

Article

Geology of the Mulkhura River Valley, Georgian Caucasus

Roman M. Kumladze ¹, Levan G. Tielidze ^{2,3,*} , Mamia Gamkrelidze ¹, Simon J. Cook ⁴  and Anzor Giorgadze ⁵

¹ Mapping Division, Department of Geology, National Environmental Agency, Ministry of Environment Protection and Agriculture of Georgia, 0102 Tbilisi, Georgia

² Securing Antarctica's Environmental Future, School of Earth, Atmosphere and Environment, Monash University, Clayton, VIC 3800, Australia

³ School of Natural Sciences and Medicine, Ilia State University, 0162 Tbilisi, Georgia

⁴ Division of Energy, Environment and Society, University of Dundee, Dundee DD1 4HN, UK

⁵ Department of Applied Geology, Faculty of Mining and Geology, Georgian Technical University, 0175 Tbilisi, Georgia

* Correspondence: tielidzelevan@gmail.com

Abstract: Geological mapping provides vital information about the structure, evolution, natural resource potential, and geohazards of a specific area. The role of geological mapping is especially valuable for mountainous countries like Georgia. In this context, we present a geological map of the Mulkhura River Valley in the Georgian Caucasus (43°3' N, 42°52' E) with accompanying cross-sections at a scale of 1:30,000, covering approximately 220 km². The geological information in the map is based on a comprehensive review of previously published geological maps and literature, combined with original analysis of satellite imagery and hitherto unpublished field data. The extensive spatial coverage and accompanying cross-sections provide detailed insights into the structure of the region. This new map will serve as a foundation for future geological research, hazard management, and resource exploration in the area, as well as for geoconservation to develop the national geotourism industry in this region.

Keywords: geological mapping; Caucasus mountains; Georgian Caucasus; geohazards; natural resources; Mulkhura river



Citation: Kumladze, R.M.; Tielidze, L.G.; Gamkrelidze, M.; Cook, S.J.; Giorgadze, A. Geology of the Mulkhura River Valley, Georgian Caucasus. *Geosciences* **2024**, *14*, 341. <https://doi.org/10.3390/geosciences14120341>

Academic Editor: Roberta Somma

Received: 1 November 2024

Revised: 6 December 2024

Accepted: 10 December 2024

Published: 12 December 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Geological mapping of mountain belts forms the basis for many other applied lines of research including understanding the geological structure of continental collision zones and regional geological evolution [1]; the potential for use or extraction of natural resources, such as geothermal energy or ore deposits [2]; and in managing geohazards, such as landslides or floods, which are strongly influenced by lithology and geological structure [3–6]. The Greater Caucasus Mountain Range is a region that is rich in raw materials and natural resources [7,8], yet there is a dearth of detailed geological study, including the generation of modern geological maps [9,10]. The Mulkhura River Valley was chosen for this study, not only for its accelerated glacier recession [11], which has revealed new areas of unstudied bedrock and superficial sediments, but also due to emerging hazards such as landslides, debris flows, and glacial lake outburst floods (GLOFs) [12,13]; the frequency and magnitude of such events may be affected by climate change [14,15]. In this study, we integrate details from existing geological studies with new observations to generate a 1:30,000-scale geological map of the Mulkhura River Valley. New details concern the accurate placement and description of geological strata, and magmatic and metamorphic complexes. This work represents the first detailed geological map of the Mulkhura River Valley in the central Greater Caucasus, which will serve as a foundation for future geological investigations in the region. Our goal is to focus on the lithostratigraphic characteristics of the Mulkhura River Valley to enhance our understanding of the distribution, deformation history, and structural framework of the central–southern section of the Greater Caucasus.

2. Study Area

The Greater Caucasus straddles Russia, Georgia, and Azerbaijan, and is the primary mountain range in the Caucasus Mountains, extending roughly 1100 km from west-northwest to east-southeast [16]. It runs from the Taman Peninsula on the Black Sea to the Absheron Peninsula on the Caspian Sea, starting near Sochi on the northeastern Black Sea coast and stretching almost to Baku on the Caspian Sea (Figure 1).

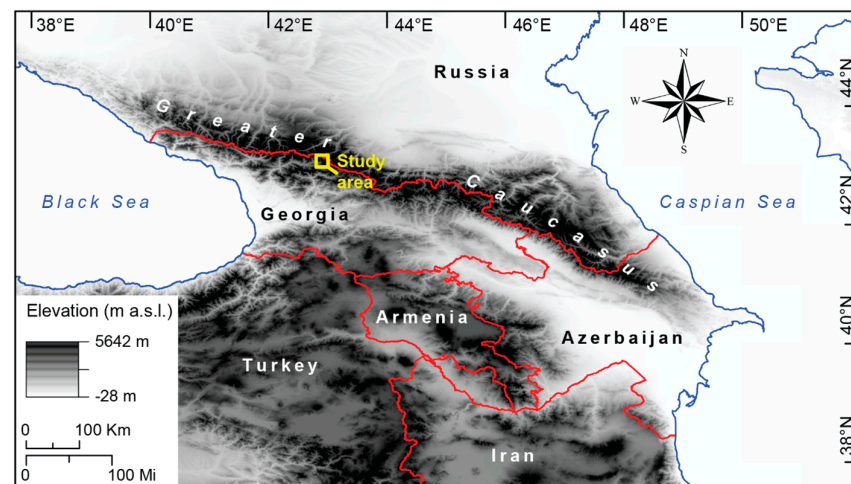


Figure 1. Location of the Mulkhura River Valley relative to the Greater Caucasus (source: ASTER DEM, 2011).

Geologically, the Greater Caucasus is characterized as a large anticline (an upstanding fold) that was uplifted along the edge of the Alpine geosyncline approximately 25 million years ago and has since undergone further erosion and uplift. Moreover, the study area represents the pro-wedge of the Greater Caucasus and is one of the most important examples of the collision-driven far-field deformation of the Arabia–Eurasia convergence zone [17]. In the western region, hard, crystalline metamorphic rocks, such as schists and gneisses, along with granites older than 200 million years, are prominently exposed. In contrast, the eastern region features softer, clayey schists and sandstones that date back to the Early and Middle Jurassic period, about 200 to 160 million years ago [18–21].

The Mulkhura River Valley is located within the central uplifted part of the fold and thrust belt of the Greater Caucasus and Kazbegi–Lagodekhi and Mestia–Tianeti zones of the southern slope of the Greater Caucasus. The region presents a variety of geological complexes: sedimentary rocks, including flysch pelagic sediments; magmatic rocks, including intrusions and dykes; and metamorphic rocks, including metamorphic grades from slates to gneisses and migmatites. More than a quarter (27%) of the mapped area is currently covered by alpine and rock glaciers [22,23] (Figure 2).

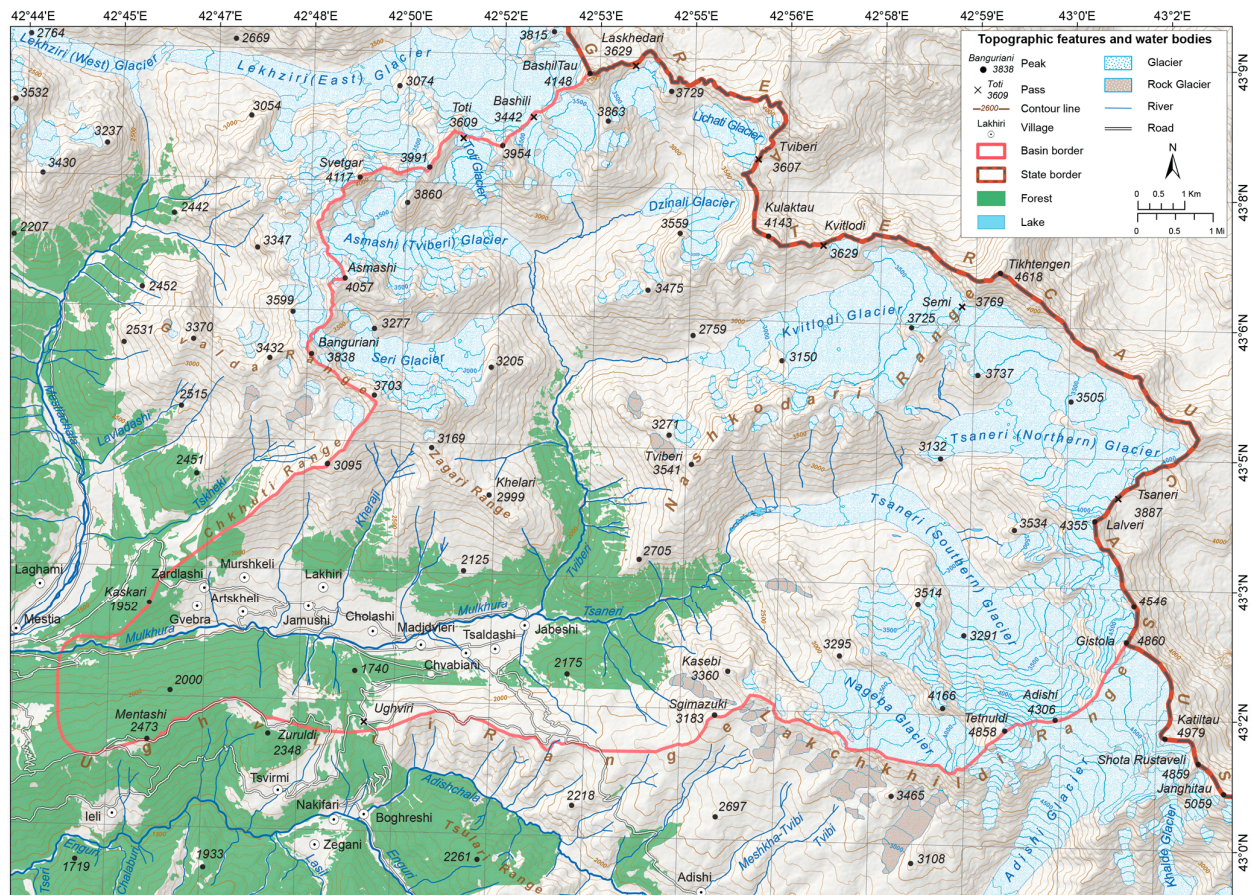


Figure 2. Physical map of the Mulkhura River Valley (source: ALOS PALSAR DEM).

