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ORIGINAL ARTICLE

Quantitative Assessment of Geotopes as an Effective Tool for Geoheritage Management

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Abstract A quantitative methodology for the assessment of geotopes that can be used for the sustainable management and conservation of the geological heritage of an area is here presented. As sustainable development, education and conservation are core issues for the successful management of any protected area, this study focuses on the development of specific indexes necessary for determining values concerning the tourism, educational and protection requirements of geotopes. The proposed methodology is based on a series of criteria that cover not only the geological and geographical importance of a geotope but also its scientific, ecological, cultural, aesthetic and economic significance. Based on these criteria, the resulting *scientific*, *ecological*, *cultural*, *aesthetic*, *economic* and *potential for use* scores of each geotope are used to estimate, respectively, the *touristic*, *educational* and *protection-need* value indexes for each geotope on a scale ranging from 1 to 10. This methodology was implemented and tested in two areas in the island of Crete, namely the Psiloritis Natural Park, a European and Global geopark, and the Lassithi Mountains, producing reliable results, which are in agreement with the geopark's activities and values. The proposed quantitative assessment method is, therefore, a useful tool. It serves the requirements for the adequate management and protection of geoheritage within a territory as it can reveal priorities for sustainable tourism development, including geotourism and educational tourism activities and the conservation of geotopes.

Keywords Geotopes · Geoparks · Geoheritage · Assessment · Geoconservation

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Introduction

Since the *Declaration of the Rights of the Memory of the Earth* was announced in 1991 in Digne, France (Martini and Pagès 1994), progress has been made towards the recognition of the value of geological heritage and geoconservation. Scientific associations like the IUGS, ProGEO, national geological surveys etc., as well as global organizations, such as UNESCO, have undertaken studies and projects to reveal the wealth of geological heritage at various scales (Eder and Patzak 2004). In addition, not only Earth scientists but the broader scientific community has increasingly recognised the significant role that geodiversity plays in our environment and its importance in environmental studies and in a holistic approach to nature. Barthlott et al. (1996), for example, describe biodiversity as mainly the consequence of an area's geodiversity (the diversity of abiotic factors), and geodiversity as a quality is in its own right of the same order as biodiversity. However, when combined within the total diversity of an area, they can be described as eco-diversity.

Geodiversity, as presented by Gray (2004), refers to “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, processes) and soil features, as well as their assemblages, relationships, properties, interpretations and systems”. Geodiversity, therefore, represents the diverse products of all of Earth history of geological as well as atmospheric processes and their interactions with the biosphere and, more recently, with the human race. Outstanding and unique features of geodiversity within an area constitute a geological heritage which merits conservation (Gray 2008). This Earth heritage is identified in specific areas or landscapes of our planet designated as geosites or geotopes (Sturm 1994), including different types of landforms which can be described by geomorphologists as “geomorphosites” (Reynard et al. 2007). Thus, the wealth of an area’s geodiversity can be expressed by the number and the variety of its geotopes.

The acceptance of the need for conservation of geodiversity resulted in some of the first official geoconservation actions which took place in Nordic countries (Johansson 2000) and even earlier in the UK within the Geological Conservation Review (Ellis 2008), which led to the identification of geological Sites of Special Scientific Interest (or SSSI; Wimbledon et al. 1995), and most recently in the implementation of Local Geodiversity Action Plans (LGAP) under the support of first *English Nature* and now Natural England (Gray 2008). Similar geoconservation activities undertaken in many other countries and regions, including Tasmania, Australia, USA, Ireland, Germany, France, Portugal etc. (Brilha 2002; Gray 2008; Erikstad 2008 and references therein) or by international organizations such as IUGS and ProGEO (e.g. the *Geosites project*; Theodosiou-Drandaki et al. 2004) indicate that geodiversity as a concept is now well accepted and geoconservation often plays a major role in nature conservation in general.

