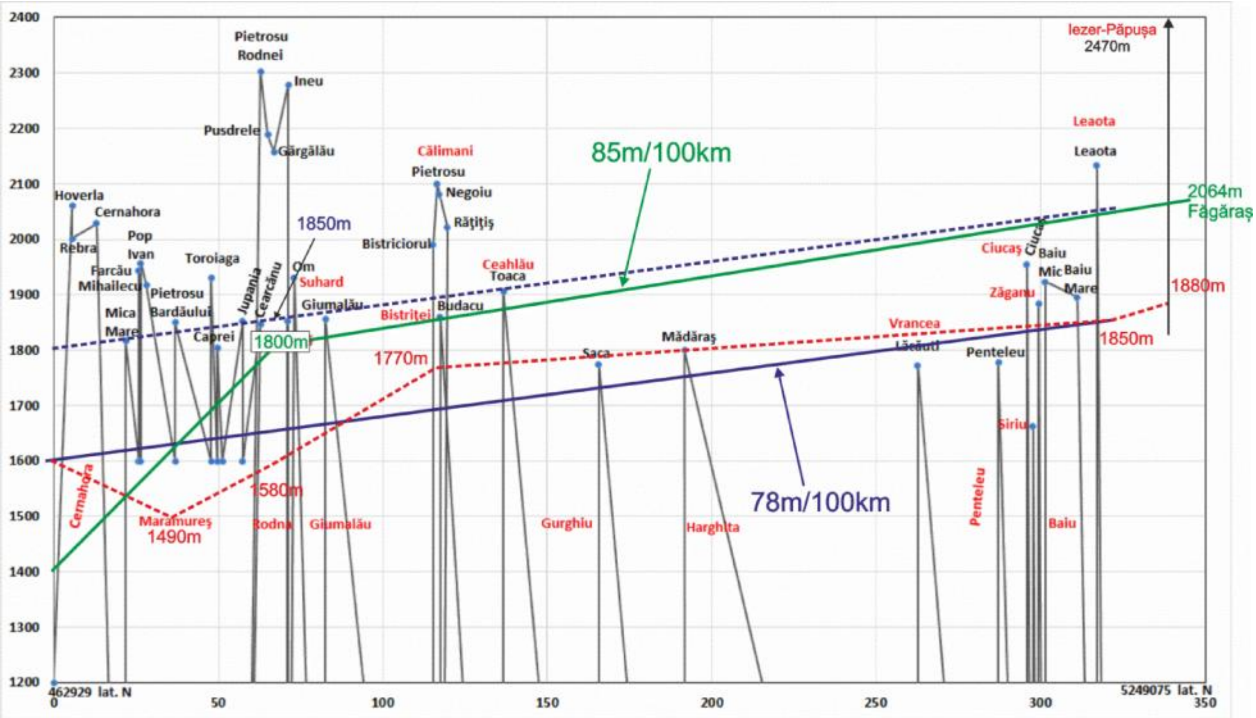

Fig. 2.7.3. Cirque floor lines in the Eastern Carpathians.

Pișota (1971) provided an inventory of 'glacial lakes' in the Southern Carpathians; essentially these are cirque lakes. Lake median altitudes rise from 1860m in the west (Țarcu and Godeanu, with 32 lakes), through 2090m in Retezat (56 lakes) and 1979m in Parâng (28), to 2170m in Făgăraș (29 lakes). This eastward rise of 310m is rather greater than the rise in cirque floors. Also the three lakes in Șureanu have a median attitude of 1780 m, which is considerably lower than 1975m for the four farther east in Cindrel as well as the 28 farther south in Parâng: *this suggests a moisture source from northwest*.

Palaeodeglaciation level

Thus far the vast majority of studies on glaciation and glacial morphology are concerned with the presence of cirques. The absence of cirques, however, provides further useful information, often neglected in studies of cirque floor altitude trends. The presence of cirques implies geomorphologically effective glaciers lasting for some time. Their absence does not exclude the possibility of glaciers, but it is found that in high relief areas only a few glaciers have sources outside cirques.

The concept of *glaciation level* (Østrem et al., 1981) or *glaciation threshold* (Porter, 1977) relates to the altitude required for a mountain or ridge crest to support a glacier, which is some 250m above the equilibrium line altitude (ELA) in southern British Columbia. Evans (1990) applied this concept to glacial cirques and thus former glaciation, establishing a palaeoglaciation level (**PGL**) which is based on the negative as well as the positive evidence. Table 2.7.1 applies this to the mountain ranges of Romania. It gives only the two highest crests (usually summits) without cirques, and the two lowest with. The PGL is not an average of these but is interpolated on the basis of these and further crests, and the surrounding topography.

This procedure requires judgement, and it is difficult to evaluate error margins, but results are expected to be within 100m of true values. By averaging out topographic variations, PGL gives a better representation of former regional climatic conditions than do ELAs based on reconstructions of individual glaciers. The former plateau glaciers tabulated by Urdea (2004) are mainly on surfaces above PGL and their inclusion would not modify the values given here.

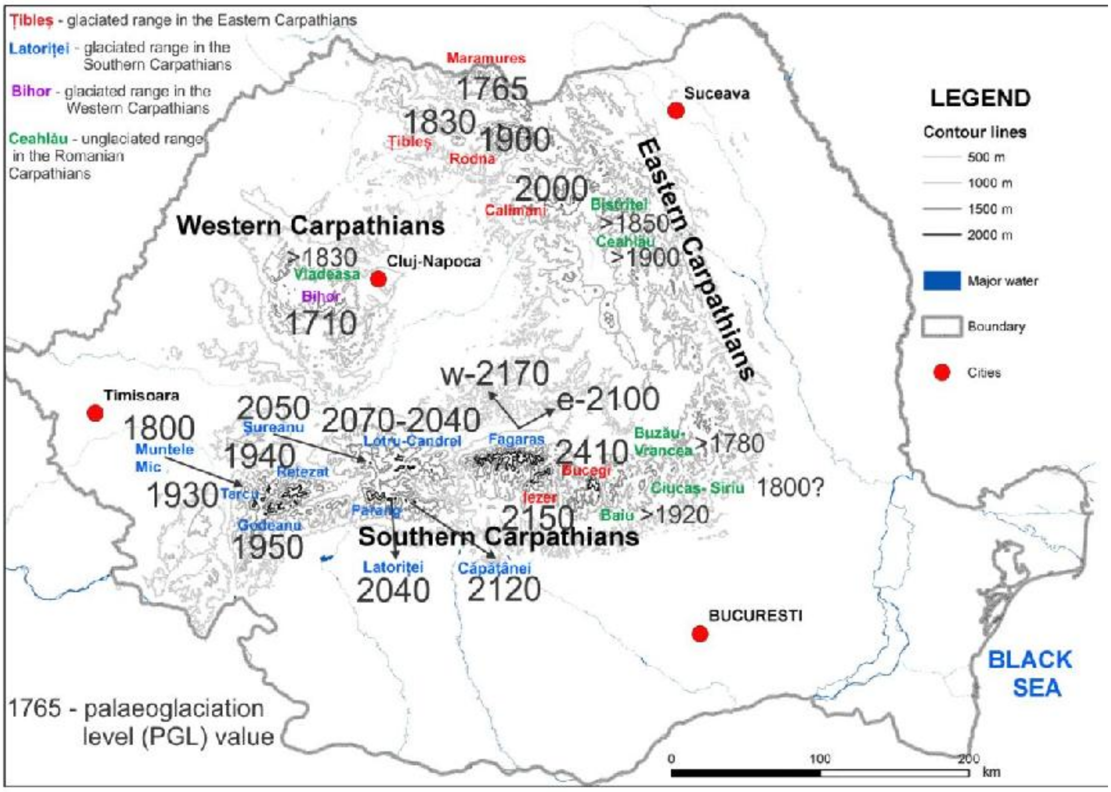

Fig. 2.7.4. Palaeodeglaciation level in the Romanian Carpathians.

The results essentially support the spatial patterns shown by cirque floors. *The lowest levels, below 1800 m, are in the north and west:* Maramureș and Bihor. Immediately northeast of Bihor, there are no cirques on the Vlădeasa Mountains (1836 m). In northern Romania, the PGL rises southward from Maramureș through Rodna to Călimani. It rises eastward from 1830m in the small Tibleș range to 1900m in the Rodna. In the Eastern Carpathians south of Călimani a series of summits between 1750 and 1907m failed to support glaciers generating cirques (Fig. 2.7.4).

In the *Transylvanian Alps*, PGL rises eastward along with cirque floor altitudes (Table 2.7.1). This clearly contradicts Pawlowski's (1936) denial of an E–W trend in former snowline. As latitude varies little, this rise is due mainly to declining precipitation at times of cirque formation. In the far west, 1801m (Muntele Mic) is just sufficient to support a poor cirque. The next three ranges – Țarcu, Godeanu and Retezat, each with many cirques – have very similar levels of 1930–1950 m. But there are no cirques in the Vâlcan Mountains, despite summits of 1946 and 1868 m: they are sheltered from the west and, especially, the northwest, by the three previous ranges.

Between the Jiu and Olt Rivers (between Petroșani and Sibiu), PGL is between 2040 and 2080m except in the southeast, where it is 2120m in the Căpățânii Mountains (east of Parâng). On the north side, PGL is 2050m in Șureanu and 2040m in Cindrel. East of the Olt, the level is around 2170m in most of the Făgăraș, except for Mezuna de Nord (national cirque no. 325), a poor valley-side cirque on a 1750m northern ridge. (Its floor gives the low outlier in Figs 2.7.2 and 2.7.5).

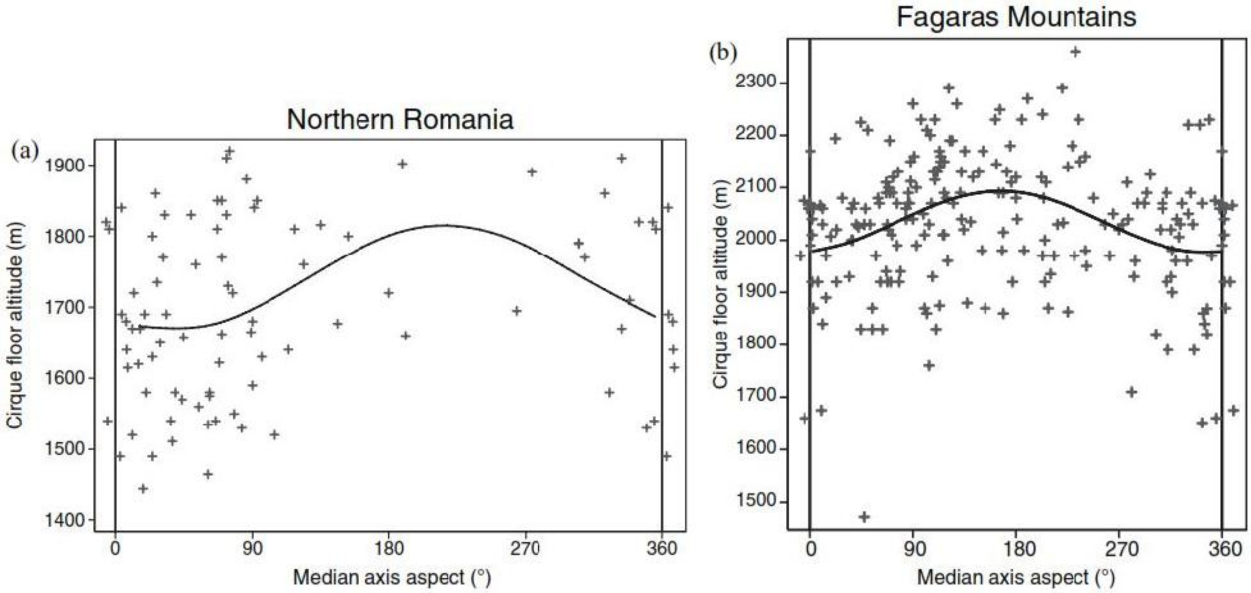

Fig. 2.7.5. Plots of cirque floor altitude against median axis aspect. The fitted lines are regressions of altitude on sine and cosine of aspect. In northern Romania, cirques facing 037^0 are lowest, 117 m lower than those facing 217^0. Fagaras, cirques facing 346^0 are lowest: 113 m lower than those facing 166^0. Because the plots are unfolded cylinders, a small overlap is given at each 'end' of the x-axis, beyond the vertical lines.