3. History of Geological Studies of the Study Area

For many years, studies of the geological condition of the Greater Caucasus and its southern slope have been a field of interest both from a regional–geological point of view and for the purpose of mapping and studying mineral resources.

The first geological studies of the region were undertaken in the 1850s by specialists invited from abroad. These included G. Nota, E. Krega, G. Abikh, E. Fournier, S. Simonovich, L. Batsevich, A. Sorokin, and others. Their work led to the need to conduct more detailed geological studies of the region [9,10].

From the 1920s to 1980s, geological studies in the Caucasus region were carried out both by Georgian specialists and with the participation of representatives of the Union Academy of Scientists, such as A. Janelidze, B. Meffert, K. Gabunia, I. Kacharava, I. Kakhidze, A. Tvaltchrelidze, K. Smirnov, P. Gamkrelidze, M. Rubinstein, and N. Bendukidze. Their work included detailed study of the regional stratigraphy, tectonics, petrology, lithology, and structure of the area [9,10,24].

By the 1980s, sets of geological maps of different scales (1:500,000; 1:200,000; 1:50,000) were compiled (geological, tectonic, mineral resources, hydrogeological, and quaternary sediments) by P. Gamkrelidze, G. Gujabidze, I. Buachidze, D. Tsereteli, V. Edilashvili, Sh. Geguchadze, L. Gvineria, etc. [9,10,24,25]. Moreover, detailed regional studies by Gamkrelidze and Shengelia [26] provided new geological and petrological data that significantly changed existing ideas about the age, interrelationship, and composition of various metamorphic and magmatic complexes constituting the pre-alpine foundation, and the polycyclic regional metamorphism of the territory of Georgia, including the Mulkhura River Valley and its surrounding area. Detailed studies of the stratigraphy, lithology, and lithoformation of the Jurassic sediments were discussed by [27].

4. Methods

Geological mapping of the Mulkhura River Valley was performed at 1:30,000 scale (Figure 3. See also main map in the Supplementary Materials). Several geological reports of the Racha–Svaneti regions, compiled between 1948 and 1984, were used as baseline data in the process of generating a new, revised geological map of the study area. Large-scale topographic maps (at 1:25,000 and 1:50,000 scale) from the 1960s, in combination with satellite imagery (Sentinel 2 and Planet), were used to identify and map topographic features such as rivers, mountain summits and passes, and contour lines that provide topographic and physiographic context. Google Earth Pro software (Version 7.3.6) was also used to cross-reference features from 3D visualizations [28]. The map was created through digitization of key geological and geographic features with ArcMap 10.8.2 using the Universal Transverse Mercator (UTM) (WGS 84 Datum, 38N zone) coordinate system. The 12.5 m resolution ALOS PALSAR Digital Elevation Model (DEM) was employed to provide digital topographic context, and to aid in landform identification in areas of complex terrain [29–32]. The geological map of the Mulkhura River Valley also includes two geological cross-sections that were mainly based on our field observations (see the main map). The final version of the map was prepared using Adobe Illustrator 2021, which offers a rich selection of design tools for communicating the geological diversity and complexity of this region [33].

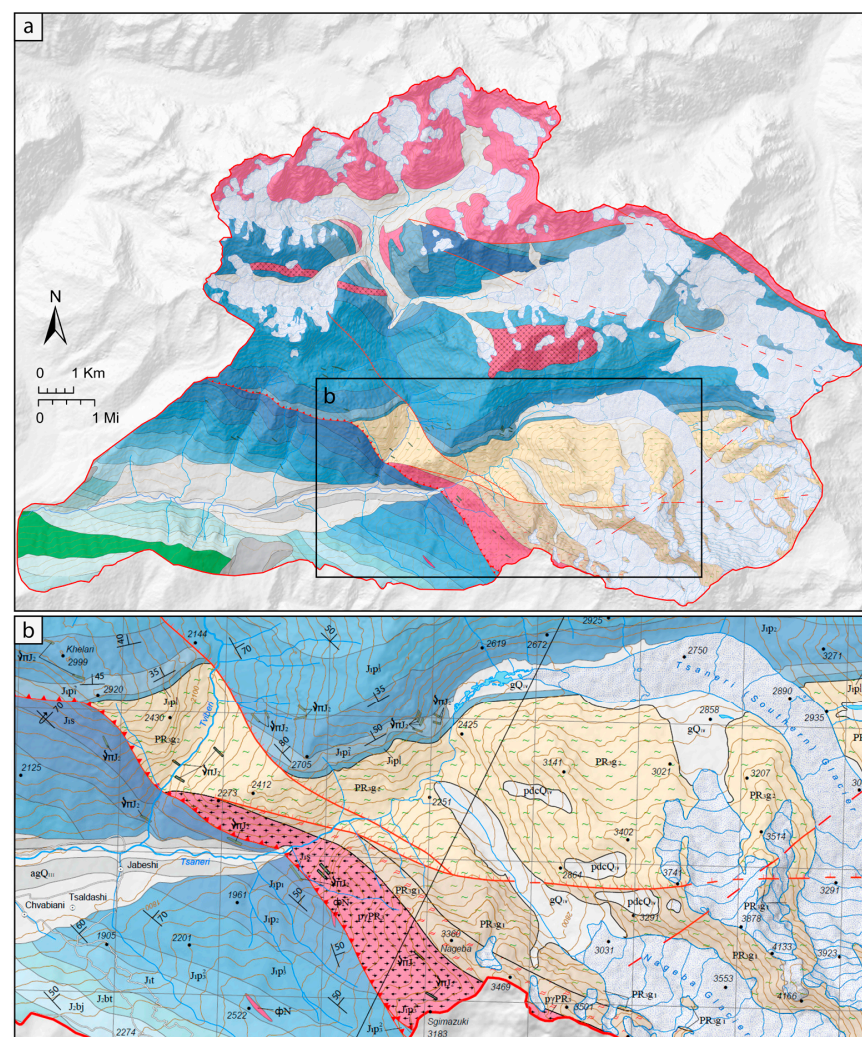


Figure 3. (a) Simplified final map. For detailed information, please see the main map. (b) Close view of the detailed mapping. See main map in the Supplementary Materials for legend description.

5. Stratigraphy

In the following sections, we provide a detailed description of the stratigraphy of the Mulkhura River study area. However, the oldest sediments in the Mulkhura River Valley are defined as of the Upper Proterozoic age, Bulgeni series, also known as the “Gvandra” suite, which is represented by mica schists, granitoids, and migmatite–gneiss-type complexes. These lithologies are the main component of the metamorphic complex of the Greater Caucasus Range. Main complexes of sedimentary rocks are located within the Kazbegi–Lagodekhi and Mestia–Tianeti zones. The first of these (Kazbegi–Lagodekhi zone) is represented by Lower and Middle Jurassic clayey-terrigenous flysch and turbidites, and base conglomerates and gravelites in the lower part, while the second (upper) part (Mestia–Tianeti zone) is presented by the Upper Jurassic–Lower Cretaceous turbidites, and flysch-like and pelagic clayey-marl-like sediments.

The oldest molasse sediments found in the region are of the Upper Carboniferous age, and known as the Sand Suite (Kvishi Suite).

There are no Upper Cretaceous, Paleogene, or Neogene sediments in the study region. During the Alpine orogeny, these sediments were eroded and transported to more distant sedimentary basins beyond the study area [26]. However, the above-mentioned Proterozoic–Lower Cretaceous rocks are covered by Quaternary sediments and modern-day glaciers. Quaternary sediments are widespread throughout the region and are mostly characterized as being of glacial, alluvial, lacustrine, diluvial, proluvial, and colluvial genesis.

5.1. Upper Proterozoic

Within the Upper Svaneti territory, Upper Proterozoic rocks are represented by Makeri and Bulgeni metamorphic complexes, which, originally, were sedimentary and volcano-sedimentary rocks. However, only the lower part of the Bulgeni metamorphic complex is represented within the study area. This complex is also known as “Gvandra” Suite, which is divided into two sub-suites.

The lower part of the lower Gvandra suite. Outcrops of rocks of this suite are visible in the northern slope of the Lakchkhildi Range, within partly outcropped parts around the Kasibi Glacier. These rocks are typically migmatized, have a thickness of 20–30 m, and are bordered by Proterozoic plagiogranites and plagiogneissic rocks of the Sgimazuki crystalline massif. The rocks from this suite are generally represented by epidotic amphibolites, with reduced quantities of biotitic, granitic, pyroxenic, and quartz amphibolites, and mixed sub-facies. Typically, these rocks are dark gray and dark green in color with a mostly nematoblastic texture. There is a large quantity of amphibole (hornblende, cummingtonite, actinolite), plagioclase, and epidote group minerals. Quartz, granite, diopside, carbonates, and biotites have reduced quantity, but in some places they reach up to 15–20%. Sphene, apatite, and others are found as accessory minerals [26].