Nevertheless, the history of geoconservation reveals that centuries ago geological monuments were important not only for scientific purposes but also for recreation and tourism purposes (Fig. 1), suggesting that “geotourism” as a human activity is far from new (Erikstad 2008). The Baumannshoehle showcave has been a tourist attraction in Germany from 1646 (Grube 1994), and the Rock of Klus in Germany was painted by Goethe in the 18th century (Roehling and Schmidt-Thome 2004). Landscapes like that of Yellowstone, the USA’s first national park, were sites for tourism and were visited and documented by famous people. Geotourism, therefore, can be regarded as an important factor for the conservation of geological heritage even though it was initially relatively underappreciated by the scientific community. Modern approaches by international organizations such as the International Union for Conservation of Nature (IUCN) promote sustainable development activities even in highly protected areas, through the “*Building Biodiversity Business*” concept (Bishop et al. 2008). The concept foresees the establishment of commercial enterprises that generate profits via activities which conserve biodiversity, use biological resources sustainably and share equitably the benefits arising from this use. Amongst the various activities promoted are ecotourism and the support of local products and services. It is expected, therefore, that *Biodiversity Businesses* have the potential to generate investment for conservation, a crucial necessity for our time, as well as for sustainable development.

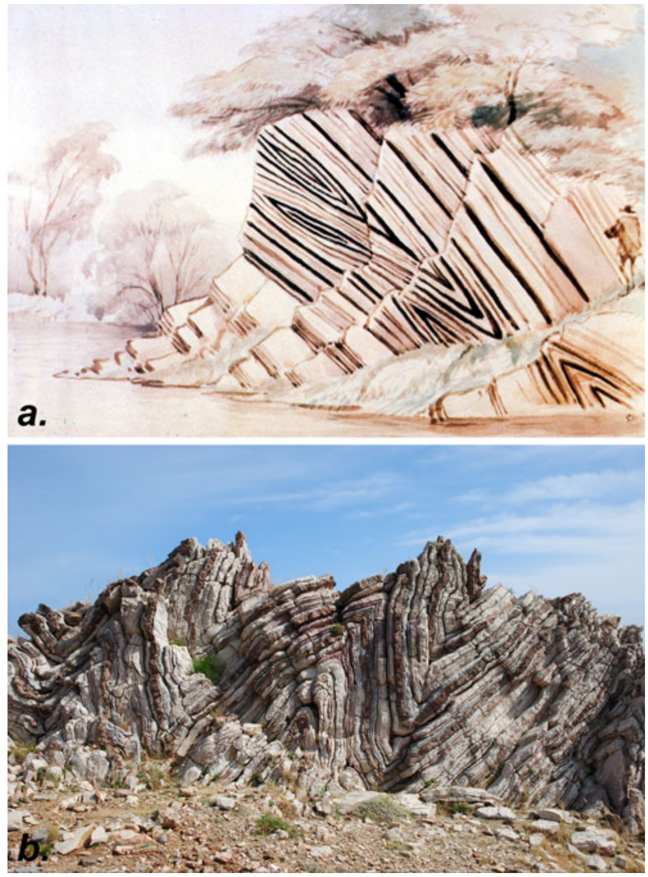

Fig. 1 Long-lasting geotourism attractions. **a.** Chert bands and Carboniferous limestone, in Kerry County Ireland, painted between 1817 and 1869 (courtesy of the Geological Survey of Ireland). **b.** The famous Agios Pavlos folds, of the oldest postal cards of the island of Crete

In the 1990s, a similar concept was developed by UNESCO in collaboration with IUGS, aiming to establish parks focused on the conservation and sustainable use of geological heritage, and described as the “Geopark” concept (Patzak and Eder 1998). In 2001 this concept was realised in four rural territories by the establishment of the European Geopark Network (Zouros and Martini 2003) supported by European Regional Funding (LEADER II).

European Geoparks aim to manage abiotic, natural heritage and cultural heritage, through networking between certain European territories in order to achieve high standards of conservation, promotion and, ultimately, real economic development (Zouros and Martini 2003). According to the existing convention (European Geoparks Network Charter), a European geopark must have an outstanding geological heritage, cover a substantial area and present an economic development strategy. It must also contain geological sites of special value as well as sites with special ecological, archaeological, historical and cultural value. The geopark has to encourage the local population to re-evaluate their heritage and to play an active role in the protection of their geological heritage and the economic revitalisation of their territories through activities that promote geotourism, education and other environmentally friendly activities. The fundamental issue of geoconservation, i.e. protection of the geological heritage, combined with related sustainable development activities, is a model that is also promoted by IUCN and embedded in the core of European Geoparks initiative. Similar networks or groups of geoparks now exist at national or continental levels (e.g. German, Chinese, Asia–Pacific networks) which aim to promote the sustainable management of the geological heritage (Roehling and Schmidt-Thome 2004; Komoo 2010).

