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Neverovsky Palaeoreef and Associated Deep-Marine Facies: High-Value Late Devonian Geoheritage from the Rudny Altai

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Abstract: The Rudny Altai is a western segment of the Altai orogenic belt. Its geological richness makes its geoheritage exploration an urgent matter. Investigations in the Loktevsky District (Altai Region, Russian Federation) have led to the finding of three notable localities, which are proposed as geosites. Field investigations and both qualitative and semi-quantitative (scoring by criteria) studies were carried out to characterize and value the geoheritage properties of these localities. The Neverovsky palaeoreef is a relatively large geosite, representing a Frasnian reef developed on a volcanic edifice. The Zolotukha section and the Razdolnoe section are smaller geosites representing deep-marine facies of the Giventian–Frasnian transition and the late Frasnian, respectively. Seven geoheritage types are established in the Neverovsky palaeoreef, and four geoheritage types are established in the other two geosites. Examination of rarity, accessibility, vulnerability, and other properties allows the ranking of the Neverovsky palaeoreef globally and the other two geosites regionally. The three proposed geosites need special geoconservation measures (especially regarding their rich fossil content). The palaeoreef can be used for the promotion of local tourism.

Keywords: carbonates; geosite; palaeogeography; Central Asia; Paleozoic

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1. Introduction

Despite the numerous achievements in the international research of geoheritage, geoconservation, geodiversity, geoparks, and geotourism made during the three past decades [1–8], the inventory of geosites still remains on the agenda [9–11]. Finding new heritage objects of this kind is especially urgent for large and geologically rich territories, the geoheritage of which has not been explored extensively. An example is the Altai (also spelled as Altay), which constitutes a vast orogenic domain of Central Asia and embraces parts of China, Kazakhstan, Mongolia, and Russia. The tectonic setting and the geological evolution of this domain are diverse and highly unique [12–18].

Despite the geological richness and the long history of geological research in the region, the Altai does not boast extensive geoheritage studies. Previous research considered the geoheritage and geotourism resources of particular areas of Xinjiang in China [19], East Kazakhstan [20–23], northeast Gobi Altai in Mongolia [24], and Zmeinogorsk and a few other localities in Russia [25,26]. The number of the studied areas and the reported geosites are too small compared to the huge size of the Altai and the diversity of its geological wonders. Nonetheless, the previous studies proved the large geoheritage potential of this region and indicated the urgency of taking step-by-step geosite inventories of its parts. A single research project aimed at the comprehension of the geoheritage of the entire Altai seems to be unrealistic. Regular, field-based investigations conducted by dozens (if not hundreds) of specialists over several decades would be required to document this geoheritage.

Among the many unique geological sites of the Altai, one should take note of the Devonian reefs [25,27,28]. They are covered only marginally in the famous PARED database [29], although their consideration can be important to better understand the shift from reef abundance in the Early–Middle Devonian to their decline at the Devonian–Carboniferous transition [30]. Moreover, the geoheritage-related knowledge of pre-Quaternary reefs, including those of Late Devonian age, remains poor [31], and, thus, investigations of the Devonian reefs of the Altai will help to fill this gap. The objective of the present paper is to analyze the Neverovsky palaeoreef and some associated features at the western edge of the Altai in terms of their geoheritage. Inventory and semi-quantitative assessment of geosites are the focus of this study. The latter follows, but does not duplicate, the previous geoheritage research on the Russian Altai [25,26], and it presents novel interpretations.

2. Geological Setting

The Altai is a large orogenic belt with a highly complex tectonic setting and a very long history of development [12–18]. Principally, it was formed near Siberia, where large and small blocks accreted during the late Proterozoic and the Early–Middle Paleozoic, followed by collisions linked to the growth of Laurasia and then Eurasia. Tectonic activity strengthened again during the Cenozoic as a distant effect of the India–Asia collision [32–36], and the present mountains were formed at the southern periphery of the Eurasian lithospheric plate (near its boundary with the smaller tectonic blocks of Central Asia) [37]. The Altai is known for Paleozoic sedimentary complexes, which are spread widely there.

The study area corresponds to the Loktevsky District of the Altai Region, which is a high-rank administrative unit of the Russian Federation. Geographically, it is situated in the southwest of Siberia, near the western edge of the Altai Mountains (Figure 1). The local landscape is hilly, with temperate continental climate and steppe vegetation. The area is drained by the Zolotukha River and its right tributary, namely the Gryaznukha River (the former is a tributary of the Aley River, which itself is a large tributary of the Ob River—one of the largest rivers on Earth).