There are granitoid lenses and diabase and porphyrite dykes in different places of crystalline schists. Migmatites are spread within the contact zone of crystalline schists and granitoids and are represented by mica, mica–granitic and mica–andalusite schists. Moreover, leucocratic migmatites are represented by plagioclase, quartz, and microcline; in some cases, there are high-temperature minerals as well. Mineral paragenesis of these rocks shows that they experienced garnet-type regional metamorphism or high-temperature green-schist and epidotic–amphibolitic-type metamorphism [26].

The upper part of the lower Gvandra suite is directly continuous with the metamorphites of the lower part and is characterized by different facial–metamorphic-type crystalline schists with terrigenous content. Rocks of this suite are well-exposed in the lower part of the Tviberi and Tsaneri River Valleys, but also fragmented ones within the territory of the Tetnuldi and Tsaneri Glaciers (Figure 4). These rocks are not well studied because they are hard to access, but their main petrographic–chemical and metamorphic facies are well-known. There is a high quantity of metapelites, chlorite–muscovite schists with interlayers of metabasites and meta-psammities with restricted presence of graphitized schists and quartzites [26].

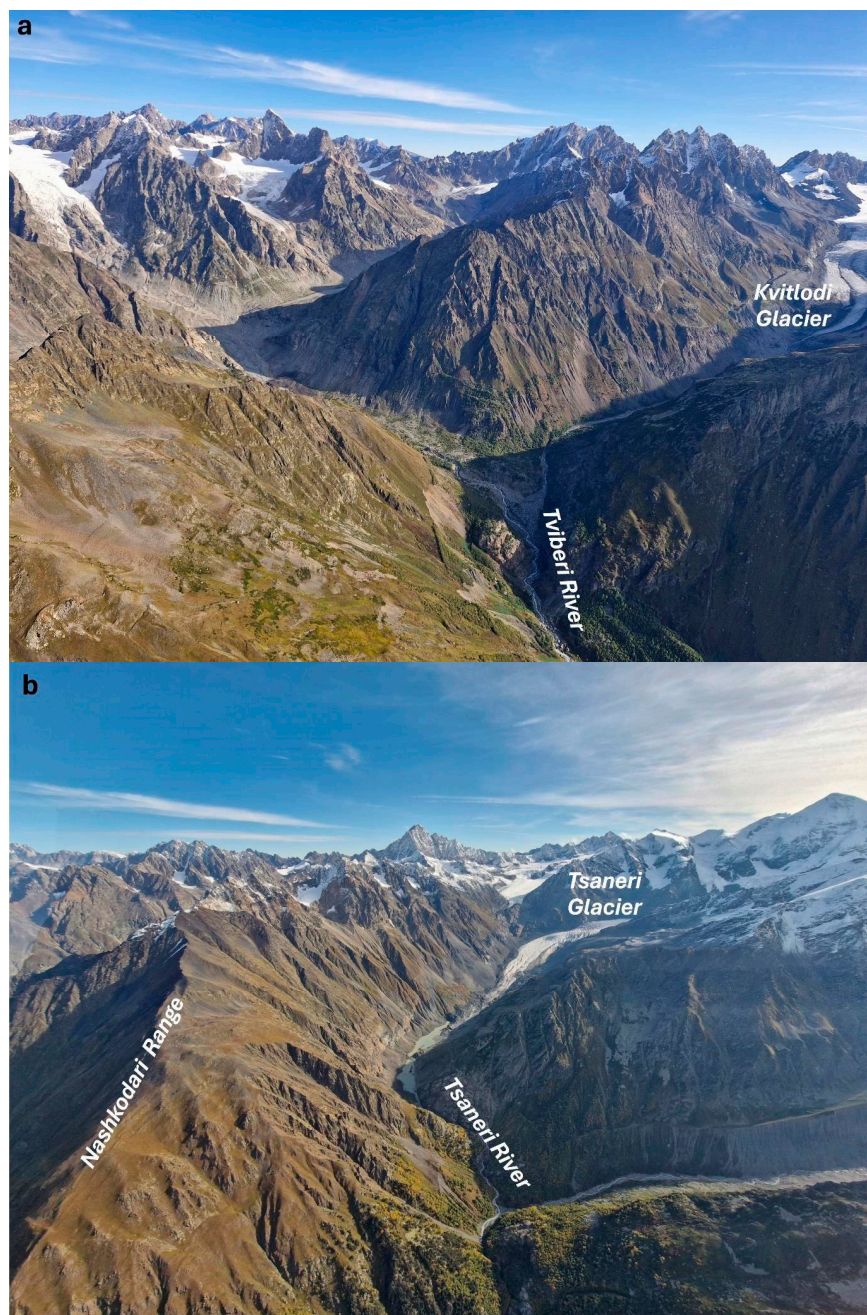


Figure 4. (a) Tviberi and (b) Tsaneri River Valleys, Mulkhura River basin (photos by L. Tielidze, September 2024).

K_2O -rich rocks are widespread and are represented by chlorite, muscovite, biotite, quartz, and plagioclase. The texture of these rocks is thin-skinned, and the structure mainly lepto-granoblastic, or sometimes porphyroblastic. The dominant minerals comprise chlorite, muscovite, albite, and quartz. Secondary minerals include garnet, biotite, and andalusite; accessory minerals include zircon, graphite, tourmaline, and apatite. K_2O -rich metapelites are mainly represented by quartz–albite–chlorite schists and biotite–epidote–garnet facies with apatite and zircon as accessory minerals. Moreover, CaO_2 -rich metapelites are represented by non-muscovite and non-quartz–albite–chlorite schists and their epidotic, carbonate, and biotitic–actinolitic facies. Their structure is porphyritic while their texture is schistic. Primary minerals are chlorite and albite (50–60%); secondary minerals are epidote and actionolite; accessory minerals are represented by sphene, titanomorphite, and other ore minerals.

Metapelites of highly saturated K_2O have limited presence and are represented by microcline–muscovite–plagioclase–quartz and microcline–garnet–muscovite–chlorite–plagioclase–quartz schists. Accessory minerals are represented by zircon, apatite, and other ore minerals. For this suite, it is typical to have lenses of quartzite, with different facies containing chlorite, muscovite, albite, etc. The thickness of the upper part of the Gvandra Suite varies from 250 to 300 m, but generally the thickness of the whole Gvandra Suite reaches up to 500 m. The age of the Gvandra Suite, as determined by absolute dating of rocks using the Pb/Pb method, is 600 ± 80 Ma (i.e., Upper Proterozoic), while dating using the Rb/Sz method gives an age of 625 ± 28 Ma [26].

Magmatic rocks are represented by the Sgimazuki massif plagiogneisses and plagiogranites, which are emplaced along the Lakchkhildi Range and extend for 11 km from the confluence of the Tviberi and Tsaneri rivers east to Lardali. Well-preserved outcrops of these rocks are recorded on the slopes of the Sgimazuki and Lakchkhildi mountains and in the valley of the Tsaneri River. To the south, these rocks are bounded by the fault of the Greater Caucasus Range and is tectonically bounded by flysch-like sediments of Lower and Middle Jurassic age. From the north to the “Gvandra group” of the Bulgeni, there are metamorphic complexes with crystalline shales.

The igneous rocks of the Sgimazuki massif comprise migmatites resulting from the late Baikal–Breton tectono-magmatic cycle located in the metamorphic shales of Gvandra and are a group of synmetamorphic granitoids.

Autochthonous plagiogneisses and allochthonous (intruded) plagiogranites are separated in the rocks of the Sgimazuki massif. The first of them occupies the lower part of the massif (horizon), while the second is spread through the upper horizons in the form of separate interlayer and intersecting veins [26].

Plagiogneiss is gray and light gray with a well-defined gneiss of thin-layered texture. The main constituent minerals of the rock are fine-grained oligoclase and quartz. Plagioclase is sericitized; no zoning is observed. Sporadic hornblende and biotite are found, as well as accessory and secondary minerals: muscovite (sericite), chlorite, epidote group minerals, sphene, magnetite, garnet, and pyroxene. Plagiogneisses are strongly cataclized and mylonitized.

Plagiogranites are common in plagiogneisses as independent lenses. These rocks are white and milky white, fine grained, with a massive texture. The main minerals are albite–oligoclase and quartz, zonal plagioclase, and microcline formed by albite; muscovite is only rarely found. Secondary minerals include biotite, chlorite, muscovite, and epidote group minerals. Moreover, the presence of dark minerals in the rock is very rare. The formation of autochthonous gneisses was determined by the regional metamorphism of the source rocks of late Baikal, staurolitic facies and Breton, biotite–muscovite facies. The formation of allochthonous leucocratic granitoids represents the differential melting of leucocratic gneisses on the young continental crust as a result of Breton regional metamorphism, where the temperature conditions were no less than high-grade biotite–muscovite gneisses. The mentioned granites were formed as a result of alternate melting of gneisses within the Gvandra Formation and are represented by granites, granodiorites, and plagiogranites of the calc–alkaline series [26].

The Upper Division of the Carboniferous System

Sediments of the Carboniferous are spread across the study area at the headwaters of the Tviberi river, in the confluences of the Tviberi, Asmashi, and Seri Glaciers, along the true right slope of the Tviberi river (Figure 5). A complete section of sediments of this age is located at the headwater of the Dolra River, in the valley of its right tributary, the Sand River, where these sediments are known as the “Kvishi (Sand) Suite”. This Suite is divided into three parts by its litho-facies structure [34,35].



Figure 5. Seri and Asmashi Glaciers, Tviberi River Valley (photo by L. Tielidze, September 2024).