Consequently, the effective and efficient management of geological heritage, regardless of whether it is seen on the scale of a geotope or a geopark, should be based on its net geodiversity value. To reveal this value, however, it is necessary to demonstrate at local or global levels their importance and contribution to science and modern civilization using a comparable and quantitative system of assessment. This issue was highlighted by Dingwall et al. (2005), who examined the World Heritage Sites (WHS) list of UNESCO in which the geological component was shown to be seriously neglected. Since 1995, only 17 areas were registered solely as geological monuments (criterion Nature III), although more than 83 geo-themes could be identified within the listed sites. The problem arose because of the difficulties in demonstrating the *Outstanding Universal Value,* within a geological context, to meet the *high level of site integrity/authenticity* essential for the definition of a WHS. This weakness becomes more apparent in the cases where decision makers or politicians are faced with a conflict between planning and human needs and geoconservation. Several examples have been recorded in which engineering works or construction unearthed important geological sites or was challenging the existence of others. In Canton Jura of Switzerland a highway construction revealed abundant dinosaur footprints that had to be excavated and protected before the completion of the highway (Marty et al. 2007), whereas in another case the construction of an airport was adding threats in an area of outstanding geological diversity (Erikstad 2008).

It is, therefore, necessary to quantify and document the value of geological heritage as well as to assess the geodiversity using a standard method, which is acceptable to geoscientists and also to the broader environmental community. Applying a standard method can increase the effectiveness of geoconservation actions, as both protection, which is the objective, and geotourism, which is a tool for its achievement, have to rely upon a robust and reliable evaluation process.

In this study we describe the development and use of a standard formula which can be used to quantify and estimate the educational, geotouristic and protection-need values of geotopes within an area, whether the area is under the protection and management of a geopark or not. We present a model of assessment based on measurable criteria by combining experience gained from other disciplines, such as geography and ecology, with the need for adequate and effective management and protection of the geological heritage. Our model was developed in Psiloritis Natural Park, a European and Global Geopark and was further tested in the nearby area of Lassithi Mountains in Crete, Greece (Fig. 2).

Materials and Methods

The Method for Quantitative Assessment of Geotopes

The scientific methodology for the evaluation and assessment of Earth heritage has been developed over the past two decades in order to minimise subjectivity in the processes of formalising results into a common and well recognisable scoring system. Although subjectivity may be an unavoidable parameter in ranking the scientific value, protection need or use potential of geotopes, the establishment of transparent criteria is necessary for the preparation of management plans that can also be socially accepted and useful (Bruschi and Cendrero 2005).

These studies were mainly applied in the assessment of geomorphosites or geomorphological assets in various contexts, such as the management of nature and national parks (Serrano and Gonzalez-Trueba 2005; Pereira et al. 2007), in environmental impact assessments (Rivas et al. 1997; Coratza and Giusti 2005) and in the identification of the touristic and exploitational value (Pralong 2005). Methods for the quantitative assessment of geotopes have also been developed (Grandgirard 1999; Bruschi and Cendrero 2009 and references therein). However, they were simply adapted for geological heritage management and conservation use. Zouros (2005, 2007) presented a method for the scientific assessment of coastal geomorphosites in