The Iezer Mountains have a more precisely defined PGL of 2150 m. East of the Dâmbovița River, there is a sudden rise to over 2400m in Bucegi, where the massive conglomerates give strong structural effects (and it is believed there was a plateau glacier: Velcea, 1973). The next range, east of Sinaia, is Baiu (1923 m), with no cirques. Immediately to the east an anomaly is encountered in the Siriu Mountains, where Muntele Mălaia (1662 m) has a well-defined valley-head cirque with a good floor (this gives the low outlier for 'Iezer-Bucegi' in Fig. 2.7.2): cirques are lacking not only on its 1657m neighbour but also on nearby Mount Ciucaș (1954 m). This area is exposed to the southeast, and is also the most tectonically active part of Romania.

Overall, however, the PGL results support the hypothesis of winds from north of west bringing precipitation: paired comparisons between Muntele Mic and Vâlcan, Șureanu and Căpățânii, and Făgăraș and Bucegi can be regarded as NW windward–SE leeward couplings. Ranges with many summits rising hundreds of metres above PGL, such as the Făgăraș and Retezat, were able to support more varied cirques, including south-facing cirques and multilevel, cirque-within-cirque features. Higher mountains are more likely to have complexes of inner cirques, tributary to outer cirques with lower floors. While 'maximum altitude above' averages 2242m for all 631 cirques, it is 2192m for valley-side cirques, 2226mfor valley-head cirques and 2326m for outer cirques. This explains the concentration of the 73 outer cirques in Făgăraă (25), Retezat (15), Godeanu (10), Parâng (7), Rodna (6) and Țarcu (5).

2.8 Cirques and palaeowind directions

Five stations on ridges above 1700 m, and two sheltered high stations, give indications of the present-day mountain climates, which are wetter and colder than temperate climates and fall into subnival, alpine and subalpine geoecological zones (Urdea and Sarbovan, 1995). The Atlas of Romania (Academia RSR, 1979) provides a series of useful maps, using altitude for interpolation.

The wettest areas in Romania, with a mean annual precipitation of over 1400 mm in the mid-twentieth century, provide a good approximation of the ranges affected by glaciation. They have more than 600 mm in both the warm and the cold halves of the year. The easterly ranges of the Eastern Carpathians are relatively dry in the cold season, whereas in the warm season precipitation is more evenly spread across Romania's mountains. In glaciated areas, precipitation now occurs on more than 170 days a year, and snow lies on the ground for more than 150 days (200 days in the core areas of ranges in the Transylvanian Alps). Even in the shadiest locations, snow patches do not now survive the heat of August.

A further characteristic of the glaciated areas is less than 1800 hours of sunshine a year, with less than 1250 in the warm season and less than 700 in the cold. Cloud cover averages over 65% (over 70% in core areas). Over 135 days are completely overcast and less than 35 days have clear sky. Global radiation is less than 146 W m^{-2}, with <106 in the warm season and <43 in the cold. There are less than 90 frost-free days. The annual temperature range is less than 19ºC, from below –8ºC in January to below 10ºC in July. Mean annual temperature (1979-99) was +0.1°C at Bâlea Lac (2038 m altitude) in the Făgăraş Mountains (Voiculescu, 2002): for 1896-1975 it was 0.0°C at Ţarcu (2180 m) further west in the Transylvanian Alps, –2.5°C at Vârful Omu (2504 m) in the Bucegi Mountains, and 1.4°C at Vlădeasa (1836 m) in the Apuseni Mountains, Western Romania. Mean annual precipitation was around 1200 mm for all four stations.

Winds at high stations come dominantly from the west (Fig. 2.8.1). This effect is strongest at Ceahlău (46.6° N in the Eastern Carpathians), where winds blow from the west 55% of the time (1971-95: calms are 17%) and at Lăcăuţi (45.8° N: from west and WNW 50%). At Vârful Omu (45.3° N: 2001-7) west winds blew 18% of the time, with a further 20% from WNW and WSW, and 21% from NW and SW, giving 59% balanced around west. These three exposed stations show the dominance of west winds, with the spread around west increasing southward.

Ţarcu in the Parâng range shows a different pattern, with 26% from north and 13% from south. Bâlea Lac shows winds from north (14%) and southeast (13%), while Iezer Pietrosu (1785 m in the Rodna Mountains, northern Romania) shows winds from east-northeast and southwest: these bimodal distributions arise because these two stations are sheltered in cirques and thus less exposed to regional winds.

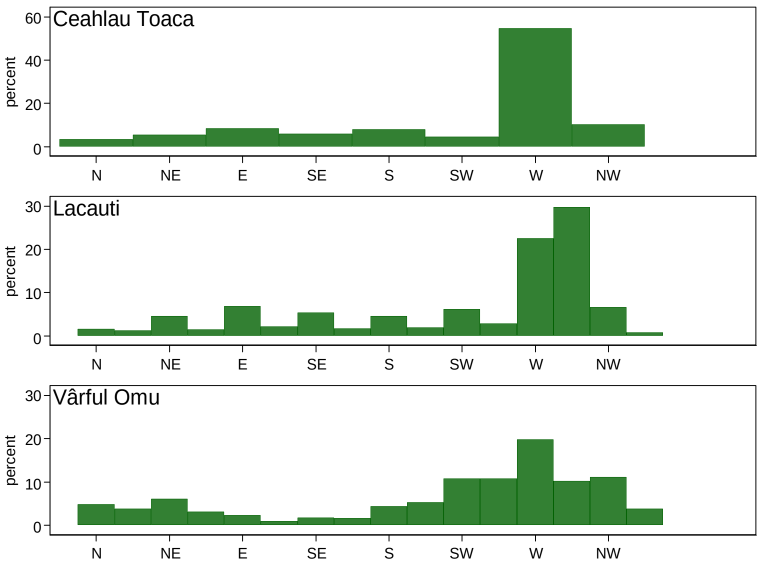

Fig. 2.8.1. Modern wind directions at Ceahlău (1971-95: 1890 m, Eastern Carpathians), Lăcăuţi (2001-7: 1776 m, Carpathian Bend) and Vârful Omu (2001-7: 2504 m, Bucegi). Frequencies are weighted by mean monthly speeds, where available (i.e. for Lăcăuţi and Vârful Omu).

Cirque aspects

Vector statistics (Fisher, 1993) are widely used for directional data (e.g. Evans, 1969, 1977); Curray (1956) gave a readable summary with geological applications. Where directions are plotted as unit vectors end-to-end, or the sine and cosine components are summed and used to define a net direction, the direction of the resultant vector is termed the vector mean. It is the best measure of central tendency on the circle, i.e. of directional data such as *wind or cirque* aspect. The degree of concentration of directions around this mean is measured by the vector strength or 'mean resultant length', the length of the resultant vector divided by the total length of vectors: here this ratio is expressed as a percentage. 100% means all directions are identical; 0% means opposing directions cancel out and there is no resultant, no net directional tendency.

Cirque aspects reflect the aspects of former glacier sources, which relate to *topographic context, solar radiation and shade, wind* (drifting snow, but also causing more melt on more exposed slopes), and morning–afternoon differences (the diurnal march of temperature and cloudiness) (Evans, 1977).

For a large dataset from a range with ridges at various orientations, the climatic controls are considered dominant over topographic ones. Range-by-range analysis of both (head)wall and (median) axis aspect distributions (Table 2.8.1) showed a contrast between the Eastern Carpathians (together with Iezer-Bucegi), and the rest of the Transylvanian Alps from the Făgăraş to Ţarcu. The 81 cirques in northern Romania have vector mean directions of $036^0 \pm 16^0$ (wall aspect) and $042^0 \pm 13^0$ (axis aspect) (Fig. 2.8.2), with vector strengths of 52% and 62% respectively.

Table 2.8.1. Vector statistics and significance tests for wall and axis aspect, by range group

Group	Obs	Wall aspect (highest part)				Rayleigh	Kuiper	**Median axis aspect**			
		Mean	Strength	95%	Limits			**Mean**	**Strength**	**95%**	**Limits**
		°	%	°	°	probabilities		°	%	°	°
Maramureş	27	44.3	62.7	21.5	67.1	0.000	0.000	**50.7**	**76.6**	**36.1**	**65.3**
Rodna	47	34.5	44.2	8.7	60.2	0.000	0.000	**41.1**	**54.7**	**21.0**	**61.3**
Călimani	7	15.5	73.7	334.8	56.1	0.016	0.014	**8.7**	**69.1**	**320.8**	**56.6**
Bucegi	13	4.2	9.8	—	—	0.887	0.844	**36.3**	**24.3**	—	—
Iezer	38	26.7	39.9	355.2	58.1	0.002	0.007	**26.7**	**38.3**	**348.4**	**65.0**
Făgăraş	206	59.4	18.6	28.7	90.1	0.001	0.005	**70.3**	**21.5**	**43.8**	**96.9**
Lotru–Cindrel	22	67.8	42.5	19.4	116.2	0.017	0.016	**82.3**	**37.0**	**21.6**	**143.0**
Parâng	56	72.1	43.8	47.4	96.7	0.000	0.000	**68.2**	**45.3**	**45.4**	**90.9**
Retezat	84	60.1	20.8	15.2	105.1	0.026	0.063	**46.4**	**22.9**	**359.6**	**93.1**
Godeanu	69	105.8	33.1	76.1	135.5	0.000	0.003	**114.1**	**30.5**	**81.0**	**147.2**
Ţarcu	59	69.7	42.4	44.8	94.6	0.000	0.000	**76.5**	**45.9**	**53.9**	**99.2**
Bihor	3	77.8	72.4	—	—	0.223	0.253	**66.8**	**71.4**	—	—
Total	*631*	*60.2*	*29.1*	*49.5*	*70.9*	*0.000*	*0.000*	***63.0***	***31.4***	***52.7***	***73.3***

95% confidence limits on the vector mean are given as northwest-most followed by southeast-most. The Rayleigh significance test gives the probability of results at least as extreme as those obtained, if the population is azimuthally uniform, tested against the alternative of one favoured mode. The Kuiper test is against any deviation from uniformity. Note that results for axis aspect (right, bold) are close to those for wall aspect, falling into two clear sets: more northward (the first five) and more eastward (the last seven). Obs, number of observations (cirques). To form 'range groups', Rodna includes T¸ibles¸ (2 cirques) and Suhard; Bucegi includes Siriu (1) and Leaota (1); Lotru–Cindrel includes S¸ureanu (4) as well as Lotru (10) and Cindrel (8); Parang includes Latoritei (4) and Capatanii (1); Tarcu includes Muntele Mic (1).