The lower part of the “Kvishi (Sand) Suite” is represented by terrigenous coarse-grained sediments; in the lowermost part there are coarse-grained sandstones and gravelites with interlayers of conglomerates. Sediments are composed of quartz, crystalline slates, quartz diorites, microcline granites, albitophores, and quartzites. Cement is mainly represented by masses of fine-grained clays and argillites.

The middle part of the “Kvishi (Sand) Suite” is mainly represented by phyllitized shales and siltstones, as well as interlayers of limestones and calcified limestones containing fossilized remains of brachiopods, gastropods, pelecypods, corals, and foraminifera, all of Upper Carboniferous age.

The upper part of the “Kvishi (Sand) Suite” is represented by fine-grained terrigenous rocks: siltstones, sandstones, argillites, and gravelites, with rare interlayers and lenses of fine-grained conglomerates.

As mentioned above, within the study area, the sediments of the “Sand Suite” are represented by its lower (base) coarse-grained terrigenous sediments, which are transgressively located on microcline granites of Upper Paleozoic age and are transgressively covered by flysch-like sediments of Lower Jurassic (Lower Permian) age.

Within the study area, the sediments of the “Sand Suite” are represented by highly metamorphosed, greenish-gray-colored gravelites, cemented by quartz–schist sandstones, which are followed by medium-grained, depleted, blackish-brown-colored gravelites and sandstones. Some places contain small inclusions of ore minerals. Quartz veins are found at different levels within the layers. In the upper part of the sediments, weakly metamorphic fine-grained gravelites are commonly found. The rocks are mostly dark brown, rarely blackish brown-colored, and have dense structure. Crystal inclusions of pyrite and pyrrhotite are often found in these rocks. The total thickness of these sediments varies between 150 and 180 m [35].

5.2. Jurassic System

Jurassic rocks are widespread throughout the northern, southern, and western part of the study area. These sediments are located transgressively on the Proterozoic–Lower Paleozoic “Bulgeni Metamorphic Complex” crystalline schists. The Jurassic system is divided into three series, which are in turn divided into other stages. These sediments were

deposited within a deep-sea offshore environment, and are mainly described as clayey flysh and turbidites, while clastic–carbonate flysh-like sediments are presented in the upper part [9,27].

5.2.1. Lower Part of the Jurassic System

Lower Jurassic sediments are represented by Sinemurian, Pliensbachian, and Toarcian stages. Hauterivian sediments are not presented within the study area. It is worth mentioning that Lower Jurassic sedimentation starts with Sinemurian transgressive formation, which is located on the main ridge crystalline schists.

Sinemurian stage—These sediments are not widespread within the study area, as they mostly outcrop along narrow river beds, including the Adishchala, Tsaneri, and Tviberi Rivers. The sediments are located to the southern part of the Sgimazuki Metamorphic Complex and are overthrust by metamorphites, occurring in narrow outcrops.

Within Mestia, these sediments are represented by basal conglomerates, quartz gravelites, and sandstones, which become slates, sandstones, and gravelites in the upper part of the outcrop; alevrolites (aleurites) and schist interlayers are also widely presented. Rocks are mainly characterized by their massive texture and linear, thin-skinned zoning. Quartz and pyrite veins are often visible in the rock matrix. The color of the rocks is mostly dark gray or blackish brown. The thickness of rocks is variable, mostly determined by thrust faults; for this reason, Sinemurian sediments are covered by Cambrian-age “Sisini” Suite and Pliensbachian shales in some cases. To the north of the village of Zhabeshi, along the Tviberi River gorge, their thickness reaches up to 230 m, while to the west, in the Mestischala River gorge, their full thickness varies from 300 to 350 m. The above-mentioned sediments are characterized by typical fauna of Sinemurian stage: *Arietites* of. *scylla* Reyn., *Coroniceras* of. *schloenbachia*, *Echinoceras* sp., and *Vermiceras* sp. In some reports, these sediments are known as the Morghouli Suite [9,27].

Pliensbachian stage—Pliensbachian-stage rocks are widespread throughout the study area and are characterized by high thicknesses. From a paleontological and lithological perspective, these rocks are divided into three sub-stages: 1. lower; 2. middle; and 3. upper. Moreover, the lower part of the Pliensbachian sub-stage is itself divided into two formations: 1. lower formation–basal formation, and 2. flysch formation. In this zone, sediments have been transgressively emplaced on the Cambrian “Gvandra” Suite metamorphic schists. Lower Pliensbachian sediments are located in the southern limb of the Greater Caucasus main ridge thrust and are represented by undismembered and non-disintegrated aspidic schists [10].

There are two main formations in the Upper Pliensbachian sub-stage sediments: Lower-aspidic and slate schists, and upper-clayey and sandstone slate and aspidic schists.

Pliensbachian sediments are known in old geological maps and reports as Tviberi, Moashi, and Tsiklauri, mainly based on their geographical location [27].

Lower part of the Lower Pliensbachian stage (undismembered)—The sediments of this stage are widespread, as mentioned above, at the southern limb of the Greater Caucasus main ridge, and in the Adishchala River, and in the north part in the valleys of the Tsaneri, Tviberi, and Kheraji Rivers. The sediments continue concordantly from the rocks of the Sinemurian age and are mainly represented by dark gray, in some places blackish-gray, aspidic shales and sandstone–clay shales with interlayers and lenses of thin-bedded fine- and medium-grained sandstones. The thickness of the sediments varies between 390 and 500 m, and in the contact zone of the fault, it varies sharply and within 150 to 200 m. Veins of highly hydrothermally altered diabase–porphyrites are found at different vertical thicknesses within the sediments, ranging from 4 to 7 m. In the contact zones of the bodies, the shales are highly calcified and hardened. Pyrite crystals are found in shales, which are often replaced by iron oxides. Sheared and hydrothermal–sulfidized zones and veins are common in clays. The aforementioned sediments are characterized by the presence of quartz veins, which vary in thickness between 10 and 15 cm [10].

The Lower Pliensbachian sediments are transgressively located on the “Gvandra” Suite metamorphic crystalline schists and are represented by two suites: lower suite and upper suite.

Lower suite—Sediments are mainly represented by conglomerates, gravelites, and sandstones. In the sandstones, thin-layered clays are found at different levels. Conglomerates are a complex of pebbles and breccias derived from wave action of the transgressive sea. They are composed of granitoids, recycled granitoids, and crystalline shales; the binding cement is arkosic sandstones, gravelites, and, rarely, clays. Sediments in the upward section are replaced by relatively fine-grained arkosic sandstones, clayey–sandy shales, and siltstones. Aspidic-like clays are only rarely found. The thickness of these sediments is 180–200 m [10].

Upper suite—The sediments conformably continue the underlying sediments and are represented by fine-grained, quartz–arkose and graywacke, thin-bedded sandstones, clayey–sandy shales, and rare aspidic-like clays. The sequence at different levels contains veins of diabase–porphyrites and quartz, whose contact zones with the adjacent rocks are hardened and calcified. The densities of clays and aspidic shales gradually increase upwards through the outcrop. The sediments are mainly represented by sandstones, sandy-clays, argillites, and thin-layered aspidic shales. The thickness of the sediments varies between 280 and 300 m [10]. It is also worth noting that strongly compressed and mildly folded zones are fixed in the Pliensbachian sedimentary distribution belt, which has anticlinal and synclinal folds of small distribution lying to the south. Moreover, small-scale faults and the areas of pyritization and sulphidization are very common.

Middle lower stage of the Pliensbachian stage—Within the study area, these sediments are well exposed in the headwaters of the Tskheki, Kheraji, and Mulkhura Rivers, east of the Tsaneri Glacier and on both slopes of the Tviberi River to the west. The sediments are mainly represented by aspidic-like, dense clays, and medium- and fine-grained sandstones. Siltstones, clay–sandstones, and argillites are found at different levels as well. Interlayer veins of diabase–porphyrites can be found at different levels of the sediments, and cross-cutting dikes are frequent. The thickness of the magmatic bodies varies sharply from 3–4 cm to several (5–6) m. The total amount of thickness ranges from 280 to 300 m [9].

In these sediments, frequent microfolds of small size and distribution are observable, whose periclinal endings are often replaced by transverse faults. Within the study area, some fossils are well-described, for instance *Amaltheus margaritatus* Montf., *Chlamys textori* Schloth., *Mitiloides dubius* Sow., and *M. gryphoides* Schloth [9].

Upper lower stage of Pliensbachian stage—These sediments continue concordantly from the Middle Pliensbachian sediments and are distributed within the same area. This lower stage is divided into two suites: lower and upper suite.

Lower stack is mainly represented by dark gray, dense and massive, weathered aspid shales, and thin-layered clayey–sandy shales. Interlayers of fine-grained sandstones are found at different levels. On the surface, the rocks have a thin, shaly texture. The rocks are highly fissured; between the fissures there are frequent quartz veins, the thickness of which ranges from 0.2 to 0.3 m. In some places, hydrothermally altered zones containing pyrite crystals and chert are found along these veins. In the clayey and clayey–sandy layers, rare diabase layers can be found, with thicknesses varying between 0.5 and 1.2 m. The maximum thickness of the lower stack is up to 300 m. Some fossils may be found, including *Pholodamya* of. *voltai* Agass. and *Ph. of. ambigua* Sow [9,10].

