Carbonates and Evaporites
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ORIGINAL ARTICLE

Karst map of Georgia (Caucasus region) scale: 1:1,500,000

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Abstract
Karst landscapes develop in soluble rocks, such as carbonates and evaporates, but also in various types of rocks that develop pseudokarst features. The main aim of this work is to introduce a new karst map of Georgia (scale: 1:1,500,000) presenting karst and pseudokarst features, which occupy about 17.9% (12,454 km^2) of the entire territory of the country and include over 1500 known caves. We distinguish two types of karst features—karst (developed in carbonate rocks) and pseudokarst, and also five subtypes, mainly based on their lithology. About 10.2% (7120 km^2) of the country is occupied by karst (carbonate rocks), and about 7.7% (5334 km^2) of the country is occupied by pseudokarst features. This karst map of Georgia will provide important assistance to local and foreign researchers interested in studying Georgian karst features.

Keywords Carbonate rocks · Karst · Pseudokarst · Limestone · Georgia

Introduction

Georgia is a mountainous country located in the Caucasus region, between Russia, Turkey, Armenia, and Azerbaijan (Fig. 1). As found in many countries in the world, Georgia is home to multiple, widespread karst massifs with well-developed karst areas and their associated landforms (Tsikarishvili et al. 2010; Asanidze et al. 2017a).

Different types of karst and pseudokarst features exist in abundance, due to the tectonic influences, nature of the bedrock, geologic structure, and hydrological complexity of the area, including both hypogenic and epigenic caves (Gunn 2004; Palmer 2007; Ford and Williams 2007).

The dominant factors influencing the development of karst landforms in Georgia are as follows: lithological and structural conditions of the rocks, climatic factors, and topography, all of which are basic foundations important for karst development (White et al. 1995; Palmer 2007; De Waele et al. 2009; Stokes et al. 2010).

Karst landscapes are particularly well developed in western Georgia (Asanidze et al. 2017a, b). They form a continuous belt (2–35 km wide) stretching 325 km in length from the Psou River to the Ertso Lake vicinity (Asanidze et al. 2017c).

The vertical distribution of karst in Georgia starts from sea level and extends to the absolute elevation of 2757 m (the Speleologists Peak, Arabika Massif, western Georgia). The karst features are relatively less intensely developed in other regions of Georgia, because of the lack of carbonate rocks and less favorable climatic conditions (Maruashvili 1973; Lezhava 2015).

Karst in the Greater Caucasus Range is characterized by numerous rivers that cross the massifs dividing them into tens of isolated areas separated by erosive gorges (Tintilozov 1961; Kipiani 1974). Fragmentation into larger and smaller size karst massifs is a characteristic of the karst landscape of Georgia (Tintilozov 1976). Karst landscapes in Georgia are characterized by very frequent and deep erosion that dissects the karst areas. This has a significant impact on the morphological and hydrogeological characteristics of the entire karst belt. Such intense dissection of the karst belt is caused by its location in the peripheral part of the continuing uplift zone where substantial erosion processes have taken place and are still intensely underway (Lezhava 2015).