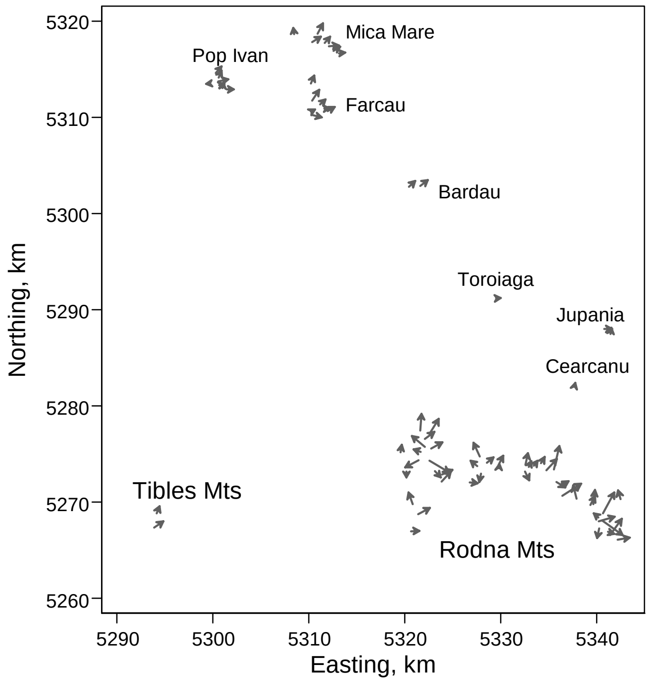

Fig. 2.8.2. Median axis aspects of cirques in the Rodna and Maramureş Mountains, Northern Romania. Arrow length is proportional to cirque size.

The 499 cirques from Făgăraş west to Ţarcu (the southwestern division) have means of 072^0±13^0 and 075^0±13^0 respectively. Moreover, the latter have a broader spread of aspects, with vector strengths of only 27% or 28%. Iezer and Bucegi have favoured cirque aspects more similar to those of northern Romania than to the rest of the Transylvanian Alps. Their combined vector mean is $025^0 \pm 36^0$ (wall) and $034^0 \pm 33^0$ (axis) and strength is 32% (wall) and 37% (axis). They show much less eastward tendency than the southwestern division (and the three in the Bihor Mountains of western Transylvania).

Could there be a topographic explanation for this? Mountain ridges are linear features, and this influences cirque aspect especially when small numbers of cirques are considered. Ranges such as the Retezat have ridges in all orientations, but the Godeanu main ridge is SW–NE and the Rodna is E–W. This may shift the mean cirque aspects, but probably by no more than 20^0 from the climatically favoured aspect. The Făgăraș main ridge trends E–W, but several long subsidiary ridges trend N–S, giving ample opportunity for east- (or west-)facing cirques to develop. The main ridge of Iezer is 18.9 km long and has a mean orientation of $060^0 \leftrightarrow 240^0$, favouring cirques facing 330^0 or 150^0. Three cirque-bearing subsidiary ridges have a total length of 16.6 km and a $179^0 \leftrightarrow 359^0$ mean orientation, favouring cirques facing east or west. Axis aspects are bimodal, with 15 Iezer cirques around 350^0 and 10 around 100^0, suggesting a strong influence of ridge orientation, although the vector mean aspect is 027^0. Wall aspects are unimodal around a mean which also is 027^0. The 19 cirques on the northern slope of Iezer face a little west of north, while the eight cirques on the southern slope face southeast on average. But the 11 cirques on eastern and western slopes have wall aspects displaced some 20^0 northward of their axis aspects. *This shows how climatic factors redirect glacial erosion to give steeper headwalls on favoured aspects, while axis aspects are more influenced by topographic trends.*

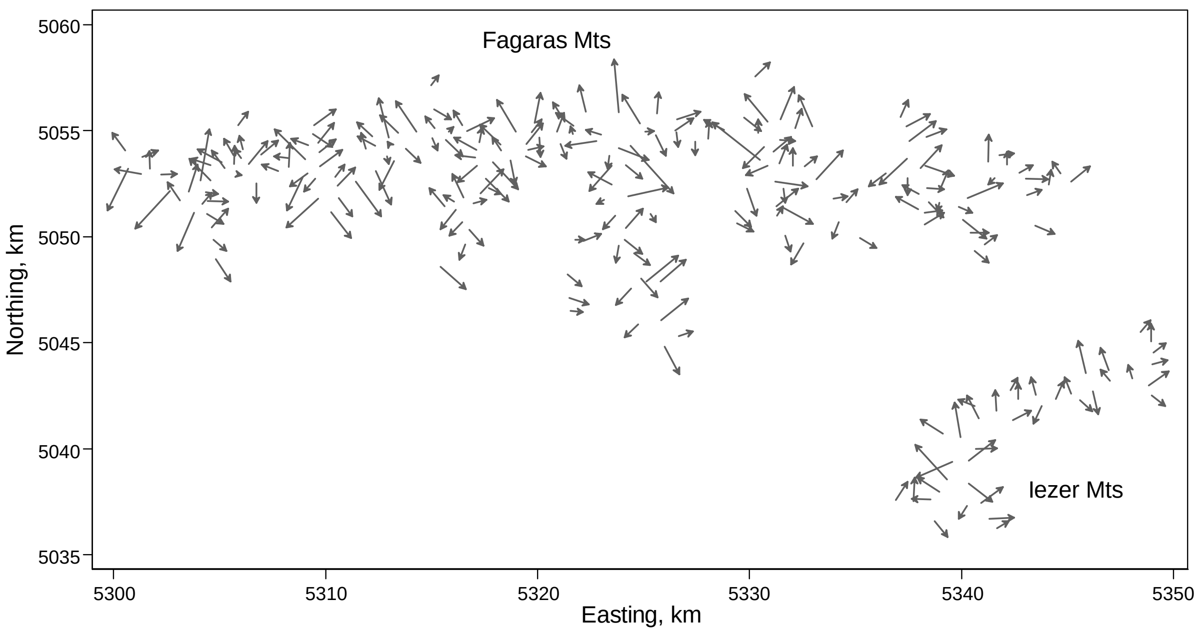

Fig. 2.8.3. Median axis aspects of cirques in the Făgăraș and Iezer Mountains, Transylvanian Alps. Arrow length is proportional to cirque size.

Like the Godeanu and Țarcu, and unlike the Făgăraș, the Iezer and Bucegi have extensive flat or rounded summit areas suitable for wind drifting of snow. It is concluded that west and northwest winds were stronger in the southwestern division than in Iezer-Bucegi and northern Romania. The Iezer (and Bucegi) Mountains (Fig. 2.8.3) are downwind of the Făgăraș and more sheltered from winds from the west and the northwest, so they fit the northern Romanian pattern.

Cirque type was classified as: valley-side, valley-head with threshold, valley-head without threshold, inner or outer. Cirque aspect statistics do not seem to vary with this classification, but in the Transylvanian Alps classic cirques and cirques with lakes have more northward tendencies. Thus aspect varies with grade but not with qualitative type. Aspect statistics do vary with altitude. In the Făgăraș Mountains, the 141 cirques on mountains above 2300m have no significant aspect tendency (P=0.05 on Rayleigh's test); their vector strength is only 10%. The 65 on lower mountains have a strength of 39% and a mean aspect of $049^0 \pm 24^0$. This is consistent with higher mountains supporting glaciers on all aspects, while lower ones can support glaciers only on the most favoured aspects (Pawlowski, 1936; Evans, 1977, p. 169). Further validation comes from cirque altitudes taken in 458 classes of aspect. The mean of each altitude variable is between 149 and 198m lower for NE-facing cirques than for SW-facing, and there is a steady variation with aspect between these extremes. In particular, the altitude of mountains above SW-facing cirques averages 192mhigher than those above NEfacing cirques (excluding the three low cirques in Bihor). The lowest mountain with a SW-facing cirque is 2102 m, but the lowest with a NE-facing cirque is 352m lower and the lowest with N-facing is 389m lower.

For the 12 mountain range groups (Table 2.8.1), Bihor and Bucegi have too few cirques for their asymmetry to be significant – although their mean directions are consistent with their neighbours. One summit in Bucegi, Vârful Omu at 2507 m, is much higher than the rest and thus has cirques on all aspects. Unimodal asymmetry (a single favoured aspect) is most significant for Maramureș, Rodna, Parâng, Godeanu and Țarcu. Vector strengths are greatest for Maramureș, Călimani and Bihor, all with small numbers of cirques, followed by Rodna, Parâng, Lotru–Cindrel and Țarcu, which have strengths of 42–44% for wall aspect and 37–55% for axis aspect. Considering axis aspect in 458 octants, Făgăraș has 61% of Romania's SW-facing cirques, Godeanu has 27% of the S-facing and Retezat has 21% of the SE-facing. This is consistent with these ranges rising higher above snowline and ELA, which permitted glacier formation on less-favoured slopes. Thus Făgăraș has the most dispersed axis aspects and the lowest (21.5%) vector strength, followed by Retezat with 22.9% (Fig. 2.8.4).

Except for Bucegi which has only 13 cirques, Făgăraș also has the most dispersed wall aspects and the lowest (18%) vector strength, followed by Retezat with 21% (Table 2.8.1). Vector means for axis aspect are between 14.5^0 clockwise and 13.7^0 anticlockwise of wall aspect means; vector strengths are within 14% of each other. Results for the two aspect variables for the whole country, however, are much closer (differences of 3^0 and 2.3%: Table 2, last row). If aspects are assigned to eight 45^0 octants, all octant means of axis aspect are displaced toward the overall vector mean (ENE); this is consistent with a unimodal model, in which frequency declines away from the mean. Means of wall aspects corresponding to each octant of axis aspect (except for NE) are displaced toward ENE, usually even further. This is consistent with glacier mass balance steering aspect towards the most favoured direction, by glacial erosion undercutting the headwall more vigorously: we expect wall aspect to be closer to the climatically favoured direction, than site (axis) aspect.

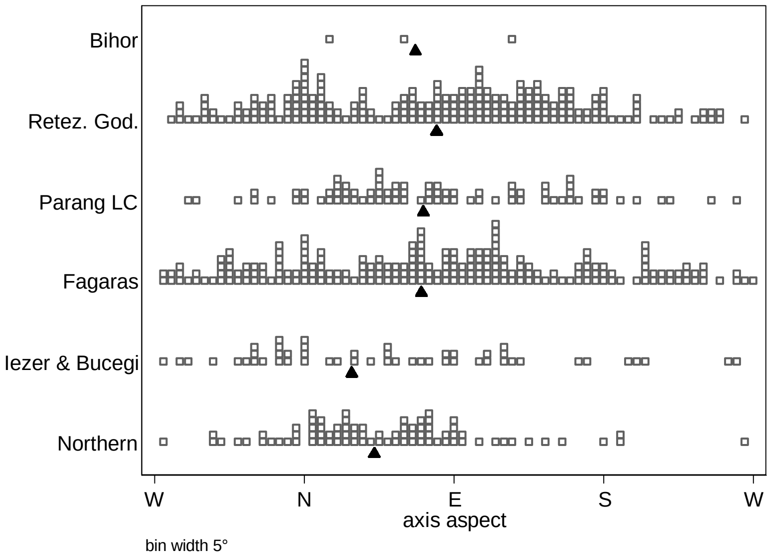

Fig. 2.8.4. Axis aspects of cirques in 6 major regions of Romania. Each square represents one cirque; the solid triangles give the vector mean aspects.