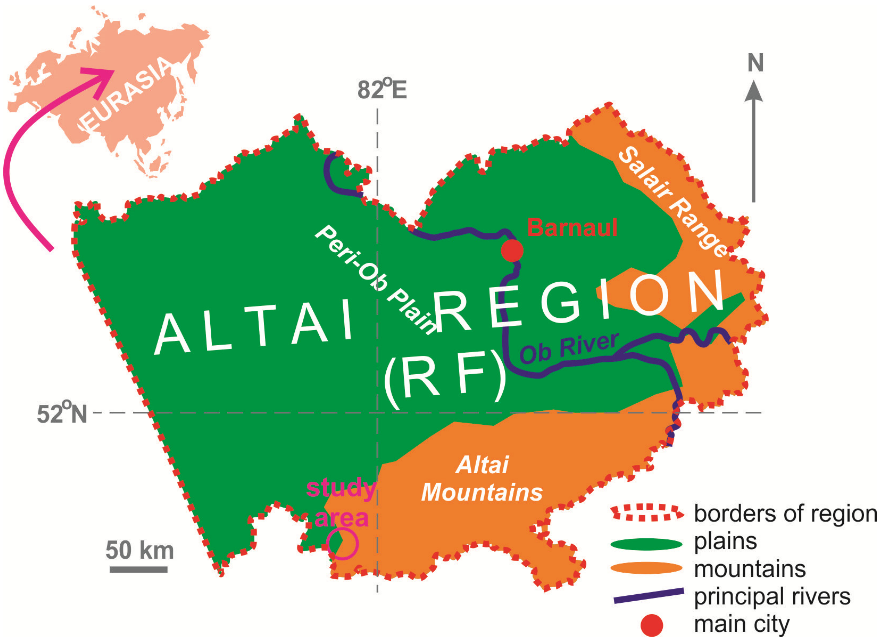

Figure 1. Geographical location of the study area in the Altai Region of the Russian Federation.

From a geological point of view, the study area belongs to the so-called Rudny Altai, which is a southwestern domain in the Altai, distinguished by relatively low elevations (<2000 m and often <1000 m) and richness in geological resources. Information about the Rudny Altai can be found, particularly, in works by Chernyshev et al. [38], Gorzhevsky and

Yakovlev [39], Kozlov [40], Mesentseva [41], Obut and Shcherbanenko [42], Saraev et al. [43], Sekerina and Egorov [44], and Seravkin and Kosarev [45]. The study area is dominated by Middle–Upper Devonian volcanosedimentary deposits with a total thickness of 3500 m (Figure 2). Their litho- and biostratigraphy were established by Afanas'eva et al. [46], Elkin [47], Gutak and Rodygin [48], and Murzin et al. [49], who used, particularly, brachiopods, conodonts, and radiolarians to determine the exact age of the respective deposits. The local stratigraphical sequence includes Devonian deposits of the Davydovskaya Formation (Middle Devonian), the Kamenevskaya Formation (upper Givetian–Frasnian), and the Pikhtovskaya Formation (Famennian) (Figure 3). These deposits crop out in the valleys of the Gryaznukha and Zolotukha rivers. The considered Middle-Late Devonian volcanosedimentary sequence was complicated by intrusions of Late Devonian quartz porphyres and Famennian basic volcanics (Figure 2).