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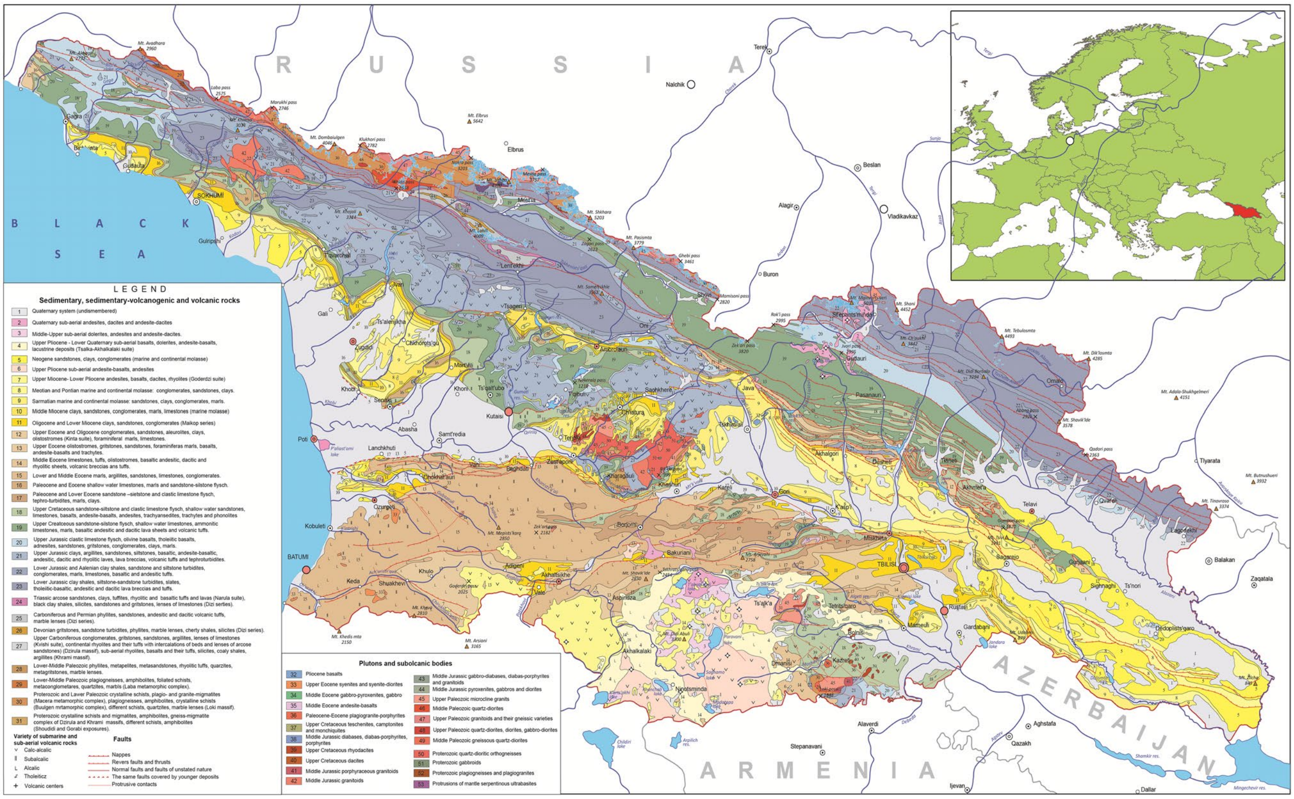

Fig. 1 Geological map of study area (Georgia), located in the Caucasus region (after Gudjabidze 2003)

Karst geology

The limestone belt of Georgia is located between the folded system of the southern slope of the Caucasus and the Block of Georgia according to the tectonic evolution of Georgia (Gamkrelidze 1964) and, as a result, presents as both orogenic and platform karst areas that are distinguished by different conditions of karstogenesis.

In the peripheries of the Caucasus, the limestone massifs are involved in the typical high-amplitude uplifting of the mountainous system of the Caucasus, and the hillock belt bounded from the north of the Kolkheti Lowland that was subjected to relatively weak movements (uplifting); in addition, tectonic stability was characteristic for certain parts of the lower altitude karst region.

In the Dzirula Massif, Duripshi Plateau, Askhi Massif, Maidan Plateau, and some regions of spreading within Georgia's block, the line of karst massifs and limestone layers is almost horizontal, and karst rocks are predominantly sloped at an angle of 20°–30° in other orogenic sections of the karst provinces (Maruashvili 1973; Tintilozov 1976).

In tectonic terms, it should be noted that the prevailing distribution in the karst belt of Georgia has linear anticlinal and synclinical folds common of the Caucasian chain and the disjunctive dislocations play a subordinate role. The aforementioned fact is related to the relatively weak occurrence of vertical fractures in the mountainous limestone regions of Georgia (Tintilozov 1976). Nevertheless, there are a number of karst massifs (Bzipi, Arabica, Migaria, Aksi, Kudaro-Buba and Racha Ridge) with significant extents of faulted, tectonic dislocations with a wide distribution of karst shafts and voids.

The Zemo Imereti Plateau (central Georgia) contrasts greatly, as it is the only karst area containing a platform structure in the whole Caucasus region (Lezhava 2015). Here, the karstification is mainly represented by subhorizontal caves associated with the widely distributed fractures in the layers of the Upper Cretaceous limestones stretched along the solid basement rock of Dzirula (Lezava et al. 2015).