If an aspect favoured in terms of cirque numbers (as shown by vector means) is due to glacier balance variations having produced a lower ELA, we expect that aspect to have cirque floors at lower altitudes (Evans, 2006b). In northern Romania (mainly Rodna and Maramureș), the NE tendency of cirque numbers shown in Fig. 2.8.4 is indeed supported by lower floors in cirques facing NE (Fig. 2.7.5b). In the Făgăraș Mountains, however, those facing NNW are lower, whereas the vector mean is ENE. In Retezat-Godeanu, floor altitude has no significant variation with aspect. Local variations in cirque floor altitude provide support for the vector analysis results mainly in terms of N–S contrasts related to solar insolation and shading, but not more generally.

Cirques and implication for former wind directions

In the Transylvanian Alps the eastward rise in cirque floor altitudes, and in palaeoglaciation level, clearly *supports winds having been from the west*. The absence of cirques from some mountains on the east side of the Eastern Carpathians, such as Suhard (1932 m), Giumalău (1857 m), Bistriței-Budacu (1859 m) and Ceahlău (1907 m), all checked in the field, is also consistent with winds from a westerly quarter, given that lower western mountains such as

Piatra Grăitoare (1658 m, in the Bihor Mountains) did support glacial cirques. Farther north in Maramureș, which is more exposed to the west, all mountains above 1811m do have clear cirques.

The eastward tendency in cirque aspects in the Transylvanian Alps has been noted by previous workers such as Niculescu (1965). Our new finding is that winds from a westerly direction had more effect on cirque glacier balance in the western Transylvanian Alps and the Făgăraș Mountains than in the easterly ranges (Iezer and Bucegi) and in northern Romania. This is crucial for inferences of palaeowind direction during the LGM and earlier maxima of mountain glaciation.

The anticyclonic circulation around the Fennoscandian Ice Sheet was fairly shallow and seems to have had little effect in the Carpathian Mountains. It may, however, have contributed to the northward weakening of westerlies observed across Romania. Thus cirques in Slovakia (Luknis, 1968) do not show a strong eastward tendency. In the mountains of northern Romania during the LGM, winds from westerly directions were strong enough to displace cirque wall resultant vectors to 044^0 for Maramures¸ and 034^0 for Rodna. Axis aspects were 051^0 for Maramureș and 041^0 for Rodna. This is explained by an eastward tendency in snow drifting and hence in cirque aspect. However, shade effects were strong enough to displace wall aspect 6^0 northward from axis aspect. In the Transylvanian Alps, winds were relatively more important in displacing cirque aspects eastward.

Although cirques probably form over a series of glaciations, it is believed that most Romanian cirques were reoccupied by glaciers in the Late Würm, around the LGM. For example, in the Retezat Mountains, Reuther et al. (2004, 2007) dated a major valley glaciation ending 16.1±1.6 ka; they regarded this as (slightly) post-dating the global LGM, during which the Carpathians may have been more arid. An earlier, somewhat more extensive glaciation could not be dated. They also dated a Younger Dryas advance, in which N-facing cirques in the Retezat were occupied by cirque glaciers (Urdea, 2000). Some cirques remained ice-free in the Younger Dryas; Fărcaș et al. (1999) cored down to a compacted clay in Tăul Zănoguții, a glacial lake 0.55m deep at 1890m altitude in a SE-facing cirque in the Retezat, obtaining an oldest 14C date of 11.1 ka BP. The two previous glaciations were much more symmetrical as well as more extensive. Thus it is likely that most Romanian cirques were glacier-occupied just after the worldwide LGM, and probably on numerous earlier occasions. Urdea (2004) gives the snowline in the Transylvanian Alps as 2200m in the Younger Dryas, 1840–2000m in 'Würm III', 1800m in 'Würm II' and 1670m in an earlier glaciation.

Winds from south of west would not give the observed contrast between Iezer-Bucegi and Făgăraș*: important snowdrifting LGM winds in the mountains must have come from the northwest quadrant*. This is supported by lower PGLs in the northwestern ranges than in the southeastern, in three parts of the Transylvanian Alps. Differences in mean floor altitudes within the latter are less clear (Fig. 2.8.5) because higher cirques are found around higher summits. The N–S narrowness of the ranges, and the importance of topographic differences between the northern slopes and southern slopes of the Făgăraş, do not provide a good test for any southward (or northward) rising trend.

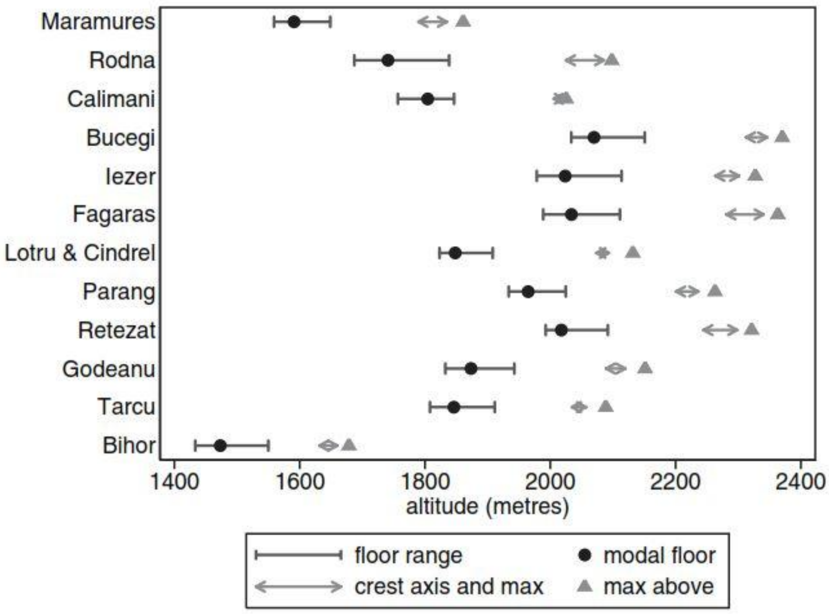

Fig. 2.8.5. Mean values of floor and crest altitudes, and maximum altitude above, for cirques in the 12 mountain range groups in Romania.Floor altitudes are lowest (per cirque), highest and modal (most representative); crest altitudes are maximum, and at the median axis. Range groups are ordered from north, to southeast (Bucegi), to west.

Niculescu (1965, pp. 35 and 228) found that, for the Godeanu Mountains, west and northwest winds were dominant in glacier formation – as they are today in snowpatch distribution. Northwest winds would be consistent with landforms in the Pannonian Plain, in central Hungary, where yardangs both in bedrock and in Late Pleistocene deposits demonstrate northwest winds (Ruszkiczay-Rüdiger et al., 2007). These may have been persistent during cold, dry glacial phases. Also south of the Transylvanian Alps on the Oltenian Plain, major Pleistocene linear dunes trend WNW–ESE (Coteţ, 1957).

Rózycki (1967) attributed linear loess ridges (gredas, analogous to Chinese liangs) to the effects of dominant winds during the Pleistocene. He mapped these ridges from Poland to Bulgaria, giving a clear pattern of wind divergence around the Slovak Carpathians, with the northern branch blowing ESE across southern Poland and turning SSE across Moldavia and Dobrogea. The internal, Pannonian branch blew SE across central Hungary, crossed the Iron Gates Gorge and blew ESE across southwestern Romania and northwestern Bulgaria. Again, this is not unlike the *present-day pattern* of west and west-northwest winds (Fig. 2.8.1). Niculescu (1965) concluded that the Carpathian mountain arc modified wind directions in the lower atmosphere in the Pleistocene as it does today. The Holocene dunes on the plains of Oltenia in southwestern Romania and the Alfold of southeastern Hungary were also formed by northwest winds (Fig. 2.8.6). By contrast, dunes in a smaller area of northeastern Hungary and adjacent northwestern Romania resulted from north and northeast winds. Loess sequences provide important and at least a partial continuous record of Quaternary palaeoenvironmental change. In addition, loess-palaeosol sequences provide valuable information concerning environmental change and climate evolution.

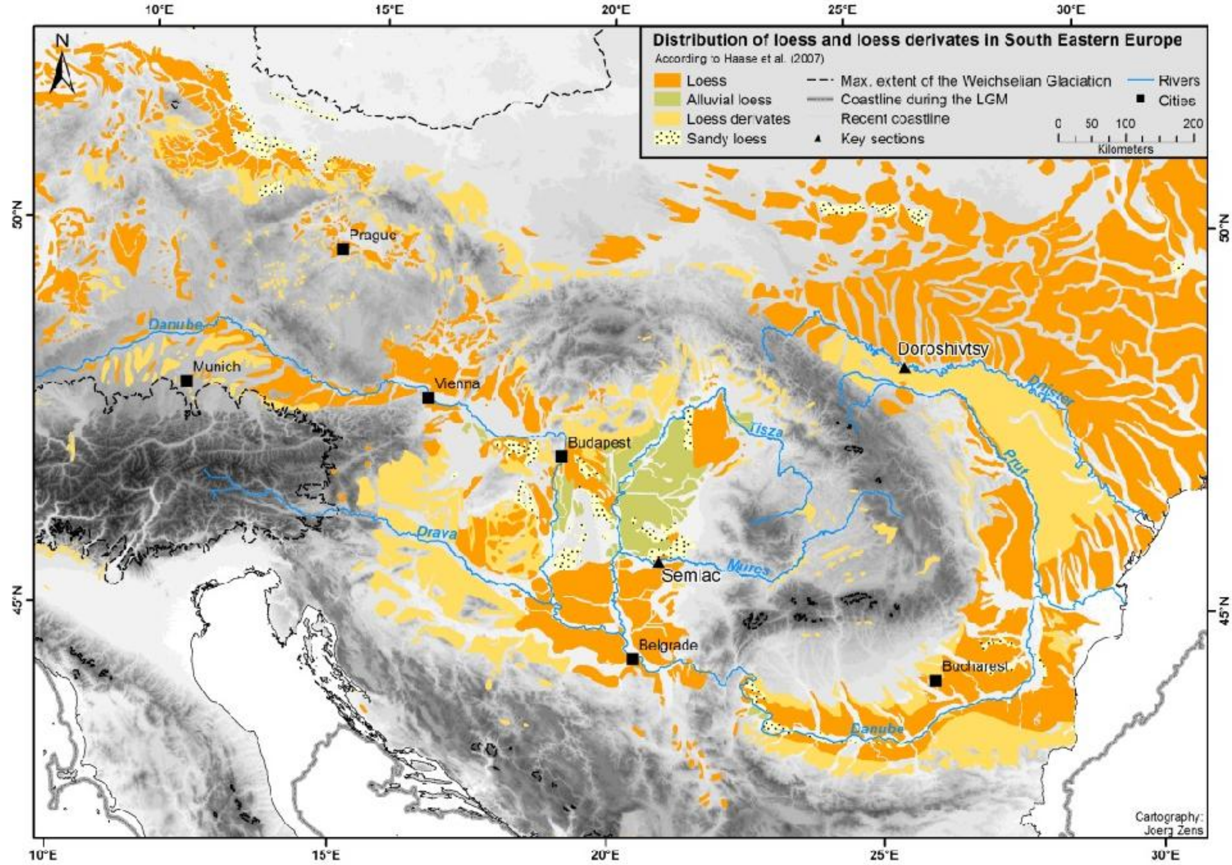

Fig. 2.8.6. Loess distribution in Europe, maximum extent of the Weichselian ice sheet, coastline during LGM (modified according to Haase et al. 2007).