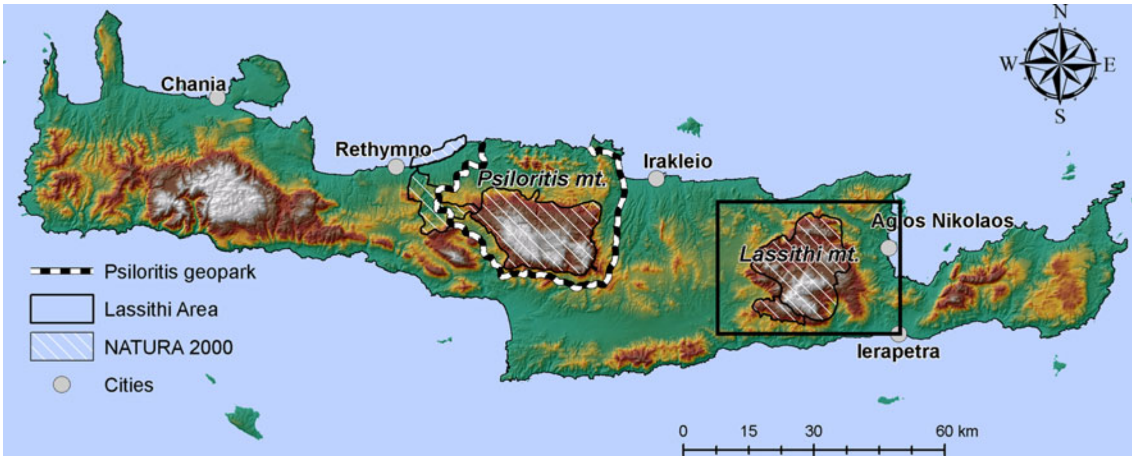

Fig. 2 Physical map of Crete with the boundaries of Psiloritis Geopark, Lassithi study area and the Natura 2000 areas

Lesvos Petrified Forest Geopark, Bruschi and Cendrero (2005) proposed a method to minimize the subjectivity effect in ranking geosites and recently Rovere et al. (2010) developed a methodology for the assessment of the submarine geological heritage.

All the methodologies listed rely on several assessment criteria: some of these repeatedly refer to rarity, representativeness or integrity, whereas others are dependent on the context and aims of the assessment (i.e. ecological, touristic and educational values).

In order to develop a method for the quantitative assessment of geotopes aimed at supporting geoconservation and management actions for geological heritage, we compared and tested several of the existing models and concentrated mainly on those suggested by Reynard et al. (2007) and Zouros (2007). However, most of these models appear to be dependent on the specific context of the studied sites and/or on specific protected environments and cannot be applied to large, multi-protected territories such as geoparks which contain a variety of geotopes. Our methodology, therefore, is based on earlier proposed criteria combined in such a way that they can be applied to all types of geotopes and be used to assess all aspects of a geotope's value (Grandgirard 1995; Rivas et al. 1997; Pralong 2005; Zouros 2007; Reynard et al. 2007). The defined criteria are defined in six main groups: (1) *scientific*, (2) *ecological and protection*, (3) *cultural*, (4) *aesthetic*, (5) *economic* and (6) *potential for use*. Each main group comprises a number of sub-criteria, and a common scoring system (ranging from 1 to 10) is applied to each group. The methodology was developed in Psiloritis Geopark in Crete using 63 geotopes (Mouriki and Fassoulas 2009) and, in addition, has been used to assess the value of the geotopes of the Lassithi Mountains (eastern Crete) where no management or geoconservation activities currently exist, in order to test the response of the method to different levels of protection and conservation (Dimitriou-Nikolakis and Fassoulas 2010).

Criteria Description and Implementation Process

As mentioned previously, the criteria used are divided into six groups, each one producing a final score for its category. The *scientific* criteria are derived mainly from Reynard et al. (2007) and aim to reveal the scientific value of a geotope. This group is subdivided under the following headings (Table 1): 1.1, *Geologic history* that depicts the contribution of the geotope to the interpretation of the overall geological history of the studied area; 1.2, *Representativeness*, which addresses the status of the site as an example of the geological heritage of the total area; 1.3, *Geodiversity*, which describes the variety of geological features and processes related to the geotope compared with the full range of an area's geodiversity; 1.4, *Rarity* that concerns the uncommonness of the geotope with respect to similar geotopes present in the study area and 1.5, *Integrity* referring to the existing state of conservation of the geotope. Human activities or/and natural processes (like erosion) may affect integrity leading to a lower score. For the collection of this data, existing literature, geological maps as well as geodiversity inventories and studies have to be used.