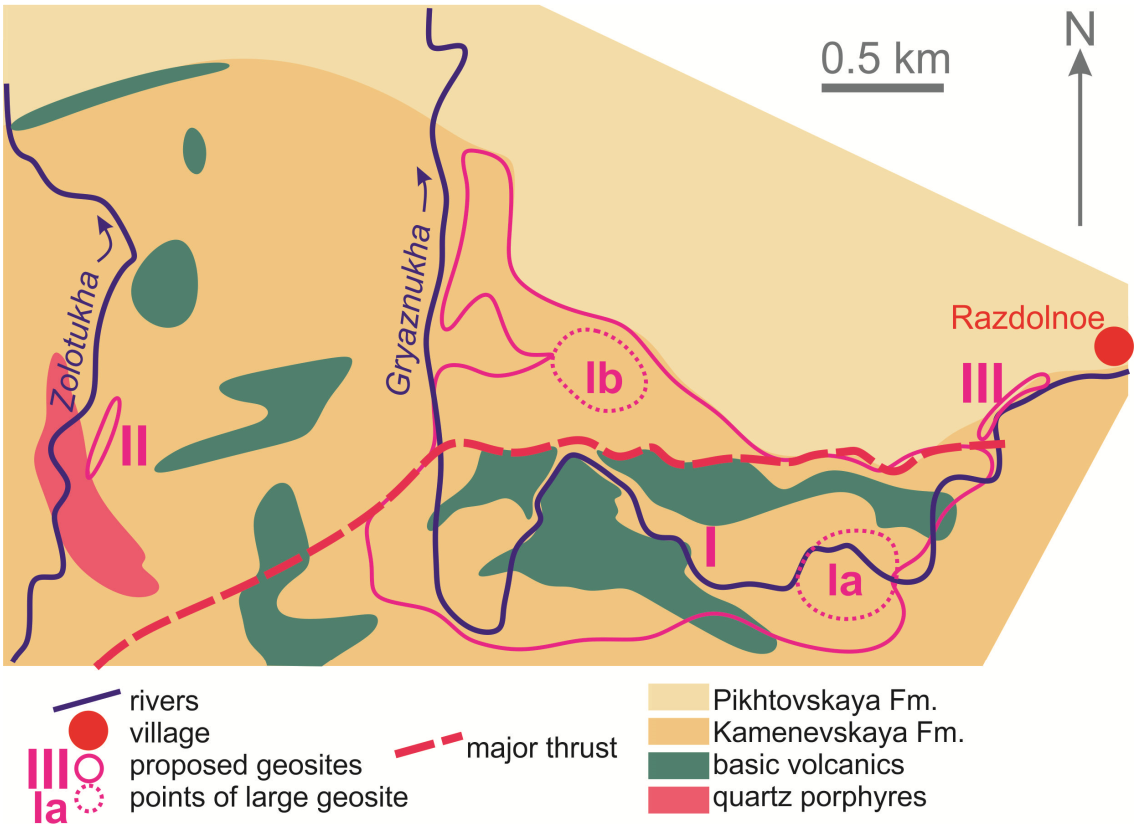

Figure 2. Geological scheme of the study area showing the location of the proposed geosites (I—Neverovsky palaeoreef (with special points Ia and Ib), II—Zolotukha section, III—Razdolnoe section).

Of special interest is the Kamenevskaya Formation, which bears the Neverovsky palaeoreef in its upper part (Figure 2). This formation includes sandstones, siltstones, shales, limestones, and volcaniclastics with a total thickness of ~2000 m. The accumulation of these deposits was related to a remote island arc with active volcanism. Siliciclastic deposits (often with siliceous material) represent deep-marine facies, whereas carbonate deposits represent shallow-marine facies. According to the global plate tectonic and palaeogeographical reconstruction by Golonka [50], the study area was situated in temperate latitudes (30–40° N) on the active margin of Siberia, which was a separate landmass; a major subduction zone stretched along this margin, which was open to the narrowing ocean basins between Siberia, North Kazakhstan, and Amuria. The global average temperatures were high [51], and they allowed reefal ecosystems to also flourish on the Siberian margin. The Neverovsky palaeoreef is the outcome of these ecosystems' development in the study area.