Interpretation of cirque aspect (mean glacier)

This discussion raises an important general conclusion. It is often inferred or implied, at least in popular works, that dominant winds came from the aspect opposite (180^0 from) mean cirque or palaeoglacier aspect. For example, the northeastward tendency in British cirque aspects is attributed to southwest winds at times of cirque formation. This is incorrect, as it implies that no factor other than wind influences aspect. As it is clear that N–S contrasts are near-universal in modern glacier populations (Evans and Cox, 2005), and morning–afternoon contrasts cause only a small displacement, usually to eastward, any wind effects are superimposed on these general effects. Thus if a wind from due west is equal in importance to N–S contrasts, in influencing azimuthal variation in glacier balance, we should expect eastward and northward tendencies to combine, giving a mean aspect near NE. Neglecting other factors, Table 2.8.2 shows, in the column 'West', the mean aspect expected from these two factors where the first column (x) shows the relative importance of a west wind. These were calculated simply as the arctangent of x, which gives the correct azimuth of the combined vector. Where the importance of this wind completely overwhelms N–S contrasts, mean aspect approaches 90^0. Column 'Northwest' shows corresponding results, by further trigonometry, for a wind from the northwest, displacing aspect toward 135^0 as its importance increases.

Table 2.8.2. Aspect (columns 'West' and 'Northwest', in degrees east from north) resulting from combination of a wind effect with importance x times the northward effect of radiation and shade. Column 'West' is for a wind from due west, giving eastward tendency; column 'Northwest' is for a wind from the northwest, giving a southeastward (135^0) tendency

x	West	Northwest
0.25	14	12
0.5	27	29
0.75	37	48
1.0	45	67
1.25	51	83
1.5	56	93
2.0	63	106
3.0	72	118
4.0	76	123
8.0	83	129
50.0	89	134

Thus the mean wall aspect of 72^0 for the southwestern division (499 cirques from the Făgăraș westward) could be produced by an infinite number of combinations of wind directions with relative importance of the two factors. If wind was from due west (on average, during times of cirque erosion), it would have been three times as important as solar radiation and shade. If it came from the northwest, wind would have had a little more effect than the latter: x 1.07. Given the evidence of cirque altitudes, a wind from somewhere between these directions is likely, probably closer to northwest than to west. This wind effect was much stronger than for glaciers today in the Alps, the Pyrenees or even Scandinavia (Evans, 2006a).

Similarly the 036^0 mean wall aspect for the 81 cirques in northern Romania could result from a west wind 73% as important as solar radiation and shade, or a northwest wind 60% as important. A northward reduction in wind effects seems reasonable, and the increased concentration of aspects (52%, compared with 27% for southwest) is due partly to this reduced interference by winds, and partly to fewer summits rising well above glaciation level. The more important wind and minor effects are, and the more their favoured aspect deviates from poleward, the lower the vector strength as more varied aspects are expected.

The Tăuşoare cave in Northern Romania, Rodna Mts (spanning the last 68 ka) data-set records "Heinrich-stadial" type cold events (low $\delta^{18}O$) throughout MIS 3. While the magnitude of speleothem $\delta^{18}O$ variability in N Romania is much less pronounced in comparison to Sofular cave in NW Turkey, the pacing is generally similar. *That suggests a common response to Atlantic millennial scale climate variability as observed in the Greenland record for Northern Romania*, but without the magnification of the $\delta^{18}O$ signal observed in

NW Turkey due to a local Black Sea source effect (Staubwasser et al., 2014). In fact, Atlantic moisture must have been broadly absent in the S Balkan, otherwise the cold events recorded in N Romania would have been recorded in S Romania as well. Essentially, this suggests that the exposure of the S Balkan to cold Atlantic air masses must have been rather limited during MIS 3 in general. Such muted cold conditions over the S Balkans may have favored the dispersal and survival of anatomically modern humans into SE Europe even between interstadials (Staubwasser et al., 2014).

Conclusions

The many glacial cirques in the mountains of Romania indicate the distribution of former glacier sources, related to former climates as well as to topography. In the Transylvanian Alps (Southern Carpathians) cirque floors rise eastward at 0.714m km^{-1}, and cirque aspects tend ENE, confirming the importance of winds from some westerly direction. There is a contrast between two neighbouring ranges: the Făgăraș where the favoured aspect of cirques is ENE, and the Iezer, where the tendency is stronger and to NNE. This can be explained by the Iezer Mountains being sheltered by the Făgăraș which implies precipitation-bearing winds from north of west at times of mountain glaciation.

Wind drifting of snow to eastern slopes had a stronger effect on cirque aspect in the Transylvanian Alps than in northern Romania. Within the former, its effects are greatest in western ranges such as the Godeanu Mountains, giving east-facing cirques. The big contrast in cirque aspects between the Făgăraș and the adjacent Iezer and Bucegi Mountains is explained by winds from north of west rather than south of west. Floor altitudes and especially palaeoglaciation levels also suggest precipitation-bearing winds from north of west. This evidence from high altitudes (1500–2500 m) is consistent with the evidence of aeolian forms at low altitudes and gives a picture of Romania being influenced by winds from WNW during glacial maxima. These winds may have been stronger in the Transylvanian Alps than in northern Romania, whereas modern winds are more consistently from the west in northern Romania.

Palaeoglaciation levels also suggest winds from north of west, which is consistent with aeolian evidence from Pleistocene dunes, yardangs and loess features in the plains of Hungary and southwestern Romania. In northern Romania (including Ukrainian Maramureș) the influence of west winds was important, but sufficient only to give a northeastward tendency in cirque aspects. This gave stronger asymmetry than in the Transylvanian Alps, as the northward (solar radiation incidence) tendency in these marginally glaciated mountains was less diluted by wind effects. Cirque floors in northern Romania are lower also in northeast-facing cirques. In general, cirque aspects result from several factors and the mean tendency is not downwind, but is displaced from poleward by wind and by minor effects.

This chapter also includes elements from the following publications:

Mîndrescu M & Evans IS (2014) Cirque form and development in Romania: allometry and the buzz-saw hypothesis. Geomorphology 208:117-136

Mîndrescu M, Evans IS, Cox NJ (2010) Climatic implications of cirque distribution in the Romanian Carpathians: palaeowind directions during glacial periods. Journal of Quaternary Research 25(6):875-888

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Chapter 3

Further work and perspective plan: *Linking lake sediments and glacial deposits chronologies in the Romanian Carpathians*

3.1 Introduction

The scientific evolution of the candidate will be linked to the development of new ideas, concepts and approaches, and state-of-the-art methods in his field of research.

During the upcoming period he envisages that the main focus of his scientific endeavors will be to link the two main research topics investigated thus far, i.e. data derived from glaciolacustrine records (laminated/varved lake sediments) and glacial features and deposits, in order to decipher the pattern of glaciation(s)/deglaciation(s) during the Pleistocene and Holocene climatic events in the Romanian Carpathians. To achieve this it is necessary to identify and investigate key regions which contain classical glacial cirques (grade I) with glacial lakes.

The candidate believes that this approach will provide new data relevant for palaeoclimate evolution at regional scale and the high-resolution sedimentological and chronological data employed will allow signal calibration and comparative analysis of different proxies and time-series. This multi-proxy approach is intended to:

a). overcome limitations of palaeoclimatic and dating methods;

b) combine different climatic signals into a composite profile; and

c) carry out palaeoclimatic reconstructions taking into account regional and global climatic profiles and identify regional constraints of rapid climate oscillations.

This perspective research plan will not be a singular effort in investigating palaeoclimate evolution in the Romanian Carpathians; however, it should be regarded as the first attempt to link chronologies derived from glacial deposits and lacustrine deposits in the Carpathian region.

3.2 Potential of the Romanian Carpathians for the study of climatic variability

At 45–48^0 N latitude, the Romanian Carpathians occupy a central position within the temperate climate zone. They provide evidence of Quaternary climates in an important transitional region between cool temperate and Mediterranean climates. They are also placed between the oceanic climates of western Europe and the arid regions of interior Asia. It is believed that the oceanic climates are most responsive to climate change in the North Atlantic, and Central Asia is the least responsive. For climatic studies, the Carpathians are thus a key region that would have recorded changes in patterns of atmospheric circulation and their consequences for precipitation gradients.

The dynamic interplay and variations in the strength of these influences can and do generate major changes in climatic regimes (temperature/precipitation) over very short distances and time intervals, which in turn are key factors in the distribution of biogeographical zones in the region. Studies of vegetation dynamics and palaeoclimate highlighted the importance of this region as glacial refugia, but also pointed out significant regional differences compared to Central and Western Europe.

However, as these studies commonly addressed solely the Late Glacial and Holocene environmental evolution, palaeoclimate data are still lacking for this part of Europe for most of the last glacial cycle and beyond. In terms of palaeoclimate data sources, lacustrine archives are widely used in the reconstruction of past environmental conditions in a variety of settings and over timescales ranging from recent to Lateglacial and beyond. Studies aimed at establishing the environmental and/or climatic context of sediment deposition require a solid and reliable chronology in order to obtain an accurate interpretation and to correlate climatic events to other regional or hemispheric proxy records. New surface-exposure dating methods using cosmogenic nuclides are substantially improving our understanding of glacier fluctuations and their relationship to climate change.

The research will be based on a variety of standard sediment analyses and dating techniques (*cosmogenic radio-nuclide, CRN:* ^{10}Be *and* ^{26}Al, *optically-stimulated luminescence – OSL,* and *radiocarbon dating -* C_{14}). The former two methods are highly suitable for dating the time of formation of glacial landforms and deposits in order to infer glaciation/deglaciation patterns (CRN), and for dating the onset of sedimentation in lake basins following glacier retreat (OSL), respectively. Radiocarbon dating of organic remains within both glacial deposits and lake sediments is useful in inferring the time of formation of these deposits and dating the onset of organic sedimentation in the lake subsequent to deglaciation and establishment of vegetation, which indicate a climate amelioration.

This perspective plan is a good opportunity to pioneer the application of an arsenal of approaches to reconstruct past climatic conditions and, thus, to tackle questions which could provide answers to a potentially important field of climate change, *the recurrent millennial-scale climate oscillations*. Also, the results will be used for calibration with other similar data obtained from research carried out throughout Europe. The work will produce detailed chronological and palaeoclimatological data with applicability in:

i) elucidating the pattern of glacier activity and climate change in Eastern Europe as compared with the first-order climatic signals specific of the North Atlantic, and

ii) provide high-quality data necessary for modelling and correlation with other records.

Due to their location, the *Carpathians are ideally positioned to capture the dynamics of changes* in atmospheric circulation, temperature and precipitation regimes in the mid latitudes of Eastern Europe. From a palaeoclimatological point of view, the Carpathians are still an "unexplored spot", with an urgent need for studies filling the gaps through detailed and chronologically-well constrained investigations. The application of the three dating methods (CRN, OSL, radiocarbon) is expected to strengthen the validity of results and help establish a more secure chronological framework than using any of the methods individually. This approach enables a cross-validation of results using several lines of sedimentological evidence and tests the quality of the age estimates, a necessary step before attempting palaeoenvironmental reconstructions in the context of rapid climate variability. This research will add considerably to the palaeoclimatology of the Carpathians - Lower Danube - Balkan region, as no other lake records older than late LGM have been found/investigated in the region.