The second category refers to the *ecological* value of the geotope and is subdivided into two criteria: 2.1, *Ecological impact* that represents the contribution of the geotope to the development of particular ecotopes or to the existence of endemic species within the area and 2.2, *Protection status*, referring to the state of actual protection and conservation of the site. These criteria require a multidisciplinary approach that should be based on the collaboration of Earth and environmental scientists.

The *cultural criteria* aim to reveal the contribution of each geotope to the cultural heritage of the area. They comprise several sub-criteria covering all aspects of culture: 3.1, *Ethic* importance, defining the relationship of the geotope to

Table 1 List of criteria used and description of the scoring system

Criteria/Score	1	2.5	5	7.5	10
1. Scientific					
1.1 Geologic history	Single type history	Combination of at least 2 types	Combination of most types	Local story	Tells the whole local story
1.2 Representativeness	No	Low	Moderate	High	Very high
1.3 Geodiversity	<5%	25%	50%	75%	> 75%
1.4 Rarity	>7	>5 <7	>3 <4	>1 <2	Unique
1.5 Integrity	Almost destroyed	Strongly deteriorated	Moderately deteriorated	Weakly deteriorated	Intact
2. Ecological					
2.1 Ecological impact	No	Low	Moderate	High	Very high
2.2 Protection status	No protection	Limited	In spots	In large parts	Complete
3. Cultural					
3.1 Ethics	No	Low	Moderate	High	Very high
3.2 History	No	Low	Moderate	High	Very high
3.3 Religious	No	Low	Moderate	High	Very high
3.4 Art and culture	No	Low	Moderate	High	Very high
4. Aesthetic					
4.1 Viewpoints	No	1	2	3	> 4
4.2 Landscape difference	No	Low	Moderate	High	Very high
5. Economic					
5.1 Visitors	< 5000	> 5000	> 20000	> 50000	> 75000
5.2 Attraction	No	Local	Regional	National	International
5.3 Official protection	International	State	Regional	Local	No
6. Potential for use					
6.1 Intensity of use	Very intense	Intense	Moderate	Weak	No use
6.2 Impacts	Very high	High	Moderate	Low	No
6.3 Fragility	No	Low	Moderate	High	Very high
6.4 Accessibility	Close to hiking trail	Close to cobble or forest road	Close to local paved road	Close to regional road	Close to highway or town
6.5 Acceptable changes	No	Low	Moderate	High	Very high

For implementation see text

existing ethics or customs; 3.2, *Historical* importance, describing the connection of the site to historical events or archaeological remains; 3.3, *Religious* importance, concerning the religious, metaphysical or mythological value and 3.4, *Art and cultural* importance that assesses the presence of the geotope in the arts at a local or regional level. The use of all available historical, cultural and folklore data from publications and oral narrations is necessary for the assessment of these criteria.

The *aesthetic value* of a geotope is obtained using the criteria established for the evaluation of geomorphosites and consists of two subcriteria: 4.1, *Viewpoints* that considers the visibility of the site based on the number of viewpoints from roads or trails that are more than 1 km away from each other and 4.2, *Landscape difference*, which considers the difference in shape, colour or morphology between background and the geotope. Field observations as well as geographical information can contribute to a more accurate assessment.

In order to reveal the *economic value* of a geotope the following criteria are used: 5.1, *Visitors* which is based on the number of visitors to the site and should always be related to the total tourism potential of the country or region; 5.2, *Attraction*, which considers the importance of the site as a national, regional or local attraction and 5.3, *Official protection*, describing the legal protection status of the geotope. It has been documented that the high protection status of an area can imply restrictions in many human activities, including economic, sometimes not even permitting the physical human presence in core zones. Protection status should, therefore, be regarded as an economic criterion, and the higher the protection status the lower the scoring should be. In cases where legal protection represents the actual situation, scoring in criterion 5.3 should be regarded as inversely proportional to the scoring of 2.2 criterion.