Upper stack conformably continues the sediments of the lower stack and is represented by fewer sandstones. Along the valleys of the Tviberi and Kherazhi Rivers, it is represented by dark gray and brownish-black clays, with thin successions of highly depleted sandstones and argillites. Carbonized plant fossils are often found in clays. The main mass of sediments is represented by clays, aspid shales, argillites, and siltstones, and very thin sandstone layers. The total thickness of sediments varies between 170 and 180 m. The tectonic conditions of the rocks are similar to that of the lower stack described above and represented by a complex of microcracks with scaly fault systems. *Atractites* sp. and *Arietites* of. were

found in the mentioned rocks along the Tviberi River Valley. *Algovianum* Oppel. is found, which indicates an Upper Pliensbachian (Upper Domer) age of the sediments [9,10].

Toarcian Stage—These sediments continue from the Upper Pliensbachian sediments and are mainly represented by dark gray and black clays, in which interlayers and lenses of fine-grained and thin-layered, mica–quartz sandstones are separated; the thickness is between 0.1 and 0.4 m. The total thickness of sediments in the northern part of the territory (along the Kheraji River) is 320–350 m, and in the south, in the vicinity of the villages of Chvabeshi and Keli, it reaches 500 m. In the same areas, sediments are distinguished by slightly different facies. The sediments in the Kheraji River gorge are dark-gray-colored, and in some places, black-colored dense aspidic clays and shales are found with interlayers of thin-layered arkosic sandstones and quartz veins [9,10].

In the southern areas, clayey and clayey–sandstone shales are characterized by low densities. Aspidic-like shales are also rare, in which thin lenses and interbeds of gravelites and quartz sandstones are found. Fragments of quartz sandstones and pelitic shales appear in the gravelites. Sandstone cement is represented by micas.

Poorly preserved faunal sinks are often found directly in the dark clays. The mentioned faunistic remains do not allow exact age dating, but in the vicinity of the Mestiachala River, the following were found: *Mitiloids* of. *dubius* Sow, *M. gryphiodes* Schl., *Graminoceras* of. *thouarensense* d’Orb, and *Hildoceras* of. *sublevisoni* [9,10].

5.2.2. Middle Part of Jurassic System

Mid-Jurassic sediments are fully represented with all four stages within the study area. Some stages (Aalenian and Bathian) are divided into sub-stages due to the presence of different facies within them. These are located along the Enguri River Valley from the village of Keli to the village of Bogresha in the east [27].

Aalenian stage—These sediments continue from the Toarcian sediments. In the areas of the Mulkhura and Mestiachala Rivers, these sediments are mainly represented by homogeneous facies sediments, so the stage is represented on the geological map as undivided. Here, the Aalenian stage is represented by clays, sandstones, and their rhythmic sequence, in which interlayers of sandstones are only rarely found. Small quartz veins, pyrite–chalcopryrite areas, and zones of hydrothermal origin are frequent in the sediments. The thickness of rocks on the right bank of the Mestiachala River does not exceed 230 m. Moreover, these sediments contain faunal remains: *Tatrophilloceras* of. *Chonomphalum* Vos. and *Leioceras* of. *opalinum* Rein., which indicate their Aalenian age [9,10].

In the southern part of the territory, along the Enguri River Valley, the Aalenian sediments are represented by two different sediment facies. The lower Aalenian is composed mainly of claystones that unconformably overlie Toarcian sediments. At the base, these sediments are composed of dense, dark gray claystones, which have a flysch-like rhythmic sequence, and aspid-like clayey–sandy shales are also found, while the upward section contains thin-bedded, fine-grained sandstone layers and lenses of small thickness. The rocks in the upper part are highly fissured and depleted. In the upper horizons, there are veins of quartz interlayers and interslice arrangement. The thickness of sediments is 140–150 m. *Tatrophilloceras* was found in the lower part of the mentioned sediments. The presence of *Chonomphalum* Vac. and *Leioceras* of. *opalinum* Rein. indicates a Lower Aalenian age for the sediments [9,10].

The above-mentioned sediments are followed by Upper Aalenian sediments that are mainly represented by sandstones and sand–clay shales, which have a weakly expressed terrigenous flysch-like nature. At the base, there is a rhythmic sequence of dense, medium-grained and thick-bedded sandstones and sandy clays, with quartz veins; lens-like concretions of carbonate sandstones are only rarely found. Interlayers of clays and aspid shales are also rare.

In the upper part of the sediments, light gray and sometimes white sandstones are found. There are alternations of soft sandstone shales and clays, between which there are frequent interlayers of sheet shales. The thickness of these rocks is 280–290 m. Fossils

include *Inoceramus pseudoinconatans* Kakh. and *Mitiloides nunuae* Kakh., indicating Upper Aalenian age [9, 10].

The sediments of the Bajocian layer are widespread in the western part of the territory on the watershed ridge of the Mestiachala River and the Mulkhura River, as well as in the south of the village of Chvabeshi in the valley of the Enguri River, near the village of Bogreshi. Sediments are mainly represented by dark gray clays, siltstones and marls, interlayers of sheet shales, marly clays and clayey marls, and interlayers of clays and sandy shales. The distribution of these sediments in vertical section is irregular and undergoes mutual replacement laterally. The sediments do not contain functional fossils, but in the east of the area, the same sediments contain *Paetschiceras* of *Abichi* Uhl., which dates the sediments as Bajocian. The thickness of rocks varies between 220 and 240 m [9,10].

The Bathonian sediments continue from the Bajocian sediments and are distributed within the same area. The sediments of this age are characterized by almost uniform sediments, which have dark gray and black clay–sandy sediments, which, during frequent precipitation and floods, cause the water to become very dark and saturated with mud; the Bajocian–Bathonian sediments are known in ancient literary sources as “Muddy Mounds” [27].

Bathonian sediments are present in the Mulkhura and the Tviberi Rivers in an undivided form. Undismembered Bathonian sediments are represented by clays and clay–sandstone shales with common thin interlayers of medium and fine-grained sandstones; rare thin-layered zones and lenses of argillites and siltstones are also found. Concretions of clayey siderites and carbonate rocks are often found within them. The main mass of sediments has a dark gray, dark brown, and, in some places, black color.

The thickness of these rocks is 300 m. Sediments do not contain fauna. Their age is considered to be Bathonian since they are placed between paleontologically dated Bajocian and Callovian (see below) sediments [9,10].

Two lithological facies are distinguished in the Bathonian sediments along the Enguri River Valley, the lower of which is mainly represented by clays and sandstones. The upper facies are represented mainly by clays, carbonate rock concretions, and lenses.

Callovian stage—The sediments of Callovian age conformably continue the rocks of the Bajocian–Bathonian age, only with markedly different facies and represented by carbonate flysch-like sediments. The distribution area of sediments covers the same area, and their outcrops are clearly visible on the watershed ridge of the Mulkhura and Tskheki Rivers, south of the village of Chvabeshi and in the valley of the Tviberi River. In the south-western part of the territory, Callovian-age sediments are well exposed in the vicinity of the villages of Tsvrimi and Bogreshi, in the valley of the Adishchala River. The sedimentary section begins with thin-bedded and shaly marls and argillaceous limestone successions, followed by thin-bedded marls and light-gray limestone successions and dense massive limestone stacks, followed again by thin-bedded argillaceous and marly limestone successions with flysch-like sediments. Marls, clayey marls, and carbonate clays finish the section. The thickness varies around 150 m in the area of the Mulkhura River, whereas it is only 80 m in the vicinity of the Adishchala River.

The sediments within the study area do not contain fossils; however, in the neighboring regions, microfaunal remains have been described, which generally date the sediments as Callovian [9,10].

Middle Jurassic granodiorites, quartz–diorites, and diorite–porphyrites (Tviberi intrusive) are located along Mount Tviberi and its ridge. Within the study area, this intrusive suite is represented by its southern peripheral part and occupies about 2 sq. km. The main host rocks of Tviberi intrusions are quartz diorites with porphyries and granodiorite–porphyries, which are macroscopically difficult to distinguish and represent a homogeneous structure and massive intrusive body. The structure of the rock is porphyry, in which large plagioclase crystals are clearly visible. The matrix is composed of plagioclase, chlorite, and quartz. Accessory minerals are apatite, zircon, and sphene [26].

Microcline granites and granodiorites are mainly distributed in the northern part of the study area, in the headwaters of the Tviberi River and in the areas of the Tviberi, Lekhziri, and Dzinali Glaciers. This group of granitoids is mainly represented by microcline granitoids and small bodies of granodiorites and pegmatites [26].

Microcline granites are widespread in the granite–migmatitic series of the Caucasus. They are exposed fragmentarily in the entire distribution area of the granite–migmatitic series and are mainly connected with anticlinal structures, where they form late-kinetic mobilized igneous bodies. Anatectic microcline granitoids are mainly represented by granodiorites and granites. Among them, chloritized biotite and chloritized double-mica varieties are distinguished, connected by a gradual transition. They are light gray, medium- to coarse-grained rocks with massive or porphyroblastic structures. Plagioclase is mainly represented by albite and oligoclase. Zoning is not observed in albite. Sausuritization and epidotization in oligoclase is only rarely observed. Biotite is represented by separate scales; during the process of microclinization, it is completely replaced by the mentioned minerals. Apatite, zircon, orthite, and garnet are spatially associated with biotite. Muscovite is a secondary mineral, which is formed at the expense of plagioclase and biotite. Muscovites, which originate from the decomposition of plagioclase, are represented in pure varieties, while those formed at the expense of biotite contain apatite and magnetite. Garnet is only rarely observed and is represented by almandine, which is characterized by a fissured surface filled with chlorite. Zircon and apatite are found as accessory minerals, and orthite and sphene are observed as well. Sillimanite, which undergoes muscovitization and fibrolitization, is less common. The process of metasomatic microclinization is observed in the granite–migmatitic series of the Caucasus. This process is intensively observed by Gamkrelidze and Shengelia [26] in the study area. It refers to both migmatites and granodiorites, microcline granites, and related pegmatites.