3.3 Objectives

The candidate envisages that his perspective research plan will attempt to attain the following objectives:

O_1. *To identify and analyze the climatic events recorded by glacial deposits (deglaciation history)*: a) spatial and temporal relationship between the last glaciation and following deglaciation phases, and the stadial/interstadial periods of last glacial cycle (LGC); b) significant latitudinal and longitudinal differences in the direction of rapid climate change between the Northern, Eastern and Western Romanian Carpathians; c) the extension of the first-order North Atlantic climatic signals transmitted along the continent and the Carpathians (and to determine if these signals were cancelled); d) the implications of these observations for the environmental history of the region, and how does the chronological, palaeoglaciological and palaeolimnological evidence relate to the data from the neighboring areas (Balkan-Mediterranean, Central and Western Europe, Eurasia);

O_2. *To create a comprehensive set of data by completing the existing records of climate variability with glacial lake sediments as climatic signals:* a) to compare optically-stimulated luminescence (OSL) dating of lake sediments with cosmogenic ^{10}Be surface-exposure ages from the glacial deposits (including moraines logging); b) to compare these sediment records with fully independent climate reconstructions; c) to test the potential of new analytical methods on the glacial lake sediments; d) to assess the effects of different widely used univariate calibration methods on the reconstructed amplitude of past climate variability; e) to explore the potential of climate reconstructions derived from glacial lake sediments from the Romanian Carpathians to preserve sub-millennial climate variability;

O_3. *To produce palaeoclimate models*: simulations and syntheses of palaeoenvironmental data in order to analyze the mechanisms of climate change during the Late Pleistocene and Holocene;

O4. *To disseminate and capitalize of the results:* international presentation and publications, organizing international workshops, editing new courses, implementing the results into the management of national and natural parks and local communities, establishing research perimeters for students and young researcher in these areas, as well as contributing to changing the level of awareness of adults regarding climate change by organizing summer camps for adult education in this field, and promoting these areas so that they may be granted full protected status.

3.4 Preliminary results

The timing and extent of glaciations in the Romanian Carpathians and the ensuing climatic oscillations during the Holocene are still under controversy, mostly due to the lack of well dated geomorphological, geochronological and sedimentological studies.

Based on the perspective research plan detailed above, the candidate has already obtained some preliminary results from the geomorphological and sedimentological analyses of glacial and lacustrine deposits in Bistricioara Valley (Fig. 3.4.1) located in Rodna Mts (Northern Romanian Carpathians).

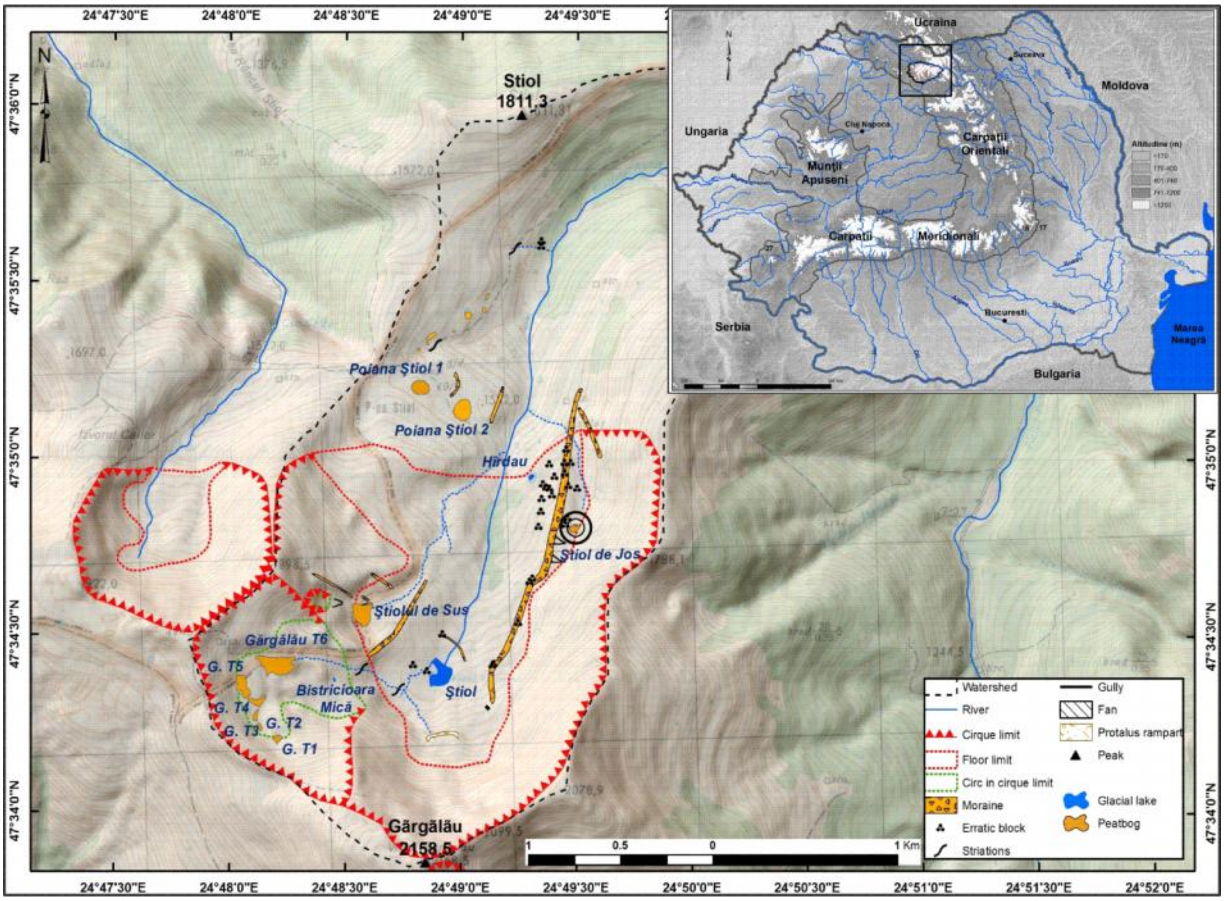

Fig. 3.4.1. Study area. Cirque and glacial valley of Bistricioara, Rodna Mts.

Ştiol de Jos (Oncul) peat bog (Fig. 3.4.2) is located at 1630 m a.s.l. and the site has been dammed by a large lateral moraine within Bistricioara Mare cirque, one of the largest glacial cirques in the Romanian Carpathians.

Fig. 3.4.2. Ştiolul de Jos (Oncul) peat bog.

The geology of this region comprises predominantly of crystalline rocks, but includes metamorphic strata such as gneiss and paragneiss, as well (see Fig. 3.4.3).

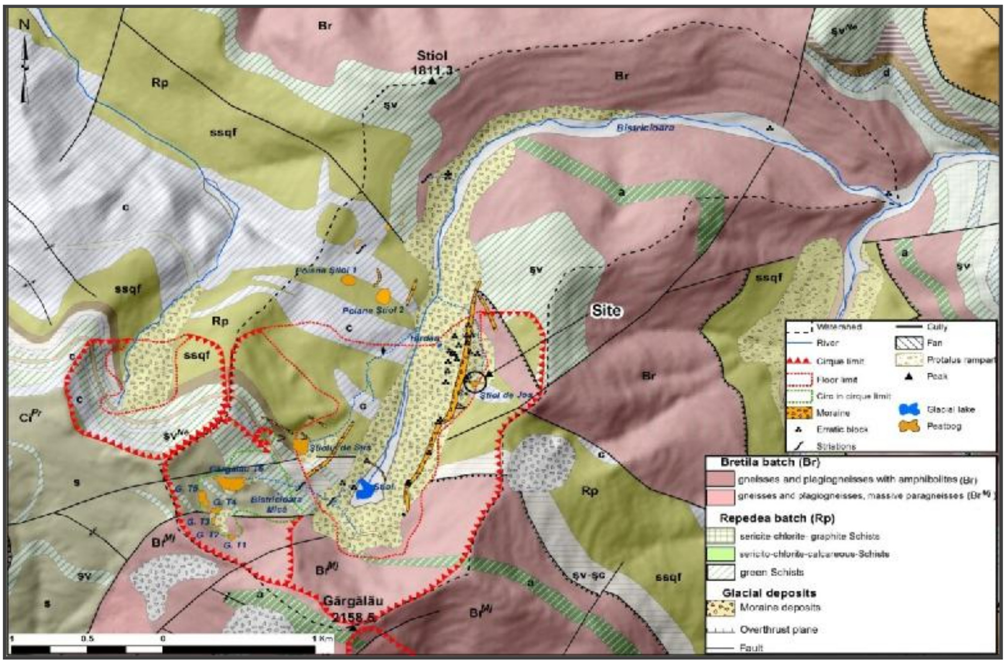

Fig. 3.4.3. Geology of the area.

Materials and methods

- Field surveys included mapping of moraines and erratic boulders using detailed topographical maps and aerial photos.
- A Russian corer was used to recover the sediment profile from the peat bog (approx. 5 m long sediment core) (Fig. 3.4.4).
- An X-ray *computed tomography* (CT) system was employed for the study of sedimentary and deformation structures (Figs 3.4.6 and 3.4.7)
- For multi-element analysis at high resolution, an X-ray fluorescence spectroscopy (XRF) was used.
- Carbonate and organic matter contents have been determined with the 'loss on ignition' at intervals of 5 cm (from 40 cm to 440 cm) and for the lowest part at 2 cm (440 cm – 500 cm).
- 3 AMS radiocarbon datings have been performed at 315, 467 and 497 cm, yielding the ages 1175 ka cal BP and 7920 ka cal BP, respectively.
- Glacial deposits from the lateral moraine in front of the peat bog were also sampled, as well as from the frontal moraines, upstream and downstream of the peat bog (Fig. 3.4.5).

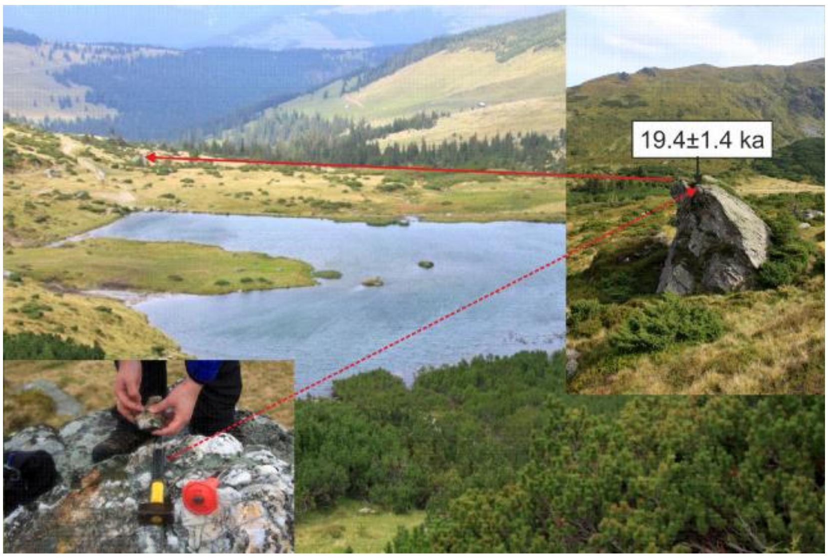

Fig. 3.4.5. Sampling for cosmogenic radio-nuclide dating on Bistricioara valley (2015).