The folds of the carbonate sediments of the southern slope of the Caucasus are characterized by complex stratigraphic, lithological, and tectonic conditions. The Upper Jurassic (Lias), Cretaceous and Paleogenic carbonate sedimentary rocks are karstified. All the tiers and subtiers of the Cretaceous system contain voids, most of which are of significant volume.

Very often, in the geological section of the Cretaceous rocks, the layered (thin, medium, and thick layered) and massive karstified units alternate. Their total width ranges from 1200 to 2600 m in individual regions. Such a wide expanse of carbonate rocks, along with other contributing factors, leads to significant complexity and diversity of hydrogeological and speleological characteristics, while the regions formed in areas with relatively narrow karst rocks (Kudaro-Buba, central Samegrelo and other regions) are characterized by less kartification (Kipiani 1974; Lezhava 2015).

Within the individual massifs, the carbonate units are underlain by Bajocian and Bathonian sandy-clay and volcanogenic sediments, which are located deep beneath local drainage level, and contribute to the activation of karst processes, circulation of karst waters at great depths, and the formation of hydrogeological basins containing karst groundwater.

The stratification and massiveness of limestone units, along with their dip and strike and other favorable geologic conditions, lead to a number of essential factors contributing to the morphology of both surface and underground karst forms. For example, the caves that are formed in the layered and inclined limestones are characterized by clear stairstepping base levels and frequent variation of the cave's main direction. In addition, in the caves of Kelasuri, Tkibula-Dzevrula, Mtiskalta, and others, the height of individual passages vary from 1–2 m to 26 m which are caused by the alternation of differentially dissolved layers of fractured limestone.

It should be also noted that the formation of karst caverns on the layered limestone massifs and the movement of underground waters are often controlled by the strata flatnesses and the tectonic fractures formed along those bedding planes; an example is Zemo-Imereti, Okriba-Argveta, and other caves.

Unlike the regions of thinly layered limestones, the caves generated in massive limestones are characterized by high vertical and sometimes cascading stairways of passages. For example, the Snezhnaya abyss has a vertical shaft of 165 m (Tintilozov 1976).

A similar situation is found in the Kudaro-Buba, Rikhva and other massifs that are not only associated with the lithological differences of the rocks, but also with the nature of their fracturing. Sometimes, even in the massive limestones, the horizontal and inclined caves are formed with profiles that are mainly related to the corresponding fracture patterns.

The study of the chemical composition of carbonate rocks in Georgia confirms the known fact that, in the case of favorable conditions, karst formation is more intensive in the rocks in which the percentage composition of insoluble materials is insignificant (Tintilozov 1976; Lezhava 2015). Mostly, it explains the concurrence of intensely karstified surfaces of the karst regions of Georgia (separate areas of the Arabika massif, Rikhva, Bzipi Range, Gumista-Psirtskha, Askhi, etc.) with the sections of relatively pure carbonated rocks of the Lower and Upper Cretaceous.

Climatic aspects

The mountain karst relief of the southern slope of the Caucasus is distinguished by significant vertical and horizontal fragmentation, alternation of meridional and latitudinal gorges and mountain ranges, and with the variable orientation of the slopes and their uneven distance from the Black Sea. These peculiarities together with the general atmospheric circulation processes that prevail in different seasons in the limestone massifs of Georgia create a great diversity of daily and annual courses of the air temperature and distribution of precipitation, which is sharply reflected on the intensity of karst processes.

In the karst belt of Georgia, like in other mountainous regions, the amount of precipitation increases with increasing elevation. On the slopes of low mountainous massifs, which face the sea, the amount of atmospheric precipitation reaches its maximum at the altitude of 300 m. The amount of precipitation at higher elevations is somewhat reduced and again increases from 1000 to 2000 m.

The critical increase in precipitation on the smoothed crests of the limestone massifs (Bzipi, Arabika, Gumishka-Psirtskha, etc.) of western Georgia takes place at the absolute heights of 1800–2000 m, where the annual amount of precipitation varies between 1800 and 2300 mm (Chirakadze 1972).

A similar situation is presented relative to the east in the Okhachkue, Askhi, and Khvamli massifs and the Nakerala and Satsalike Ranges, the southern slopes of which are under the constant influence of marine, humid air masses.