Pegmatites are exposed in the granite–migmatitic series where the processes of migmatization and granitization take place. Pegmatites are mainly associated with areas of intense microclinization. They build vessels, lenses, and nests of various capacities and strength.

Pegmatites are divided into quartz–microcline–biotite, quartz–microcline–muscovite, microcline–quartz, microcline–muscovite, quartz–albite–microcline, quartz–microcline, albite–microcline, microcline, and albite varieties. Plagioclase is represented by albite, which forms crystals 2–4 cm in size. Albitization often precedes the process of microclinization. Quartz is represented by two generations. Muscovite replaces acid plagioclase or is formed by the crystallization of small scales of muscovite and sericite. Garnet, sphene, magnetite, orthite, apatite, and tourmaline are observed in different amounts.

The origin and formation of the group of granitoids described above took place during the Late Hercynian (Sudetic) tectono-magmatic orogenic phase and belongs to the calc-alkaline group of the high-potassium normal alkaline and subalkaline series. The age of granitoids is determined by the potassium–argon radiological method and is equal to $K\text{--}Ar = 117 \text{ to } 330 \pm 15$ million years [26].

Middle Jurassic diabase–porphyrites and diabases are represented in the form of subvolcanic dyke-like bodies, which are widely represented in the Jurassic flysch-like sediments spread along the southern slope of the Greater Caucasus. Their thickness is 10–15 cm, while the spread is several hundreds of meters. Diabases (ophitic diabases), gabbro-diabases, and diabase porphyries are well distinguished in the mentioned group of rocks. The most common of them are diabases; the main mass is represented by fine-grained macroliths–albitized plagioclase, chlorite scales, sericite, and carbonates. They also contain accessories of ore minerals and plagioclase phenocrysts belonging to labradorite, and in some places to albite. Secondary minerals are represented by minerals of the epidote–zoisite group, calcite, chlorite, and hornblende.

Gabbro-diabases have a relatively small distribution and represent a rock of hypidiomorphic structure, which is built mainly by plagioclase and augite in the central part of the bodies. Ilmenite, sphene, and magnetite are found as accessories [26].

5.2.3. Upper Part of Jurassic System

The Upper Jurassic sediments are known as clastic–calcareous flysch and are mainly composed of calcareous flysch-like, pelagic marls, carbonate clays, and shales; rarely, sandstone turbidites are also found. There are frequent rhythmic sequences of limestones and carbonate clays, which have a lateral distribution, but these sediments within the Mestia–Tianeti tectonic zone have a uniform habit and represent one of the main supporting formations outside the Mestia–Tianeti tectonic zone.

Within the study area, Upper Jurassic sediments are divided into two parts with slightly different facies formations: 1. Lower Oxfordian mainly clastic–limestone flysch; 2. Upper Oxford–Kimmeridge–Tithonian thin-bedded limestone, marl flysch, and sandstone turbidites [9,10].

Lower Oxfordian—Sediments unconformably continue the Lower Jurassic sediments and are distributed within the same area. The sediments are represented by carbonate formations: medium- and thick-layered limestones and marly limestones, which are replaced by dense, shaly marls, and clays as frequent interlayers. Limestones are mostly medium- and coarse-grained and characterized by clastic–textural features. Interlayers of white, dense, and medium-grade pelitomorphous limestones are also only rarely found. Marly limestones and marls are of relatively low density, have a thin-layered structure of light brown and gray color, and interlayers of carbonate clays and sandstones are often found, the quantitative share of which is very small. The sediments on the lateral distribution undergo mutual replacements giving individual layers a lenticular shape.

The thickness of the sediments ranges from 150 to 180 m, and fossils are represented in them in the form of poorly preserved, crushed, and deformed microfauna: *Pseudocycharina* sp. and *Textularia* sp., which generally date sediments as Upper Jurassic, but outside the territory, in particular in Zemo Racha, these sediments are paleontologically dated as Lower Oxfordian [9,10].

Upper Oxfordian and Tithonian sediments have a limited distribution within the study area. The outcrops are spread from the valley of the Mestiachala River, to the east through the Ughviri Pass, to the valley of the Adishchala River where these sediments represent the core sediments of the Mestia–Adishi syncline. Along the northern flank of the syncline, along the Mestiachala River and the Ughviri Ridge, sediments are represented by thick layers of marl-bearing limestones, carbonate and sandy limestones, micro-conglomerates, and breccia limestones. In some places, thick stacks of coarse-grained carbonate sandstones are well distinguished; the thickness of these rocks is 20–25 m. The sediments of this age along the southern flank of the syncline are built with similar facies, only in this part the sediments are relatively thin, and marly limestones prevail, with a succession of medium-grade pelitic limestones and marls. Thin-layered marls and carbonate shales can be found in different parts of the territory. To the east, in the valley of the Adishchala River, the sediments are well-compressed, while in some places the layers have a vertical arrangement. The sediments in this area are mainly represented by medium-weight limestones, greenish-gray carbonate shales, sandy limestones, and carbonate sandstones. The thickness is 230 to 250 m. The sediments contain fossils: *Stillina tubulifera* Philips., *Epistilia* of. *delemontana* Koby., *Lotiphyllia suevica* Quenst., and *Thamoceras amodei* Etallon., which date the sediments as Upper Oxfordian–Kimmeridgian–Tithonian [9,10].

5.3. Cretaceous System

Cretaceous sediments have a limited distribution within the study area. Berriasian–Valanginian-age sediments are located from the confluence of the Mulkhura and the Mestiachala Rivers to Mount Ughviri. The Mestia–Adishi syncline fold propagates along the mentioned strip, the central part of which is filled with clastic–calcareous flysch-like sediments.

Berriasian and Valanginian—These sediments unconformably extend the Upper Jurassic sediments and are represented by carbonate rocks of similar composition and facies. In the section of the northern limb of the Mestia–Adishi syncline, along the Mulkhura River Valley, the sediments are represented by medium- and thick-layered marls and sandy

limestones, thin-layered marls, and karstic shales, which do not undergo facies changes. On the southern limb of the syncline, the Cretaceous sediments unconformably continue the Upper Jurassic sediments with slightly different facies. In the lower part, there are thick-layered sandstones, limestones, and marls. At the base, there are layers and lenses of micro-conglomerates. The layers of limestones and marly limestones increase in the ascending section; interlayers of sandy limestones and marls are rare. The outcrop ends with flysch-like thin-layered, pelitomorphous limestones, and thin-layered marls [9,10].

Lower Cretaceous sediments are well exposed along the Zhamushi–Ughviri road, where these sediments are represented by clastic–limestone and sandstone turbidites, alternating with thin-bedded limestones, marls, pelagic clays, and carbonate sandstones.

The full scale of the sediments is not exposed within the study area, since the central part of the Mestia–Adishi syncline experiences uplift here, and the Cretaceous sediments east of Mount Ughviri are no longer exposed. To the west, outside the mapped area, the full thickness of these sediments is 350–400 m, and within our mapped area it ranges from 200 to 250 m. The age dating of sediments is determined by the presence of fauna: *Berriasella* of. *delphinensis* Kil., *Spiticeras* exgr., *orientalis* Kil., and *Berriasella richteri* Opp. [9].

Neogenic albitophyres also represent dyke bodies of small-distribution subvolcanic generation, which are placed in Lower Middle Jurassic flysch-like sediments. Albitophyres are light gray to gray microcrystalline rocks and are mainly plagioclase–albite with sericitized zoning. They mainly contain small deposits and accumulations of quartz, chlorite, carbonate, and ore minerals. Thickness is 15–30 cm, mostly up to 3–4 m, but 300–350 m in some places. The internal formational zonation is observed in the thick veins. The central part of the body is represented by granite–porphyrites, composed of light-gray, fine-grained porphyry quartz, plagioclase, apatite, and sphene. Sericite, chlorite, albite, and calcite are only rarely found [9].

5.4. Quaternary

Quaternary sediments are widespread within the study area. Their origin and accumulation were caused by the rapid uplift of the relief and the formation of the Greater Caucasus Belt as a result of the collision during the Pliocene–Quaternary period, which was accompanied by rapid erosional and depositional processes. As a result of the development of glaciers through the Quaternary, there are widespread moraines, fluvioglacial outwash, and alluvial terraces. Genetic types of Quaternary sediments within the study area are glacial, fluvioglacial, colluvial, alluvial, diluvial, proluvian, landslide, lacustrine, and others, as well as polygenetic formations. Quaternary sediments are divided into Lower, Middle, and Upper Quaternary.

5.4.1. Lower Quaternary Deposits

Lower Quaternary is represented by glacial and lacustrine formations. The first of these is glacial in origin and is spread in the western and eastern peripheral parts of Mount Ughviri and on the true left slope of the Mestiachala River. Lacustrine sediments are found on the watershed ridge of the Mulkhura and Mestiachala Rivers.

In the area of the Ughviri Pass, at an altitude of 1960–1980 m, there are widespread lateral moraine accumulations along the ridge, which end at the northern peripheral approaches of the village of Tsvrimi (Figure 6). These glacial sediments represent lateral moraine accumulations, the masses of which were eroded and transported from the glacial moraines that were developed along the Mulkhura River Valley in the Lower Quaternary. Similar glacial sediments are distributed on the southern slope of the Mestiachala River, at 1880–1920 m above sea level, on the western slope of Mount Kasari.