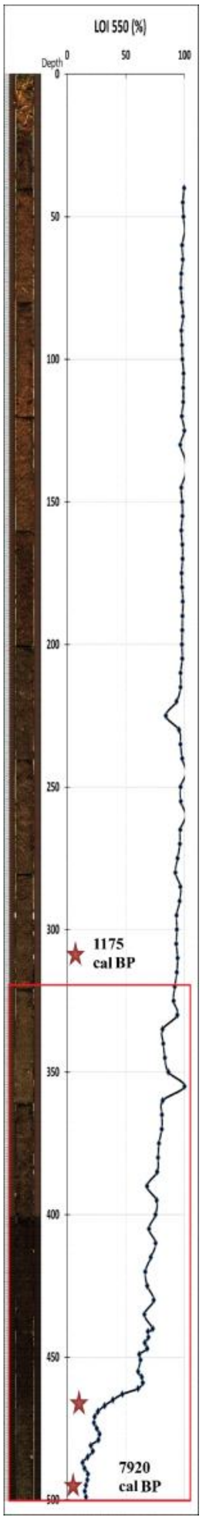

Fig. 3.4.4. Peat bog profile.

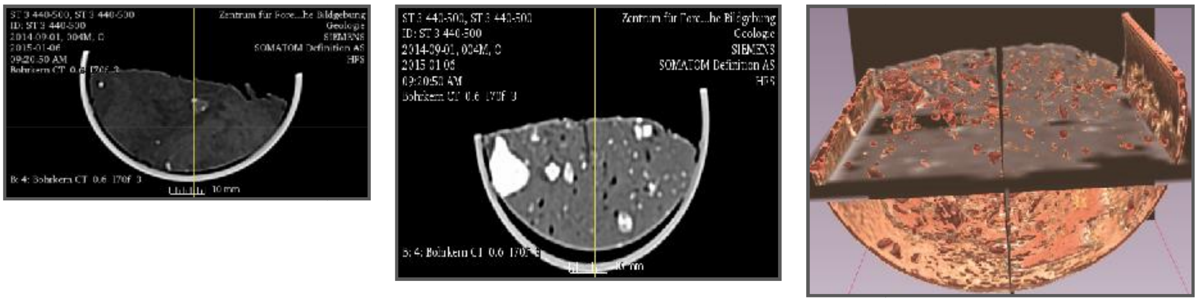

Fig. 3.4.6. CT scan slice view at 450 cm (section without rock fragments)-left; CT scan slice view at 490 cm- middle; CT scan slice view at 490 cm (particle dimension in red color) - right.

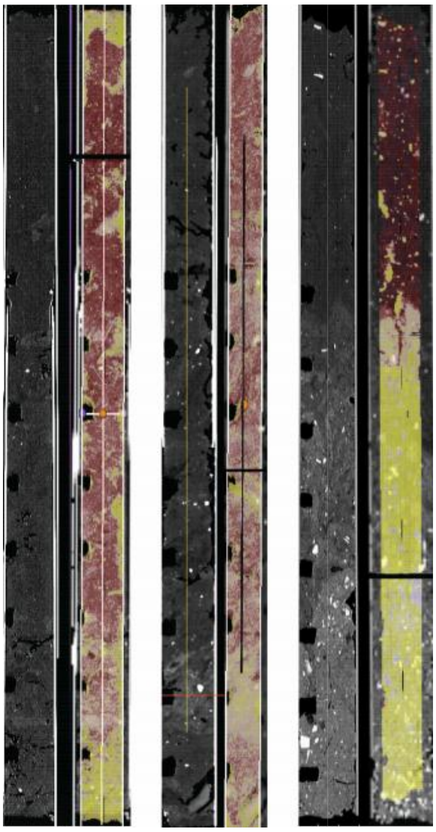

Fig. 3.4.7. X-ray computed tomography (CT) of some core sections: A : 360-420 cm (left); B : 400 -460 cm (middle); C : 440-500 cm (right).

Results

- The lake sediment succession shows an evolution from a basal glacially-influenced lacustrine environment to a shallow lake and eventually to a peat bog.
- The transitions from the clastic-rich lowest 40 cm of the profile to the overlying units reflects a change in the detritic input that is mostly related to initial proximity to a glacial source.

- Loss-on-ignition analysis shows organic matter values ranging from 10 to 90 % with high variability between 40 and 460 cm depth and an overall decreasing trend down core (Fig. 3.4.4).
- Element concentrations of Ti, K, Rb and Zr in the lower part of pofile indicate a high minerogenic input in lake, Ca and Sr related to carbonate weathering in the catchment and Si to diatom productivity (Fig. 3.4.8).

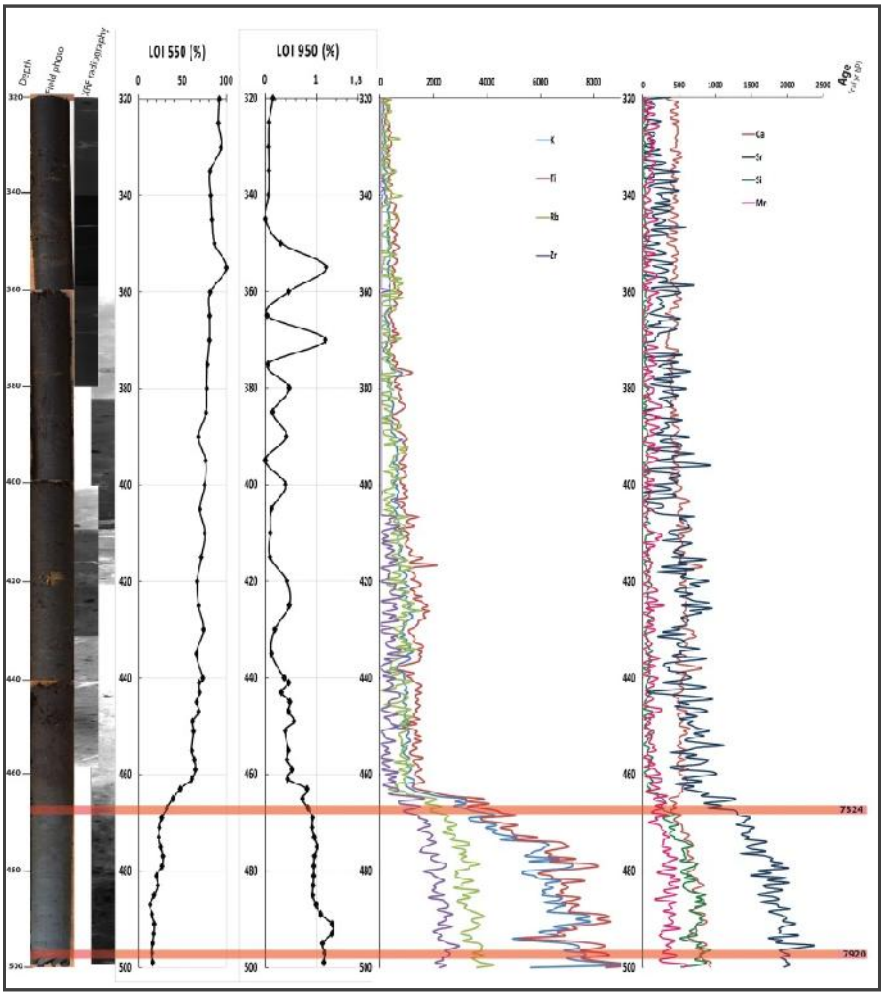

Fig. 3.4.8. XRF profiles.

- Lake sediments started to be deposited around 8000 yr BP.
- Field mapping shows a series of moraines which indicates the occurrence of several glacial phases.

Overall, it has been determined that Bistrita valley (Bistricioara) in Rodna Mts is among the key regions suitable for combined investigation of glacial deposits and lacustrine sediments in the candidate’s perspective plan due to the diversity of glacial features and sediment traps (i.e. glacial lakes and peatbogs) in the area. The age of these deposits ensures a continuous chronology throughout the Late Pleistocene and Holocene which could prove very valuable for the study of climatic variability and the assessment of long-term human impact.

Chapter 4

Professional activity

The candidate graduated from „Al. I Cuza" University of Iasi at the Faculty of Georaphy in 1997 and proceeded to attend the postagraduate courses of the Dynamic Geomorphology master. He went on to enrol for his doctoral studies at the same academic institution and in 2006 he defended his PhD thesis tackling the „Geomorphometry of the glacial cirques in the Romanian Carpathians" for which he was awarded the *Magna Cum Laude* distinction.

From 1999 onwards he carried out teaching and research duties at the University of Suceava, where he progressed from instructor to associate professor. Furthermore, during the same year (1999) the candidate was awarded a scholarship at Durham University in UK where he has the opportunity to study glacial geomorphology under the supervision of the renowned specialist in this field, PhD professor Ian S. Evans. During the past 16 years the candidate participated in over 30 teaching and training missions within the Erasmus framework in a number of prestigious European universities, such as Durham University, University of Salford, University of Manchester (UK), Humboldt University in Berlin (Germany), Pedagogical University of Cracow (Poland), University of Bern (Switzerland), University of Ljubljana (Slovenia), Eötvös Loránd University (Hungary) etc. These provided excellent opportunities for improving the candidate's knowledge and abilities, particularly in the fields of glacial geomorphology and palaeolimnology.

In 2009 the candidate was invited to become a member of the scientific committee of Science for Carpathians (MRI Europe) and in 2013 he was elected chair of South East Europe Mountain Research (SEEMoRe). On a general note, during the past decade the candidate was very invested in promoting cooperation and interdisciplinarity in geoscience in the Carpathian-Balkan area, as illustrated by the various scientific meetings tackling this region organized by him and his closest collaborators, as well as by the Carpathian-Balkan working group.

His research activities resulted in several Web of Science publications (11 published and 5 under review) in prestigious internation journals, such as *Journal of Quaternary Science, Geomorphology, Quaternary International, The Holocene, Regional Environmental Change, Tree Genetics and Genomes, Biological Conservation.* His papers were cited over 120 times (available at https://www.researchgate.net/profile/Mindrescu_Marcel). The candidate's work as a Guest editor for Quaternary International resulted in the publication of two special volumes dedicated to geoscience in the Carpathian-Balkan region.

As regards envisaged meetings and conferences, the candidate will chair two events, the first of which tackles *climate changes* (supported by Past Global Changes – PAGES, with the participation of the steering committee of the organization) in May 2016 in Cluj-Napoca, and the *populations of Pinus cembra in the Carpathian Mountains* (supported by Alpine Forest Genomics Network – AforGen) in late June 2016 in Sacel, Maramures.

4.1 Research

a. International workshop organizer

During the past 5 years the candidate was very focused on promoting interdisciplinary research from the Carpathian-Balkan area carried out by local or foreign scientists and making their results more visible to the regional scientific community, as well as creating opportunities for collaboration for further advancing this research. To date three international workshops were organized for which he obtained financial (as well as scientific) endorsement from prestigious institutions, such as PAGES (Past Climate Changes), MRI (Mountain Research Initiative), the Romaniawn Authority for Higher Education and Research and various universities and professional associations.