As a result of favorable orographic and synoptic conditions, the excessive atmospheric precipitation is sometimes observed at very low hyphaeometric levels as well. For example, the annual sum of precipitation reaches 2301 mm in the Samegrelo region (village of Mukhuri, 260 m above sea level). In other favorable conditions, the activity of karst processes increases with the increase in precipitation. For example, there is an increase of chemical denudation activity from increasing atmospheric precipitation by 100 mm in the high-mountainous zone at 8 m^3/km^2 a year, while in the foothills, it is 4 m^3/km^2 a year (Pulina 1971).

The limestone massifs of Georgia receive quite a high amount of precipitation in all seasons of the year. The western section of the limestone belt is particularly distinguished with this regard, where the value of annual sum rarely is below 1500 mm both in low- and high-altitude massifs (Chirakadze 1972).

Effectiveness of atmospheric precipitation on the limestone surface depends not on the absolute values of precipitation, but on the effective amount after evapotranspiration (Tintilozov 1976). The annual value of evaporation within Georgia's limestone massif fluctuates from 815 to 470 mm up to an elevation of 3000 m above sea level. With the increase in altitude, evaporation lessens. In general, the moisture balance in the karst belt of western Georgia is quite sufficient for the active course of karst process throughout the year (Vladimirov et al. 1974).

In the limestone belt of Georgia, precipitation in the form of snow is anticipated everywhere. The thickness and duration of the snow cover is closely related to the hyphaeometric location of the area. Besides the individual exceptions, the snow cover height exceeds 1.5 m in almost every decade in the mountain belt. With the increase of the elevation of the location, due to the protection of the exposed slopes and individual area of high relief, the thickness of the snow cover significantly increases.

The aforementioned concerns the surfaces of the glacial-nival peaks of high-mountainous limestone massifs (Arabika, Rikhva, Bzipi, Okhachkue, Racha, Askhi, etc.), the karst areas of which are buried under thick snow cover during winter. It is notable that at the hypsometric levels (1644 m above sea level) of Gagra (Apkhazeti) weather station a snow cover of 1 m above sea level is common from the first decade of January to the third decade of April. The duration of snow cover at the height of 1800 m is 182 days a year, at 2200 m—196 days and at 2500 m—222 days a year (Kordzakhia 1961).

Meteorological conditions favor the emergence of thick snow cover in mountainous massifs during winter months. For example, the temperature of the coldest month (January) is − 3–5 °C within 1600–1800 m of elevation, while the average temperatures for 4 months fall below 0 °C (Kordzakhia 1961). Based on the above climatic data, we can conclude that in most of the cold period (XI–III months), the course of karst processes is likely ceased at over 1600 m above sea level, or at least has an unsubstantial effect.

The impact of the snow cover, along with unfavorable hydrometeorological conditions, significantly determines the wide distribution of underdeveloped, partially formed karst features in high-mountainous massifs.

As for the hypsometric interval below 1600 m, which corresponds to the mountain forest area, the karst processes are underway very actively throughout the year. The proof of this is not only the giant sinkholes and caves scattered throughout the southern angled slopes of the limestone massifs, but also the widely distributed features on the low mountainous surfaces (Tintilozov 1976).

Within the low elevation karst, the number of snowy days is very low; e.g. the number of snowy days at 500 m above sea level reaches 10–23 days/year, from 500 to 1000 m; it reaches 56–90 days (Kordzakhia 1961), while snowfall amount varies between 10 and 70 cm. In the mentioned hypsometric interval, the snow cover occurs several times during the winter, which is promoted by the average positive temperature of the month of January (+ 2 °C, + 3 °C).

This fact is important for the formation of low-temperature, aggressive waters, the important role of which in karst formation is well documented. Hypsometric layout of the caves on the southern slope of the Caucasus confirms our opinion. In particular, a large number (75%) of the caves currently researched in Georgia are located at 1100 m above sea level (Lezhava 2015).

Thus, the above data suggest the conclusion that the limestone massif of the southern slope of the Caucasus are provided with abundant atmospheric precipitation throughout the year, resulting in the intense and continuous processes of the karstification in medium and low elevation mountainous limestone massifs.

Data resources and methods

A geographic information system (GIS) was used to analyze the spatial distribution of the geographic information, modeling its interactions, and finding patterns and relationships in the data that may be overlooked by previously used techniques (Szukalski 2002).