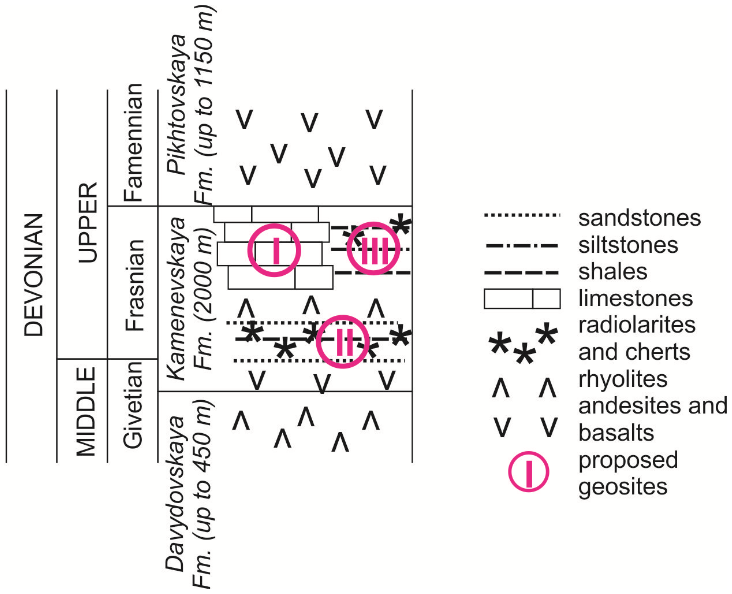

Figure 3. Composite stratigraphical section of the study area showing the location of the proposed geosites (I—Neverovsky palaeoreef (with special points Ia and Ib), II—Zolotukha section, III—Razdolnoe section).

3. Materials and Methods

Field investigations in the study area allowed collection of the necessary materials for the present study. Particularly, promising localities were selected and examined. Realizing that they could be proposed as geosites allowed for focus on their peculiarities related to the broad spectrum of geoheritage properties (see below).

The approaches for the inventory and the (semi-)quantitative assessment of geosites are numerous and differ to a certain (even significant) degree [11,52–59]. They are equally important, but successful application of each approach depends on the local and national contexts. For the purposes of the present study, we prefer the approach already tested in various places of the world [54]. Its previous application in Russia and, particularly, Siberia, makes it particularly suitable for the Rudny Altai to maintain the consistency of the geosite reports within the large country. This approach is not explained in detail to avoid repetitions of the already published information, but the related ideas and terminology were reconsidered and systematized (Table 1). This was necessary to clearly differentiate between words such as "category", "grade", "property", "rank", and "type" when they are used in geoheritage studies. This systematization is the methodological novelty of the present study.

The approach consists of two main procedures. First of all, the proposed geosites are characterized geologically. The related information was collected in the field and also from some relevant literature sources [46–49]. The descriptive properties (Table 1) were analyzed qualitatively. Then, the proposed geosites were assessed semi-quantitatively by criteria that correspond to the assessment properties (Table 1). This procedure is essentially similar to that used by Gutak et al. [54]. The categories were scored as follows: rarity—+50. . .+500, number of geoheritage types—0. . .+50, accessibility—−25. . .+25, vulnerability—−50. . .+25, need for interpretation—−25. . .+25, scientific, educational, and touristic importance—0. . .+25 (for each of them), and aesthetic importance—0. . .+50 (scores for the particular grades of these categories are specified below). The total sum of the scores allowed for the establishment of a rank for each given geosite and to compare geosites in the same area by their values.

Table 1. Terminological basis of this study.

Level 1	Level 2	Level 3	Explanatory Notes
Geoheritage			Most general term (idea) reflecting the presence of the intrinsic and extrinsic heritage values in geological (also geomorphological) phenomena (features)
Geoheritage resource	Potential resource	Geological bodies, geological landscapes, geological (tectonic) domains	Phenomena (objects and processes) Geoheritage may exist, but its manifestations have not been inventoried
	Proven resource	In situ and ex situ manifestations such as geosites (also geomorphosites), geoparks, mineral and fossil collections, special exhibits, etc.	Geoheritage exists, and its manifestations have been inventoried
Geoheritage properties			Characteristics
	Descriptive categories		Descriptive properties can be established, but not measured; commonly, they are linked to the heritage values only indirectly
		Type (geological content, essence), form (physical appearance such as natural outcrop, quarry, collected specimen, etc.), size, shape (configuration, geometry), age, dynamics, color	Particular descriptive properties correspond to different grades of these categories
	Assessment categories		Assessment properties can be established and measured (quantitatively or semi-quantitatively); commonly, they are linked to the heritage value directly; these categories can be considered as assessment criteria
		Rank (relative uniqueness, rarity), number of types, accessibility, vulnerability (also conservation state), need for interpretation, importance (scientific, educational, touristic), aesthetic attractiveness	Particular assessment properties correspond to different grades of these categories; rank is related to the intrinsic heritage value, and the other categories are technical (functional) and related to the extrinsic heritage value

4. Results

A total of three geosites can be proposed for the study area, namely the Neverovsky palaeoreef, the Zolotukha section, and the Razdolnoe section (Figure 2). These geosites differ in both their descriptive and assessment properties. Although they are located geographically close, these geosites show distinct geological features.