Figure 6. Ughviri Range between Enguri and Mulkhura River Valleys (photo by L. Tielidze, September 2024).

Moraines are built with weakly worked boulder–breccia masses of granites, crystalline slates, and infills of pebbles and sandy-clay masses. Depleted breccias and outcrops of Jurassic clays are only rarely found. The current (residual) masses of glacial sediments are 25–26 m thick, but we speculate that these sediments have been substantially eroded and note that, in the area of Mount Ughviri, the thickness of moraines reached 100 m. The age of the moraines should correspond to the Lower Quaternary.

Lacustrine deposits are widespread on the watershed ridge of the Mestiachala and Mulkhura Rivers, at an absolute height of 1950 m, in the vicinity of Mount Kasari. The sediments in the western part are covered by Lower-Quaternary-age glacial moraines of Mestiachala, and therefore their age is also considered to be Lower Quaternary. Lake sediments have a planform elliptical shape, and are in the order of 700–750 m long and 200 m wide; their thickness varies between 8 and 10 m. Lacustrine sediments are represented by thin-layered yellowish sandstones, gray clays and loams, lenses and interlayers of sandy loams and gravelites, and light-gray- and white-colored sands and clays. At the base of the lacustrine sediments, there are relatively coarse sediments, comprising pebbles, gravel, and gravelites, with small boulders of weakly worked and crushed rocks; the total thickness of this layer is 4 to 4.5 m [9,10].

5.4.2. Middle Quaternary Deposits

Sediments of the Middle Quaternary only have a limited distribution within the study area and are found only along the Tskheki River Valley and on the ridge of Mount Ughviri; they are of glacial origin.

On the ridge of Mount Ughviri, 250–300 m above the floodplain of the Mulkhura River, widespread moraine sediments are preserved, represented by large and dense granitoid blocks and boulders. The matrix between the boulders is diverse, and consistent with glacial till and diamictons of glacial origin: pebbles, gravel–sand masses, and clay. The geomorphology of glacial sediment-mantled landscapes is one of hummocky moraines and small ponds and lakes. Sediment thickness is variable along the ridge at 20–25 m, and along the slopes and in elevated terrain, it varies between 12 and 15 m [9,10].

Middle-Quaternary-age glacial sediments of a similar type and morphostructure are also found on the true left slope of the Mestiachala River and on both slopes of the Tskheki River, which are spread at an altitude of 220–250 m above the Mestiachala River Valley. Eroded moraine sediments, represented by bulk material of crystalline bedrock boulders and breccias, are widespread in the flat areas of the terrain. The thickness of glacial sediments is 21–23 m [9,10].

Erosional landforms include straightened glacial troughs, including the remnants of the Riss trough of the Mestiachala River, which is similar to the glacial troughs of the Enguri River [10].

5.4.3. Upper Quaternary Deposits

Upper Quaternary deposits are represented by glacial and fluvio-glacial formations, which belong to the Late Würmian glacial period. The sediments are generally better preserved than those of the Lower and Middle Quaternary deposits.

Moraines are found on the true left slope of the Mestiachala River, at the head of the Mulkhura River on both slopes, and on the southern slope of Mount Ughviri. In the area of the Mestiachala River, sediments are located at an absolute height of 1600–1800 m and spread from north to south at a distance of 4–4.5 km. These sediments are 40–80 m above the valley and represent lateral moraine, built by boulders of plagiogranites, quartz diorites, and breccias. The thickness of these sediments is 200 m [9,10].

5.4.4. Modern Quaternary Deposits

Sediments are quite widespread in Upper Svaneti and can be found along the valleys of the Enguri, Adishchala, Mulkhura, and Mestiachala Rivers, as well as on mountain slopes and fragmented mountain ridges. The genetic types of sediments are mainly represented by glacial, fluvio-glacial (alluvial–proluvian–glacial), proluvial–diluvial–colluvial, and fluvial formations.

Modern glacial moraines are associated with extant glacier termini or recently deglaciated terrain (Figure 7). The sediments are mainly composed of unsorted boulder–breccias and angular–fragmentary masses, which were formed as a result of intense physical weathering. The sizes of fragmented boulders are highly variable, ranging from 0.8 to 50 cubic meters. Matrix is mainly represented by pebble, pebble–clay, sandy–clay, and clay masses. Glacial sediments can be found in the headwaters of the Meshkha Tvibi, and Adishchala Rivers, as well as along the southern slope of Mount Tviberi. The thickness of sediments (moraines) does not exceed 8–10 m [9,10].



Figure 7. Modern glacial moraines and deposits. Dzinali Glacier forefield (photo by L. Tielidze, September 2024).

Modern proluvial–diluvial–colluvial sediments are spread along river valleys, namely on the slopes of the Mestiachala and Mulkhura Rivers. It is not possible to divide the sediments into separate genetic types, since these sediments alternate with one another, vertically and laterally. In addition, there are small areas in which individual genetic areas are well separated. Proluvial sediments are mainly present in the form of silt deposits,

which are periodically generated as a result of heavy precipitation (rains, snow) events, and are represented by pebbles, gravelites of granitoids and crystalline slates, and conglomerates, which have been eroded from older glacial sediments. In some areas, these sediments contain inclusions of colluvial and diluvial sediments. The thickness of individual layers ranges from 5 to 12 m [9,10].

Diluvial deposits are represented by angular–fragmented and depleted small (10–20 cm) masses, with clay and clay–pebble filling. Crushed particles are represented by weathered rocks of granitoids of crystalline shales, and remnants of flysch-like sediments of Jurassic age.

Colluvial deposits are represented by poorly cemented masses of large fragmental rocks of the host rock, composed of granitoids, crystalline shales and rarely Jurassic silty–sandy flysch-like, clay and pebble filler, and cement. The sediments of this formation vary within 5–10 m at different levels of the outcrop.

Alluvial–proluvial–glacial sediments are distributed along the valleys of the main rivers and in the lower part of their tributaries. Morphologically, these sediments are located within the upper first terraces of river floodplains and have a flat and slightly hummocky surface. Sediments are mainly represented by eroded and displaced cobbles, boulders and gravel masses, boulder–breccias, and remnants of rock fragments. Lithologically, the sediments are composed of granitoids, crystalline shales, dense sandstones, and clayey–sandy rocks. The sediments are mainly eroded masses of old glacial moraines, slope colluvial–diluvial, and proluvial sediments combined with river alluvium.

These sediments are found across the entirety of the Mestiachala and Mulkhura Rivers, but in the valleys of the Tsaneri and Tviberi Rivers, these sediments are found at their confluences. The sediment thickness varies widely from 10–20 m in the Mulkhura River Valley to 40–50 m in the Mestiachala River Valley; the thickness is 5–8 m in the downstream areas of the Tsaneri and Tviberi Rivers [9,10].

Modern alluvial deposits are widespread in the valleys of the Enguri and Lasili Rivers and are represented by boulder–pebble, pebble, gravels, gravelites, sand, and rarely clay and clay loams, which fill river floodplains. The thickness ranges from 3 to 7 m and has a limited distribution.

6. Conclusions

The geological map presented here (see main map in the Supplementary Materials) is the result of several years of research by our team focused on the central section of the Georgian Caucasus. Utilizing advanced cartographic software, we have integrated field mapping data, satellite imagery, topographic information, and previously published geological maps to produce a more accurate, geospatially referenced update. This high-resolution mapping offers a valuable resource and significantly enhances our understanding of the area's geological diversity, which has important implications for future geological studies as well as engineering, geohazard, and environmental sciences.

Moreover, this is the first geological map of the upper part of the Mulkhura River Valley (scale of 1:30,000). Two main metamorphic complexes have been distinguished based on our survey, which has high national-level importance in terms of the study of regional geology, tectonics, geomorphology, and glaciology of the Mulkhura River Valley.

The results of our research once again show the importance of integrating and adapting new interdisciplinary methods of geological sciences.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/geosciences14120341/s1>.

Author Contributions: Conceptualization, R.M.K., L.G.T. and M.G.; methodology, R.M.K., L.G.T., M.G., S.J.C. and A.G.; investigation, R.M.K., L.G.T., M.G., S.J.C. and A.G.; writing—original draft preparation, R.M.K., L.G.T., M.G., S.J.C. and A.G.; writing—review and editing, R.M.K., L.G.T., M.G., S.J.C. and A.G.; visualization, R.M.K., L.G.T. and M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG; grant no. YS-22-171).

Data Availability Statement: The main map (geology of the Mulkhura River valley with scale of 1:30,000 in PDF format) is available in the Supplementary Materials of this paper.

Acknowledgments: Levan Tielidze was supported by the Australian Research Council (ARC) Special Research Initiative (SRI) Securing Antarctica’s Environmental Future (SR200100005).