GIS data layers were collected and derived from a variety of sources. The data used in our study were based on 1:200,000 scanned and geo-referenced (Projection: Universal Transverse Mercator, Geographic Coordinate System: WGS-1984) geological maps (Gudjabidze et al. 1977), as well as 1:25,000 topographical maps and aerial images. From the geological maps, zones were extracted, where all types of karst and pseudokarst features are distributed, and all the zones were grouped and analyzed. State border, coastline, major cities, and rivers were selected and digitized from a topographic map at a scale of 1:50,000.

From topographic maps, orthophoto and Google Earth imagery, regional and national speleological features were revealed. In addition, field data were also introduced into the GIS. Karst areas were selected on the base of relief forms and geology, and scientific knowledge. These were categorized and mapped into two types of karst features, and five subtypes. All these steps were performed in ArcMap 10.

Results and discussion

The Karst map of Georgia (Scale 1:1,500,000) presented in this paper is prepared from many years of field and literature research. We distinguish two types of karst features—karst (developed in carbonate rocks) and pseudokarst (developed in clays, clays and sandstones, and volcanic rocks), and also five subtypes (limestones and dolostones, and conglomerates and sandstones in carbonate rocks; clays, clays and sandstones with gypsum content, and volcanic rocks as pseudokarst), mainly based on their lithology. We also identify distribution areas of karst and pseudokarst features. Figure 2 shows the areas with karst and pseudokarst features in Georgia.

Spatial statistics were calculated from all areas of Georgia. About 17.9% or 12,454 km^2 of the entire territory of Georgia is occupied by karst and pseudokarst features. About 10.2% (7120 km^2) of the country is occupied by karst (carbonate rocks). Within this category, 9.3% (6517 km^2) is composed of limestones and dolostones, and 0.9% (603 km^2) is conglomerates and sandstones with carbonate cement. About 7.7% (5334 km^2) of the country is occupied by pseudokarst features. Within this category, 0.8% (523 km^2) is composed of clays, 1.0% (694 km^2) is clays and sandstones with gypsum content, and 5.9% (4117 km^2) is volcanic rocks with potential pseudokarst features).

Karst features are primarily developed in carbonate rocks (limestones and dolostones, and conglomerates and sandstones with carbonate cement). They are mainly of Cretaceous age, and subordinately of Upper Jurassic and Lower Paleogenic ages; however, Upper Jurassic and Paleogenic carbonate rocks are mostly thin layered and less karstified. Lower Cretaceous limestones and dolostones are very common and occupy significant territories of Georgia. Lower Cretaceous (Urgonian) limestones are distinguished by pure chemical composition and mass. The intensity of karst processes is especially dominant in these areas, where the capacities of limestone dissolution reach significant values.

Conglomerates and sandstones with carbonate cement are mainly present in western Georgia in the Central Odishi and Duripshi Plateaus (Samegrelo and Apkhazeti regions), where caves of significant size develop. For example, Kalichona Cave (length is 830 m) is the longest horizontal cave in the Caucasus region developed in conglomerates (Tatashidze et al. 2009). In some areas, the conglomerates are represented by limestone fractures, and in some areas by mixed lithologies of limestones and insoluble rocks (e.g., porphyrites), although this does not prevent the development of karst features.

In Georgia, the morphological characteristics of the caves developed in conglomerates are wide entrances to the cave, erosive terraces, and poorly developed speleothems (Lezhava 2015). The pseudokarst features developed