CBW 2011 (first edition)

In June 2011 the candidate was the chairman and main organizer for the first interdisciplinary workshop in geoscience in Romania held at the University of Suceava (Suceava, Romania, 9 - 12 June 2011: http://www.pages-igbp.org/calendar/127-pages/1208-carpathian-balkan-2014-workshop and http://atlas.usv.ro/www/climatechange). The main goal of the workshop *Climate change in the Carpathian-Balkan region during the Late Pleistocene and Holocene* (Fig. 4.1.1) was to bring together an international group of scientists (senior, as well as younger researchers) interested in the Carpathian-Balkan region to discuss research results and promote opportunities for interdisciplinary and international collaboration.

Furthermore, as coordinator of the workshop he was offered to lead publication of the more advanced workshop contributions in a special issue of the journal Quaternary International (vol. 283/2013: http://www.sciencedirect.com/science/journal/10406182/293).

Another product of this international gathering was the creation of the "Suceava working group" aimed at promoting/organizing follow-up activities, under the lead of Marcel Mindrescu, Angelica Feurdean, Enikő Magyari and Dan Veres.

IGCB 2012 (first edition)

In 2012 the candidate organized the 1st Workshop on "*Interdisciplinarity in Geosciences in the Carpathian Basin*" (IGCB) held at the Department of Geography at the University of Suceava (Romania), between the 18th - 22nd October 2012.

The area on which this workshop was focused, i.e. the Carpathian Basin, is to date one of the least studied (and known, in general) mountain areas in Europe, despite its significant scientific potential and relevance to the European space. This is also the case with regard to Romanian research which needs to be updated in terms of scientific approach, concepts and methodology. Therefore, much as the previously mentioned event, IGCB succeeded in bringing together international scientists and local researchers which created good premises for collaboration in research topics such as geography, environment, geology and botany, ecology etc in the Carpathian Basin.

Moreover, the candidate had the initiative to include in the event the Honoris Causa Degree ceremony for Reader Emeritus Dr. Ian S. Evans of Durham University (UK) awarded by the University of Suceava as recognition of his merits in promoting its Department of Geography and Romanian geographical research in general, for making a significant contribution to the development of Romanian geomorphology by collaborating with academics from several universities (e.g. Suceava, Timisoara, Iasi, Bucuresti) during the past four decades, as well as for his achievements in international scientific research.The two main topics Dr. Ian Evans has made his own throughout his career, and are recognized as such, are glacial and general geomorphometry.

CBW 2014 (second edition)

The *"Late Pleistocene and Holocene climatic variability in the Carpathian-Balkan region"* workshop (CBW 2014) held in Cluj-Napoca, Romania (6 - 9 November 2014: http://georeview.ro/ocs/index.php/late-pleistocene-and-holocene/late-pleistocene-and-holocene, http://www.pages-igbp.org/calendar/127-pages/1208-carpathian-balkan-2014-workshop, see Fig. 4.1.1) was a step forward for palaeo research in the region which saw the completion of collaborations established after the first edition (CBW 2011), many of which resulted in presentations in the workshop, as well as the emergence of novel research topics. Furthermore, the event provided a platform for young scientists to introduce and discuss their results with an international multidisciplinary audience.

Over the duration of the workshop proceedings 62 researchers from 11 countries (Canada, UK, Switzerland, Germany, Poland, Hungary, Ukraine, Bulgaria, Bosnia and Herzegovina, Serbia and Romania) conducting studies in the Carpathian-Balkan region presented over 60 contributions covering an ample timeframe (Late Pleistocene to present) which tackled topics as diverse as climate and/or vegetation changes inferred from lacustrine and riverbed sediments, tree rings, speleothems, loess-paleosol sequences, glaciers and glaciation, refining research techniques employed for palaeoenvironmental investigations, human impacts, archaeological findings etc.

Finally, it has been agreed, as one of the main legacies of this meeting, that without better data coverage and expertise exchange, difficulties will remain in understanding local-scale changes, let alone developing regionally significant palaeoclimate reconstructions, and proposing plausible predictions of future climate evolution.

The more advanced contributions will be published in a special volume of the journal Quaternary International, also guest edited by the candidate as the main organizer, to which over 25 author groups have submitted papers (*issue under review, will be printed in 2016*).

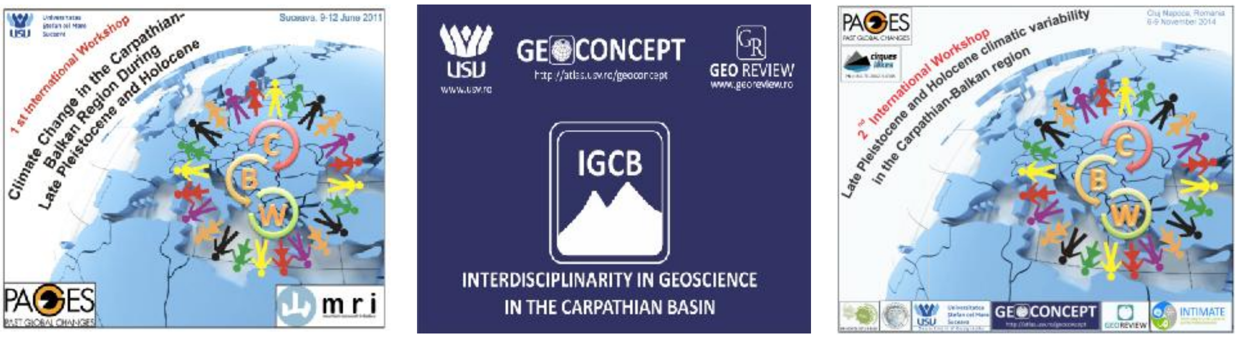

Fig. 4.1.1. Workshop logos: CBW 2011, IGCB 2012 and CBW 2014.

b. International and national visibility

Chair of South East Europe Mountain Research (SEEmore)

On the occasion of the SEEmore Meeting in March 2013, Sofia, Bulgaria, the candidate was elected as the new chair of SEEmore Working Group, which gave him significant responsibility. This nomination indicated that the SEEmore network is open to exploring new opportunities and challenges. On a personal level, it motivated the candidate to lift research in the Southeastern European region, which has great and unexploited potential, to a higher level. Therefore, using the SEEmore umbrella, it is high time to move research forward together: http://mri.scnatweb.ch/en/140-networks/mri-europesouth-eastern-europe/1646-editorial-a-vision-for-seemore-join-in-and-share-your-ideas-by-marcel-mindrescu. The Carpathian-Balkan area is indeed a very complex and heterogeneous region, comprising of countries which became young democracies in the recent decades, which could be an advantage in building a friendly and capable regional scientific community. Every researcher who is a member of SEEmore, as well as other scientists interested in this region, are welcome to join in and share ideas and innovations in order to make our group a better team.

International conference board member

- *Forum Carpaticum 2010* (FC2010), Krakow, Poland
- *Forum Carpaticum 2012* (FC2012), Stará Lesná, Slovakia
- *Carpatho-Balkan-Dinaric Conference on Geomorphology* 2011, Ostravice, Czech Republic
- *Water resources from Romania. Vulnerability to the pressure of man's activities* 2010, Targoviste, Romania, http://www.limnology.ro/water2010/committees.html

- *Water resources and wetlands* 2012, Tulcea, Romania, http://www.limnology.ro/water2012/Committees.html
- *2nd International Conference "Water resources and wetlands"* 2014 Tulcea, Romania, http://www.limnology.ro/water2014/committees.html

Member of international scientific communities

- Mountain research initiative (MRI) Europe-Carpathians
- South Eastern Europe Mountain Research (SEEmore)
- Past global changes (PAGES)

NGO membership

- President of the Association of Applied Geography GEOCONCEPT (since 2010). Geoconcept is an NGO designed for environment protection and conservation and promoting sutainable touristic activities (http://www.atlas.usv.ro/geoconcept/contact.php)
- Member of Asociaţia Română de Limnogeografie, ARLG (since 2007)
- Member of Asociaţia Geomorfologilor din România, AGR (since 2014)

Moderator and Keynote speaker

No	Name of section	Place and date
1	Fluvial Geomorphology at Annual conference of the Czech Association of Geomorphologists, *Moderator*	10 – 13 March 2015, Plzeň, Czech Republic
2	Late Pleistocene and Holocene climatic variability in the Carpathian-Blakan area, *Moderator*	6 – 9 November 2014, Cluj Napoca, Romania
3	Seminarul geografic Dimitrie Cantemir. Gestiunea resurselor de apă, *Moderator*	17 – 19 October 2014, Iasi, Romania
4	Exercises of geomorphometry for identifing and analyzing glacial cirques in the Carpathians at Mountain observatories. A global fair and workshop on Social-Ecological Systems, *Moderator*	16 – 19 July 2014, University of Nevada, Reno, USA
5	Seminarul geografic Dimitrie Cantemir. Gestiunea resurselor de apă, *Moderator*	18 – 20 October 2013, Iasi, Romania
6	Climate change in the Carpathian-Balkan region during Late Pleistocene and Holocene	9 – 12 June 2011, Suceava, Romania

Scientific community services

Since 2011 the candidate has established the international journal ***Georeview*** (www.georeview.ro) as a continuation of the regional journal *Scientific Annals of "Ştefan cel*

Mare" University. Geography series and currently acts as the editor-in-chief of the aforementioned journal.

Marcel Mîndrescu is guest editor for the Web of Science journal *Quaternary International* for which he has lead the publication of a special issue dedicated to climate change in the Balkan-Carpathian area (vol. 293/ April 2013) and is currently working for the second volume. He is also member of the editorial board of international journals such as *Acta Scientiarum Polonorum* and *Georeview*.

The candidate has been a reviewer for several international Web of Science journals: *Central European Journal of Geosciences, Quaternary Science Reviews, Lakes & Reservoirs: Research and Management, Quaternary International, The Holocene.*

Research projects

Project director:

- Climate Variability Recorded by Glacial Deposits and Lake Sediments (2012-2015) (PN-II-RU-TE-2012-3-0386)
- Exploratory Workshop: Interdisciplinarity in Geoscience in the Carpathian Basin (2012) (PN-II-ID-WE-2012-4-056)
- Climate Change in the Carpathian-Balkan Region during the Late Pleistocene and Holocene (2011, Suceava), financially endorsed by PAGES Switzerland and MRI Europe
- Late Pleistocene and Holocene climatic variability in the Carpathian-Balkan region, financed by PAGES Switzerland
- Glacial cirque development and distribution in the Romanian Carpathians. General Assembly & Congress European Geosciences Union - EGU 2008

Project collaborator

- Sciex Fellowship 13.341: NROM - Assessing climate variability and human impact based on the study of sediments and glacial deposits in Rodna Mountains, Northern Romania
- Protecting forests and livelihoods in the Romanian Carpathians through community management practices. Funded by The Trust for Mutual Understanding, USA
- Forest response to climate change predicted from multicentury climate proxy-records in the Carpathian region - CLIMFOR (EEA-JRP-RO-NO-2013-1-0204) nr. 18 SEE/2014
- Collaborator for 10 national research projects

Scientific expeditions: glacial geomorphology and glacial lake survey

- Himalaya, Nepal, Aprilie-May 2011
- British Columbia, Canada, July-August 2014

4.2 Teaching

1998 – present: "Ștefan cel Mare" University of Suceava, Faculty of History and Geography, Department of Geography

Main courses taught:

- Geomorphology
- Environmental geography
- Hydrology
- Oceanography
- Limnology/Palaeolimnology
- Glacial geomorphology
- Quaternary and Holocene chronology and palaeoclimate