Finally, the capability for exploitation of a site is qualitatively evaluated under the *potential for use* criteria: 6.1, *Intensity of use*, which shows the present use of the site by humans; 6.2, *Impacts*, which assesses the negative effects of existing human activities on the site; 6.3, *Fragility*, referring to the degree of resistance of a geotope's physical features with respect to potential degradation; 6.4, *Accessibility*, describing the potential for approaching the site by road or trails and 6.5, *Acceptable changes*, that consider the resistance of a geotope to changes without risking degradation of its physical features. The last criterion is dependent on the intensity of use and fragility of the geotope, for instance an intensely used or geotope of low fragility cannot experience further changes without increasing the risks of endangering its physical features and context. We consider that it is necessary in such studies to separate *economic* and *potential for use* criteria because the *economic* assessment describes the present activity in a site, while the *potential for use* describes future capability. Potentiality thus gives a future prosperity for the economic development of a site which at present might not be used in this way.

The scoring system developed ranges from 1 to 10 so that the final results can be shown on the same scale. However, in certain criteria (representativeness, ecological and cultural criteria, landscape difference, intensity of use, or acceptable changes) ranking is based on a more qualitative approach and is dependent on the evaluator's experience. This is a process not easily avoided in such studies, as Bruschi and Cendrero (2005) have discussed in detail, and it is possibly the only way to evaluate the intangible heritage of geotopes. In Table 1, the various criteria used and the attributed scoring system are presented: obviously values for criterion ranges must be between 1 and 10.

For the implementation and testing of the method a multidisciplinary group was established by Earth scientists in the Natural History Museum of Crete and post-graduate students in the Biology Department of the University of Crete. Technical support was provided by the Museum Library and the GIS Department, as well as by Psiloritis Natural Park. Firstly, the group catalogued the bibliography related to the nature, history and geology of the studied areas. Examples include the Geological Heritage of Psiloritis (Fassoulas 2008), the Field Guide for the Geology of Crete (Fassoulas 2001) and many other popular publications (Platakis 1975; Rackham and Moody 1997; Fassoulas et al. 2007). Additional information was then gathered through field studies, questionnaires and personal communications and stored in a database. For the collection of field information a special template or identification card, which was compatible with the database and the statistical analysis sheets, was developed for each geotope in order to record geographical, geological, environmental, cultural and physical observations (Table 2). The coding of data refers to the Geopark's Identification Survey for Psiloritis Natural Park where geotopes are listed in accordance with their subpark location (Fassoulas and Skoula 2006; Fassoulas 2008), and to an independent labeling developed for the Lassithi area. Database and statistical sheets were subsequently combined in GIS software for the final visualisation of the results.

Synthesis of Value Indexes

We decided to implement the proposed scoring system using the 63 well-known, studied and managed geotopes of Psiloritis Geopark in order to assess the *scientific*, *ecological*, *cultural*, *aesthetic*, *economic* and *potential for use* values for each site (Mouriki and Fassoulas 2009). The implementation results identify some very important geotopes which coincide with the sites previously suggested to be of international or national importance (Fassoulas and Skoula 2006; Fassoulas et al. 2007). Sites with lower scores coincide with sites previously regarded to be of regional or national importance (Fassoulas et al. 2007).

For the development of the quantitative value indexes we tested several models proposed to date, from which the indexes and related formulae used to evaluate geotopes in this account were derived. To achieve this aim we used the geotopes of Psiloritis Geopark for which an early qualitative assessment was made (Fassoulas and Skoula 2006; Fassoulas et al. 2007) and their values were already known through the various geotouristic and educational activities of the geopark. In addition, to evaluate the response and the differences in the resulting data from the tested models, we have chosen geotopes of various and contrasting types, i.e. of high and low scientific or touristic value, easily accessible or remote sites, protected or non-protected areas, popular or unknown caves etc. Thus, from the 63 geotopes analysed, we initially selected as a model 18 representative geotopes which are already used for multi-geopark purposes, such as tourism, education and conservation (Table 3). The derived formulae were later tested in Lassithi Mountains in eastern Crete, an area where no organized geotouristic or geoconservation activities currently exist (Dimitriou-Nikolakis and Fassoulas 2010).