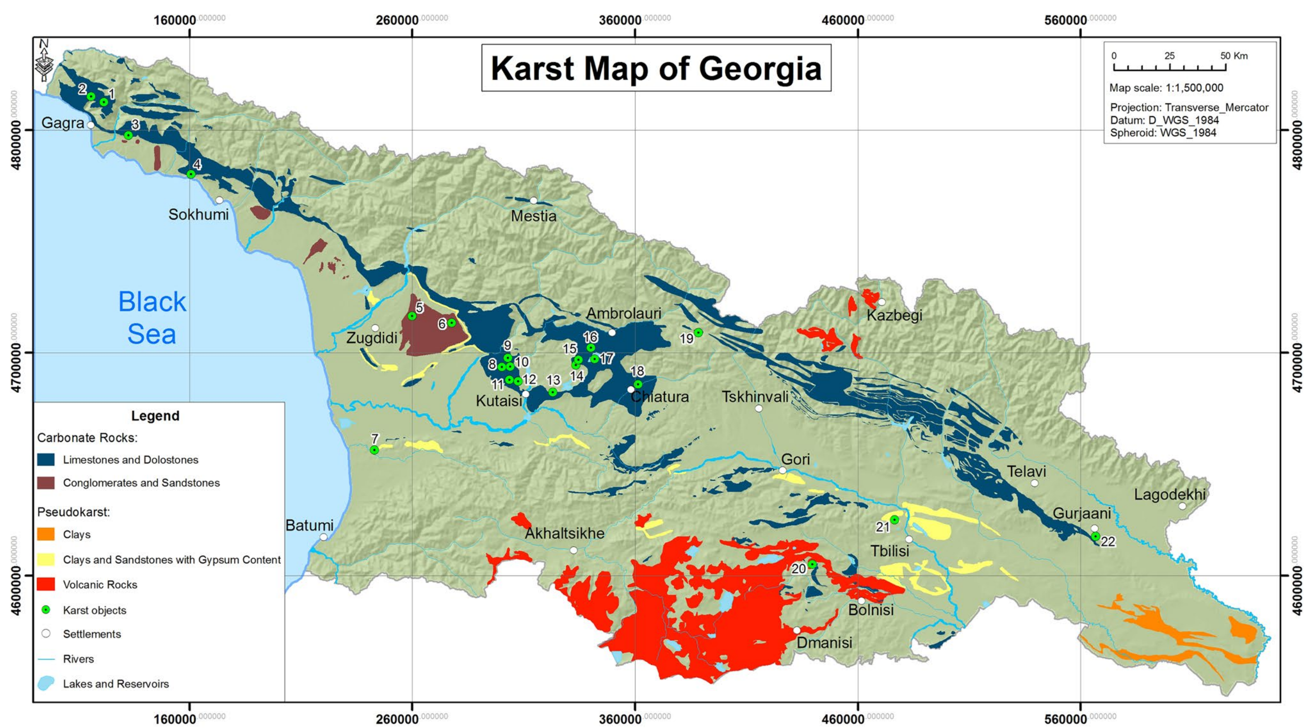

Fig. 2 Distribution of karst and pseudokarst features in Georgia. The areas depicted by green dots on the map represent both regional and national speleological features (Table 1). However, it should be said that the number of such features in Georgia is likely higher than those represented in the karst map of Georgia

Table 1 The known regional and national speleological features in Georgia

	Name	Description	Karst type
1	Veryovkina	The deepest cave in the world (2204 m)	Limestones and dolostones
2	Krubera	Second deepest cave in the world (2197 m)	Limestones and dolostones
3	Mchishta Vaucluse	The biggest karst Vaucluse in the Caucasus region (max. 197 m^3/s)	Limestones and dolostones
4	New Athos	First show cave in the Caucasus region	Limestones and dolostones
5	Kortskheli	The longest cave in the Caucasus region (790 m)	Sandstones
6	Kalichona	The longest cave in the Caucasus region (830 m)	Conglomerates
7	Chochkhati	One of the rare horizontal caves	Clays and sandstones with gypsum content
8	Ghliana	The biggest bat's colony in Georgia	Limestones and dolostones
9	Satsurblia	Active speleotherapy cave in Georgia	Limestones and dolostones
10	Prometheus	The most visited show cave in the Caucasus region. Also, it is the longest cave in Georgia (over 15 km)	Limestones and dolostones
11	Tetra	First speleotherapy cave in the Caucasus region	Limestones and dolostones
12	Sataplia	Show cave with historical interest (footprints of dinosaurs)	Limestones and dolostones
13	Tsutskhvati	Cave with 13 levels	Limestones and dolostones
14	Tskhrajvari	Important paleontological cave (*Ursus spelaeus*)	Limestones and dolostones
15	Muradi	Interesting cave with beautiful examples of pool speleothems	Limestones and dolostones
16	Nikortsminda	Cave with ice	Limestones and dolostones
17	Shaori Polje	The biggest karst polje in the Caucasus region	Limestones and dolostones
18	Dzudzuana	The ancient linen fiber (thread) place in the world	Limestones and dolostones
19	Tsona	Important paleontological cave (human's former dwelling)	Limestones and dolostones
20	Khorkhebi	Cave with ice	Volcanic rocks
21	Lisi	One of the rare vertical caves	Clays and sandstones
22	Vejini	Small beautiful horizontal cave	Clays

in clays, clays and sandstones with gypsum content, and volcanic rocks with potential pseudokarst features are distributed over considerable areas, both in eastern and western Georgia; however, such pseudokarstic areas do not contain cave systems of significant size, but only contain some surface pseudokarst morphologies.