4.1. Neverovsky Palaeoreef

The Neverovsky palaeoreef is the largest geosite of the study area and occupies its central part; the configuration of this geosite corresponds to the contours of the noted palaeoreef (Figure 2). This palaeoreef, with a thickness of >150 m, occurs in the Kamenevskaya Formation [49]. Some detailed geological descriptions were given by Elkin [47]. The reef-building organisms were algae, tabulate and rugose corals, and stromatoporoids. The reef ecosystem also included bivalves, brachiopods, bryozoans, crinoids, gastropods, and trilobites. Microfossils include ostracods, fish teeth, and conodonts. Brachiopods and conodonts were useful for establishing the Frasnian age of this palaeoreef [49]. The latter grew on an edifice of a submarine volcano. Reefal limestones are underlain by a 1.5 m thick layer, which is essentially a weathering horizon developed on volcanics. The development of this reef ended in the end-Frasnian, when a new phase of volcanism perturbed the local environments and resulted in the intrusion of Famennian volcanic rocks into the reef body (particularly, volcanic necks were recorded). Although this geosite is rather large, two particular points should be distinguished. The first of them is situated in the valley of the Gryaznukha River (Ia in Figures 2 and 3), with a typical reefal limestones outcrop (Figure 4). The second point is found in the northern portion of the palaeoreef (Ib in Figure 2), where an abandoned and partly drowned limestone quarry represents the sequence of reefal limestones, including its base (Figure 5).

The proposed geosite can be attributed to seven geoheritage types (Table 2). Its form is complex, because it includes natural outcrops (particularly, along the Gryaznukha River) and an abandoned quarry. The size is relatively large and measures a few kilometers. This is an areal geosite because it embraces the area corresponding to the contours of the palaeoreef, and its configuration is irregular (Figure 2). The age of the Neverovsky palaeoreef is Frasnian (~375 Ma). This geosite is static because it represents ancient geological features and not any ongoing process. The quarry is not operating currently, but its gradual degradation, as well as the slow denudation of the palaeoreef are signs of weak dynamism. Finally, the rocks of the palaeoreef are distinguished by red (Figure 4) and yellow (Figure 5) colors, which facilitate their easy distinction in outcrops.

Figure 4. Representative outcrops of the Neverovsky palaeoreef geosite (point Ia in Figures 2 and 3).

Figure 5. Abandoned quarry in the Neverovsky palaeoreef geosite (point Ib in Figures 2 and 3).

Table 2. Distribution of geoheritage types in the proposed geosites.

Types (Dominant Types Are Marked with *)	Geosites (Characteristic Features Related to Particular Types Are Indicated)		
	Neverovsky Palaeoreef	Zolotukha Section	Razdolnoe Section
Palaeogeographical *	+ (palaeoreef facies and ecosystem)	+ (deep-marine facies)	+ (deep-marine facies)
Stratigraphical *	+ (Frasnian stratigraphy)	+ (Givetian–Frasnian transition)	+ (age of the Kamenevskaya Fm.)
Palaeontological *	+ (richness in fossils)	+ (richness in fossils)	+ (richness in fossils)
Sedimentary	+(carbonate rocks)	+(siliciclastic rocks and radiolarites)	+(siliciclastic rocks)
Igneous	+ (volcanic features)	-	-
Economical	+ (abandoned quarry)	-	-
Geomorphological	+ (reefs expressed in local landforms)	-	-

4.2. Zolotukha Section

The Zolotukha section is a small geosite in the western part of the study area, where the lower interval of the Kamenevskaya Formation crops out (Figures 2 and 3). This is the only locality in the entire Russian Altai (not only the Rudny Altai) where the Givetian/Frasnian boundary is represented in a continuous section. A member of siltstones and radiolarites with a few interlayers of conglomerates bearing fossiliferous limestone clasts in shaly matrix and a total thickness of 50 m is represented at this geosite. Fossils include radiolarians, which are very helpful for age determination [46]; brachiopods, corals, ostracods, and trilobites were also found in this section. The exposed deposits were formed in a deep-marine environment.

The proposed geosite can be attributed to four geoheritage types (Table 2). It corresponds to the natural outcrop stretching along the right bank of the Zolotukha River. It is relatively small and linear; it measures just a few hundred meters (Figure 2). The age of the Zolotukha section is Givetian–Frasnian. This geosite is static. The color of the siltstones and the radiolarites is greenish grey.