In contrast to the quantitative assessment method of Reynard et al. (2007) where the final synthetic results are described as a quantitative and qualitative summary for global, educational and endangerment values, or the method suggested by Zouros (2007) where the total sum scored for the criteria is used, we developed an approach more similar to the one proposed by Pralong (2005). Based

Table 2 Spreadsheet used for the collection of the data (example of LA 02)

Name	Dictaion Andro	**Petrology**	Mesozoic limestone
Prefecture	Lassithi	**Category**	Cave
Longtitude	25,44532	**Nappe**	Tripolitsa
Latitude	35,16307	**Altitude**	972 m
Code	La 02		
General Notes			
A most important archaeological site of the mountains. Impressive decoration. Half is open to visitors. Heavily degradated colour of stalagmites and stalactites due to inappropriate lighting used for many decades. Few decades ago, more than 1200 candles were used per day for the visitors needs. 75000 visitors in 2009 (more than 100.000 several years ago)			
Geodiversity	Cave system, impressive decoration with stalagmites, stalactites, columns and curtains. Small lake at the deepest part of accessible cave		
Integrity	Medium to high		
Ecological Impacts	Medium to high impact. Two endemic species of Crete (*Doscoptila lindbergi, Schizidium perpelexum*)		
Protection Status	In spots, the internal part		
Ethics	High visibility due to archaeological importance		
History and Archaelogy	The most important archaeological and historical place of the mountains		
Religious and Metaphysical	The myth for the birth of Zeus (king of ancient greek gods)		
Art and Culture	Many references in songs, poems and local art		
Viewpoints	Low visibility, only by trail		
Landscape difference	Low		
Accessibility	High. Parking, disabled people assistance		
Visitors	Highest		
Intensity of Use	Highest, already replete		
Fragility	High due to improper lighting in past		
Natural Risks	Low		

Table 3 Results of Psiloritis Geopark's geotope assessment (for discussion see text)

Code	Name	LON	LAT	Scientific score	Ecology score	Cultural score	Aesthetic score	Economic score	Potential use score	F_{ecol}	V_{edu}	V_{prot}	V_{tour}
A1	Fodele HP fossils	24.91889	35.38333	8.0	3.0	1.0	3.8	2.4	4.4	0.2	4.8	3.9	4.8
A4	Vossakos folds	24.84611	35.35778	8.5	1.8	2.4	3.8	4.6	7.5	2.5	5.0	4.8	6.3
B10	Kourouna dolines	24.77335	35.2564	6.0	3.0	1.8	5.5	3.4	6.7	5.0	4.5	4.0	4.8
B2	Idaion Andro cave	24.82889	35.2083	5.5	7.5	8.1	7.5	4.6	4.0	0.5	6.8	4.0	5.6
B8	Stefana sinkholes	24.89268	35.26503	5.0	4.3	1.4	7.5	4.6	7.5	7.5	4.6	5.3	4.7
C4	Kroussonas faults	24.96897	35.23435	5.0	1.0	1.0	7.5	4.0	8.5	1.0	3.9	3.2	4.7
C5	Grandma's Pies	25.01057	35.16127	7.5	1.8	3.4	10.0	6.3	8.5	2.5	6.0	3.7	6.6
C8	Zaros spring	24.91222	35.13917	3.7	2.5	3.0	5.0	6.3	4.5	1.0	3.6	3.6	4.2
C9	Rouvas forest and gorge	24.90972	35.16722	7.5	7.5	3.4	10.0	5.0	6.0	2.0	7.2	4.3	5.9
E1	Sfentoni cave, Zoniana	24.84015	35.34499	7.0	10.0	4.4	8.8	4.0	6.0	1.0	7.4	4.7	5.7
F1	Gonies section	24.92583	35.29528	9.5	3.0	2.1	10.0	4.6	9.0	5.0	6.8	6.0	7.0
F4	Marathos detachment	24.98306	35.34528	6.0	1.0	1.0	3.8	3.4	9.0	1.0	3.6	3.5	5.1
A3	Talea Ori section	24.89111	35.38548	8.5	3.0	0.5	5.0	4.4	8.0	5.0	5.1	6.5	6.0
C3	Gonies gorge	24.99194	35.28278	3.5	1.0	2.8	8.8	5.0	7.5	1.0	3.9	3.5	4.5
D4	Cliffs of Vistagis	24.69572	35.24453	2.9	1.8	1.0	7.5	3.4	9.0	2.5	3.2	3.0	3.8
D2	Pantanassa formation	24.60933	35.25539	5.0	1.8	2.4	6.3	3.4	8.0	2.5	4.1	3.7	4.8
B3	Petradolakia, Nida	24.86806	35.21667	6.5	7.5	2.4	7.5	2.1	4.0	2.0	6.1	4.0	4.3
C6	Agia Varvara evaporites	24.99148	35.12604	5.5	1.0	1.0	3.0	3.8	8.5	1.0	3.2	3.3	4.9