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Carosi, R.; Montomoli, C.; Iacopini, D.; Petroccia, A.; Simonetti, M.; Oggiano, G. Geology of the Asinara Island (Sardinia, Italy). *J. Maps* **2024**, *20*, 2317136. [\[CrossRef\]](#)
- Summino, L.; Domenighini, G.; Giorno, M.; Barale, L.; Bertok, C.; Martire, L.; Fiori, N.L.; Schivo, E.; Piana, F. Geology of the Arera-Vedra Valley mining area (Gorno district, Orobic Alps, Italy). *J. Maps* **2024**, *20*, 2422545. [\[CrossRef\]](#)
- Sánchez, L.G.; Macías, J.; Sulpizio, R.; Osorio-Ocampo, L.; Pellicioli, C.; Pola, A.; Avellan, D.; Cisneros, G.; García, F.; Ocampo-Díaz, Y.; et al. Geology of La Reforma caldera complex, Baja California, Mexico. *J. Maps* **2019**, *15*, 487–498. [\[CrossRef\]](#)
- Parsons, A.J.; Law, R.D.; Searle, M.P.; Phillips, R.J.; Lloyd, G.E. Geology of the Dhaulagiri-Annapurna-Manaslu Himalaya, Western Region, Nepal. 1:200,000. *J. Maps* **2014**, *12*, 100–110. [\[CrossRef\]](#)
- Klimeš, J.; Kilnar, J.; Kopačková-Strnadová, V.; Pánek, T.; McColl, S.; Jelének, J. Landslides in the glaciated mountains of the Cordillera Blanca, Peru—Types, spatial distribution, and conditioning factors. *Landslides* **2024**, *21*, 1–17. [\[CrossRef\]](#)
- Hanžl, P.; Guy, A.; Battushig, A.; Lexa, O.; Schulmann, K.; Kuncová, E.; Hrdličková, K.; Janoušek, V.; Buriánek, D.; Krejčí, Z.; et al. Geology of the Gobi and Mongol Altai junction enhanced by gravity analysis: A key for understanding of the Mongolian Altaides. *J. Maps* **2019**, *16*, 98–107. [\[CrossRef\]](#)
- Tvalchrelidze, A.G. Mineral Resource Base of Georgia in the XXI Century. In *Mineral Resource Base of the Southern Caucasus and Systems for Its Management in the XXI Century*; NATO Science Series; Tvalchrelidze, A.G., Morizot, G., Eds.; Springer: Dordrecht, The Netherlands, 2003; Volume 17. [\[CrossRef\]](#)
- Kekelia, S.A.; Kekelia, M.A.; Kuloshvili, S.I.; Sadradze, N.G.; Gagnidze, N.E.; Yaroshevich, V.Z.; Asatiani, G.G.; Doebrich, J.L.; Goldfarb, R.J.; Marsh, E.E. Gold deposits and occurrences of the Greater Caucasus, Georgia Republic: Their genesis and prospecting criteria. *Ore Geol. Rev.* **2008**, *34*, 369–386. [\[CrossRef\]](#)
- Geguchadze, S.; Gvineria, L.; Kalikina, E.; Beradze, P. Geological Map of the Racha-Svaneti Region, Scale 1:50,000. Georgian Geological Fonds No. 17000. 1974. (In Russian)
- Gvineria, L.; Kazarov, E.P.; Abkhazava, M.I.; Kodjaeva, R.S.; Samkurashvili, M.I.; Bregvadze, G.O.; Cheishvili, A.S.; Makharadze, A.S.; Shengelia, D.M.; Kakhadze, R.G. Report of the Upper Svaneti GSP. According to Geological Survey Works M-ba 1:25,000 Within Sheets: K-38-38-B-b, K-38-26-G-a,v,g., Georgian Geological Fonds No. 16457, 1984. (In Russian)
- Tielidze, L.G. Glacier change over the last century, Caucasus Mountains, Georgia, observed from old topographical maps, Landsat and ASTER satellite imagery. *Cryosphere* **2016**, *10*, 713–725. [\[CrossRef\]](#)
- Huggel, C.; Zraggen-Oswald, S.; Haerberli, W.; Käb, A.; Polkvoj, A.; Galushkin, I.; Evans, S.G. The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: Assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 173–187. [\[CrossRef\]](#)
- Evans, S.G.; Tutubalina, O.V.; Drobyshv, V.N.; Chernomorets, S.S.; McDougall, S.; Petrakov, D.A.; Hungr, O. Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. *Geomorphology* **2009**, *105*, 314–321. [\[CrossRef\]](#)
- Shahgedanova, M.; Hagg, W.; Hassell, D.; Stokes, C.R.; Popovnin, V. Climate Change, Glacier Retreat, and Water Availability in the Caucasus Region. In *Threats to Global Water Security*; NATO Science for Peace and Security Series C: Environmental Security; Jones, J.A.A., Vardanian, T.G., Hakopian, C., Eds.; Springer: Dordrecht, The Netherlands, 2009. [\[CrossRef\]](#)
- Toropov, P.A.; Aleshina, M.A.; Grachev, A.M. Large-scale climatic factors driving glacier recession in the Greater Caucasus, 20th–21st century. *Int. J. Clim.* **2019**, *39*, 4703–4720. [\[CrossRef\]](#)
- Maruashvili, L. *Kavkasiis Fizikuri Geografia (Physical Geography of the Caucasus)*; Monograph. Publ. “Metsniereba”: Tbilisi, Georgia, 1981. (In Georgian)
- Alania, V.; Melikadze, G.; Pace, P.; Fórizs, I.; Beridze, T.; Enukidze, O.; Giorgadze, A.; Razmadze, A. Deformation Structural Style of the Rioni Foreland Fold-and-thrust Belt, Western Greater Caucasus: Insight from the Balanced Cross-section. *Front. Earth Sci.* **2022**, *10*, 968386. [\[CrossRef\]](#)
- Brunet, M.-F.; Korotaev, M.V.; Ershov, A.V.; Nikishin, A.M. The South Caspian Basin: A review of its evolution from subsidence modelling. *Sediment. Geol.* **2002**, *156*, 119–148. [\[CrossRef\]](#)
- Ershov, A.V.; Brunet, M.-F.; Nikishin, A.M.; Bolotov, S.N.; Nazarevich, B.P.; Korotaev, M.V. Northern Caucasus basin: Thermal history and synthesis of subsidence models. *Sediment. Geol.* **2002**, *156*, 95–118. [\[CrossRef\]](#)
- Saintot, A.; Brunet, M.-F.; Yakovlev, F.; Sébrier, M.; Stephenson, R.; Ershov, A.; Chalot-Prat, F.; McCann, T.; Gee, D.G. The Mesozoic-Cenozoic tectonic evolution of the Greater Caucasus. *Geol. Soc. Lond. Mem.* **2006**, *32*, 277–289. [\[CrossRef\]](#)

21. Adamia, S.; Zakariadze, G.; Chkhotua, T.; Sadradze, N.; Tsereteli, N.; Chabukiani, A.; Gventsadze, A. Geology of the Caucasus: A Review. *Turk. J. Earth Sci.* **2011**, *20*, 489–544. [\[CrossRef\]](#)
22. Tielidze, L.G.; Nosenko, G.A.; Khromova, T.E.; Paul, F. Strong acceleration of glacier area loss in the Greater Caucasus between 2000 and 2020. *Cryosphere* **2022**, *16*, 489–504. [\[CrossRef\]](#)
23. Tielidze, L.G.; Cicoira, A.; Nosenko, G.A.; Eaves, S.R. The First Rock Glacier Inventory for the Greater Caucasus. *Geosciences* **2023**, *13*, 117. [\[CrossRef\]](#)
24. Edilashvili, V.Y. Geological Report of the Upper Svaneti Region (K-38-26-V; K-38-26-G), Tbilisi. 1948. (In Russian)
25. Gudjabidze, G.E. *Geological Map of Georgia (Scale 1:500,000)*; Georgian State Department of Geology and National Oil Company “Saknavtobi”: Tbilisi, Georgia, 2003.
26. Gamkrelidze, I.; Shengelia, D. *The Precambrian-Paleozoic Regional Metamorphism, Granitoid Magmatism and Geodynamics of the Caucasus*; Scientific World Publisher: Singapore, 2005. (In Russian)
27. Topchishvili, M.; Lominadze, T.; Tsereteli, I.; Todria, V.; Nadareishvili, G. *Stratigraphy of the Jurassic Deposits of Georgia*; Janelidze, A., Ed.; Institute of Geology, Georgian Academy of Sciences: Tbilisi, Georgia, 2006.
28. Tielidze, L.G.; Charton, J.; Jomelli, V.; Solomina, O.N. Glacial geomorphology of the Notsarula and Chanchakhi river valleys, Georgian Caucasus. *J. Maps* **2023**, *19*, 2261490. [\[CrossRef\]](#)
29. González, P.D.; Cábana, M.C. Geology of the Anecón Grande area, Patagonia (Río Negro), Argentina. *J. Maps* **2013**, *10*, 402–408. [\[CrossRef\]](#)
30. Cieszkowski, M.; Kysiak, T.; Szczęch, M.; Wolska, A. Geology of the Magura Nappe in the Osielec area with emphasis on an Eocene olistostrome with metabasite olistoliths (Outer Carpathians, Poland). *Ann. Soc. Geol. Pol.* **2017**, *87*, 169–182. [\[CrossRef\]](#)
31. Basilone, L. Geological Map of the Rocca Busambra-Corleone region (western Sicily, Italy): Explanatory notes. *Ital. J. Geosci.* **2011**, *130*, 42–60. [\[CrossRef\]](#)
32. Basilone, L.; Di Maggio, C. Geology of Monte Gallo (Palermo Mts, NW Sicily). *J. Maps* **2016**, *12*, 1072–1083. [\[CrossRef\]](#)
33. Plougarlis, A.P.; Tranos, M.D. Geology of Ammouliani Island (Northern Greece)—Implications for the tectono-magmatic evolution of the Serbo-Macedonian Massif. *J. Maps* **2014**, *11*, 552–560. [\[CrossRef\]](#)
34. Adamia, S.; Pegerski, D. Geodynamics of the Caucasus (Experience in Palinspastic Reconstructions). Problems of Geodynamics of the Caucasus. 1982. (In Russian)
35. Adamia, S. Pre-Alpine Basement of the Caucasus—Composition, Structure, Formation. Tectonics and Metallogeny of the Caucasus. 1984. (In Russian)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.