4.3. Razdolnoe Section

The Razdolnoe section is a moderate-sized geosite in the eastern part of the study area, where the upper interval of the Kamenevskaya Formation crops out (Figures 2 and 3). The exposed portion of the formation is a lateral, deep-marine analogue of the Neverovsky palaeoreef. A lengthy section of Frasnian siliciclastics is available there, and some related geological descriptions were provided by Elkin [47]. These deposits include black bituminous shales, sandstones, siltstones, limestones, and cherts with a total thickness of ~50 m. Ammonoids, bivalves, conodonts, radiolarians, and tentaculites occur in them and imply the Frasnian age (the presence of the lowermost Famennian deposits cannot be excluded). These deep-marine deposits are found close to shallow-marine limestones of the Neverovsky palaeoreef, but their contact is marked by a major thrust fault (Figure 2). This geosite represents the deepest part of the Frasnian basin in the study area.

The proposed geosite can be attributed to four geoheritage types (Table 2). Its form is simple because it corresponds to a natural outcrop stretching along the right bank of the Gryaznukha River; some outcrops were also found directly in the stream. This geosite is moderate in size and linear (curvilinear), measuring several hundreds of meters (Figure 2). The age of the Razdonboe section is Frasnian. This geosite is also static. Notably, the exposed rocks are variegated: green, blue, red, yellow, and black colors are present in this geosite, and the intercalation of thin layers creates a spectacular pattern.

4.4. Values of the Proposed Geosites

The three proposed geosites demonstrate a rich geological content (Table 2) and peculiar assessment properties. The latter are summarized and valued semi-quantitatively in Table 3 and are also explained below.

First of all, the proposed geosites differ by their rarity (Table 3). There are well-preserved Late Devonian reefs in different places of the world [29], including the Canning Basin in Australia [60], the Banks Island in Canada [61], and the Pechora Urals in Russia [62]. However, examples of a Late Devonian reef with associated volcanic features are few, and the most notable of them was reported several decades ago in Harz in Germany [63]. In this regard, the Neverovsky palaeoreef seems to be rare on the global scale. The other two geosites, namely the Zolotukha section and the Razdolnoe section, are rare (even exceptional) on the regional scale because of the representation of the Giventian/Frasnian boundary and the general stratigraphical importance, respectively (see also Elkin [47]).

The number of geoheritage types established in the geosites varies between seven and four (Table 2), but this property can be assigned to the same grade (Table 3). Two important properties, namely accessibility and vulnerability, are equal for all three geosites (Table 3). The latter are situated in a rural, but well-populated area with good road infrastructure and connectedness to the other parts of the Altai Region and entire Russian Federation. Visiting the considered Late Devonian outcrops and their close observation and sampling is easy. The local landscape does not raise any natural barriers for hiking in the study area. This is why accessibility is perfect in all cases. The examination of the geosites did not lead to the identification of any natural or anthropogenic threat to their current state, and, thus, they are not vulnerable to any negative influence. The only accumulation of slope debris can mask some geological features, but this process is slow, and slopes can be cleaned easily.

Table 3. Semi-quantitative assessment of the proposed geosites (criteria and scores are based on [54]).

Criteria (Assessment Categories) and Scores	Geosites		
	Neverovsky Palaeoreef	**Zolotukha Section**	**Razdolnoe Section**
Rarity: global (+500), national (+250), regional (+100), local (+50)	+500	+100	+100
Number of geoheritage types: >10 (+50), 4–10 (+25), 2–3 (+10), 1 (0)	+25	+25	+25
Accessibility: easy in populated area (+25), easy in remote area (0), difficult (−25)	+25	+25	+25
Vulnerability: no danger (+25), potential danger (0), partly damaged (−25), fully destroyed (−50)	+25	+25	+25
Need for interpretation: absent (+25), basic geological knowledge required (0), professional geological knowledge required (−10), scientific analysis required (−25)	0	−10	−10
Scientific importance: international (+25), local (0)	+25	+25	+25
Educational importance: international (+25), local (0)	0	0	0
Touristic importance: international (+25), local (0)	0	0	0
Aesthetic importance: high (+50), medium (+25), low (0)	+25	0	0
TOTAL SCORES	625	190	190
Finally justified rank: global (G)—>499, national (N)—250–499, regional (R)—100–249, local (L)—<100	Global	Regional	Regional