It is noteworthy that most of the karstic caves of Georgia are subhorizontal, or inclined, cavities that can be explained mainly by the fact that the subhorizontal alignment of bedding planes along with the limestone massifs creates favorable geomorphological and hydrogeological conditions for the formation of caves. Indeed, a significant part of the caves studied on the southern slope of the Caucasus are originated and developed in layered limestone massifs (Lezhava 2015).

Locally, very impressive karst features (surface and subsurface) have developed, such as sinkholes, dolines, springs, waterfalls, caves, speleothems, and many others (Fig. 3).

Most of the caves in Georgia are formed in limestones and dolostones, and also in conglomerates and sandstones with carbonate cement. Currently, the total number of traced and partially studied caves in Georgia is over 1500 (Asanidze et al. 2017d). The total length of documented caves is 275 km and the greatest depth is over 80 km. Most of the researched caves are gathered at plateau-shaped and inclined surfaces, or are opened on the slopes of river gorges, and in the limestone massifs (Tatashidze et al. 2009). According to their altitudinal distribution, two categories of karst relief are distinguished in Georgia, including: (1) foothill and intermontane limestone massifs (up to the height of 1000 m above sea level); and (2) medium- and high-mountainous limestone massifs (over 1000 m above sea level).

Foothill and intermontane limestone massifs (up to a height of 1000 m above sea level) are distinguished with horizontal, or gently sloped, karstified massifs and simple hydrodynamic profiles of relatively small capacity, with a wide distribution of subhorizontal and horizontal caves, as well as the caves which often have formed in stages (Kipiani 1974). It is in the subhorizontal layers that one of the largest caves in Georgia—Akhali Atoni is formed, which is also the first show cave in the Caucasus region. In contrast, the Tsutskhvati multi-storey cave complex is presented in 13 levels, and is also an important archeological site in Georgia. Deep caves are distributed in the mid- and high-altitude mountainous massifs of the karst belts of Georgia. Some of the high-mountain limestone massifs also contain glaciokarst features (Sendra and Reboleira 2012; Klimchouk 2012).

It is noteworthy that four out of ten of the world's deepest caves are located in Georgia (Asanidze et al. 2017e).

Fig. 3 Photographs of Georgia's karst features. **a** Spherical examples of pool speleothems in Muradi cave, which could be formed from water level fluctuations over time. **b** Pool calcite speleothem deposited subaqueously at multiple places in Muradi cave. X-ray diffraction (XRD) analysis confirmed these are 100% calcite deposits (Asanidze et al. 2017a, 2018). **c** Karst features from central part of Georgia. **d** Classical karst doline full of water from western part of Georgia

Currently, the first, second, third, and fourth deepest caves are distributed between Veryovkina (2204 m), Krubera (2197 m), Sarma (1830 m), and Illyuzia-Snezhnaya-Mezhennogo (1753 m)—all located in the high mountainous limestone massifs of Georgia. Among these, Veryovkina Cave is currently the deepest cave in the world (Demidov 2017). Medium- and high-mountainous limestone massifs located within the limestone belt of Georgia are distinguished by the diversity of archeological and paleontological monuments. The dwellings of ancient humans in Georgia (Lower Paleolithic) are found in about 20 caves. It is notable that within the karst belt of Georgia (central part of Georgia—Dzudzuana Cave), the world's oldest (34,000 years) flax fiber was discovered (Bar-Oz et al. 2008).

Conclusion

From studying the karst in Georgia, this research contains significant information, including the following findings: (1) we identified two types of karst features: karst (developed in carbonate rocks) and pseudokarst; (2) we identified their distribution areas which are important and essential in studying the karstology and speleology of Georgia; (3) we classified five subtypes: limestones and dolostones and conglomerates and sandstones in carbonate rocks; and clays, clays and sandstones with gypsum content, and volcanic rocks as pseudokarst.

In total, the karst landscape (karst and pseudokarst features) occupies 17.9%, or 12,454 km^2, of the entire territory of Georgia. Therefore, the authors of this work hope that the karst map of Georgia will be practically applicable in the future and will provide important assistance both to local and foreign researchers interested in studying Georgian karst.

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