The Neverovsky palaeoreef is a typical object of its class, and, thus, the basic geological background is enough to comprehend the essence of this geosite (Table 3). The other two proposed geosites are more specific, and interpretation of their content requires much deeper knowledge. Indeed, all three geosites can be employed for the purposes of geological research, education, and tourism. However, the only scientific utility seems to be international (Table 3). At least, the previous studies [46,48] demonstrated that the Late Devonian sequence of the study area can be important for long-distance stratigraphical correlations and palaeontological discoveries. The field examination of outcrops and the revision of the published information imply that the potential for new high-class research remains high. This is especially important taking into account the relatively small volume of Late Devonian reefs in the world [30]. Indeed, palaeoreefs are important for extending the knowledge of university students and training their skills [64–66], as well as for tourist attractions [67,68]. Nonetheless, palaeoreefs are numerous in the world [29], and, thus, the Neverovsky geosite (not speaking about the other two geosites) can be employed for only local geoeducational and geotouristic activities (Table 3). Aesthetically, the Neverovsky palaeoreef is attractive due to the color of the rocks, their impressive exposures, and the picturesque landscape (Figure 4), which are characteristics related to common visitors' judgments of beauty [69–73]. The other two geosites look ordinary in the aesthetic aspect (Table 3).

Taking into account the total scores, the Neverovsky palaeoreef can be proposed as a global geosite, and the Zolotukha section and the Razdolnoe section seem to be regional geosites (Table 3). The Neverovsky palaeoreef dominates the study area (Figure 2), which allows its extensive involvement in the high-class geoheritage management. The existence of the other two geosites can facilitate and diversify the related activities.

5. Discussion and Conclusions

Geoheritage related to Devonian reefs is not abundant on the global scale [Ruban, 2023]. Two representative examples include the Schlade Valley in the Rhenisch Massif of Germany [74] and the Jebilet region in the Jebel Ardouz massif of Morocco [64]. They are known as sources of precious materials for geological and palaeontological research. An important question is how to manage such geoheritage. The high rank of the Neverovsky palaeoreef and its high potential for scientific investigations require official designation and certain conservation procedures. Although this geosite is not vulnerable to any negative influences, the distribution of the knowledge of it can attract not only specialists, but also amateurs. In this case, risks of fossil overcollecting and occasional damage may appear. Such risks are common for palaeontological localities [75–77]. Moreover, the same risks can appear simultaneously to the Zolotukha section and the Razdolnoe section due to their palaeontological importance. Special measures to prevent (or, at least, to mitigate) such risks are necessary, and these may include (but are not limited to) the installation of special signs warning against uncontrolled fossil collecting and protective fences. Regular monitoring of the proposed geosites will also be necessary. The international developments and experience of geoconservation [78–86] should also be taken into account. Local museums, which are available in several cities and towns of the Altai Region of Russia, can be responsible for the management of the Neverovsky palaeoreef and the other two proposed geosites.

Although the local touristic utility of the proposed geosites is noted (see above), the related opportunities should be emphasized because the Russian Altai (and the Rudny Altai as its constituent) boasts outstanding touristic and recreational resources, which have been actively explored and exploited [87–89]. Moreover, the entire Altai has promising perspectives for the transboundary tourism development [90,91]. Tourists can be interested in diversification of their experiences, which implies, particularly, the demand for geotourism (in combination with adventure tourism, ecotourism, and gastronomic tourism). An optimal strategy for the study area may be a focus on the reefal essence of the main geosite. The broad public is well-aware of modern reefs, and the latter attract tourists [92,93]. The Altai is in the core of Eurasia, and it is a typical continental domain, with the distance to the closest sea measured by thousands of kilometers. Seeing that there was an ancient reef ecosystem is an exciting opportunity to gain knowledge and experience of it, which is hard to imagine in this geographical domain. The related interpretations can be developed by the local professional community of geologists and promoted actively by the tourism and recreation industry of the Altai Region. The perfect accessibility of the proposed geosites (Table 3) allows their easy integration into tours and excursions available in the Rudny Altai.

Conclusively, the present study has permitted the reporting of a new portion of the high-value geoheritage of Late Devonian age from the Rudny Altai. A total of three geosites are proposed, from which one (Neverovsky palaeoreef) is given a rank of global importance. These geosites need adequate geoconservation, and they can be very useful in international research and local tourism. The findings in the study area indicate on the high potential of geoheritage exploration in the Rudny Altai. The region is large, and many other geosites can be identified there.

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