LON longitude, *LAT* latitude

on the scored results of the various groups of criteria, we formulated three indexes referring to the *touristic* (V_{tour}), *educational* (V_{edu}) and *protection need* (V_{prot}) values of each geotope. The suggested formulae were analysed in combination with the scoring of the criteria groups described previously using, for each, differently weighted coefficients, depending on the studied value. In contrast to the average values used by Pralong (2005) for his estimation of the tourist and exploitation value indexes, it was decided to introduce weighting coefficients because modern needs for tourism or education are dependent on a wide range of factors. Sustainable tourism, for example, is not based only on picturesque views of landscapes but also on the cultural and economic (local productivity) aspects as well as the capacity of an area to absorb more pressure. Similarly, for environmental educational purposes the scientific value is very important, maybe more than the aesthetic, cultural and ecological values that should also be considered.

Therefore, to estimate the *educational value index* we combine the scoring of scientific, ecological, cultural and aesthetic criteria. However, for the educational process the scientific value should be at least more important than the rest by a factor of one order. Thus the proposed formula (Eq. 1) for the estimation of educational value index is:

$$V_{edu} = 0.4\,Scientific + 0.2\,Cultural + 0.2\,Aesthetic + 0.2\,Ecological \tag{1}$$

Using the same method, for the estimation of the *touristic value index* we combine (Eq. 2) the scoring of aesthetic, cultural, potential for use and economic criteria which together constitute the overall touristic value of a place (Honey 1999), taking into account that for the tourism industry the aesthetic value should be regarded as more important by a factor of at least one order. The proposed formula is therefore:

$$V_{tour} = 0.4\,Aesthetic + 0.2\,Cultural + 0.2\,Potential of\,Use + 0.2\,Economic \tag{2}$$

Finally, for the definition of the *protection-need value index* (Eq. 3) we considered the average score of the scientific criteria score plus the individual score of integrity which can minimize the need for protection if high (we used the formula 11 minus integrity score so that the resulting value will range between 1 and 10, which is in accordance with our scoring system (Table 1)), plus a new factor, the *ecological risk factor*. This *ecological risk factor* (F_{ecol}) is defined by the ecological impact score (criterion 2.1) divided by the protection status score (critetion 2.2) (F_{ecol}= *Ecological impact score/Protection status score*). The ecological risk factor is greater if the ecological impact scoring is high and the protection status scoring is low.

$$V_{prot} = \{Scientific + F_{ecol} + (11 - Integrity)\}/3 \tag{3}$$

This means that the higher the ecological impact score or/and the lower the actual protection status score, the higher the risk is. For example, Diktaion Andro in Lassithi Mountains is a highly protected cave, which has, however, only a medium actual protection status score due to inappropriate past management of the showcave; thus the ecological risk factor appears very high. Simultaneously, Diktaion Andro is of high scientific importance as a cave, giving a low integrity score. Consequently, in calculating Eq. 3 the protection need value should appear considerably high.

Results

The Study Areas

Crete is located in the center of the Hellenic Arc where the subduction of the African lithosphere under the Aegean has been taking place for more than 23 million years (Le Pichon and Angelier 1979). Tectonic processes, however, resulting from the late Alpine orogenesis have taken place in the south Aegean from Eocene times, resulting in the development of a series of nappes on the island of Crete (Fassoulas 1999). The great geodiversity of the Island of Crete has resulted from a variety of geological processes and rock types (Fassoulas 2001; Fassoulas et al. 2007). Almost all rock types can be found in the island's lowland basins and high mountain chains. A number of active tectonic and erosion processes have shaped the island over millions of years forming gorges, caves, plateaus, karstic depressions, valleys, mountains, cliffs, gulfs, lakes, rivers and smaller islands. As a result, the island is characterised by a mosaic of landforms, ecosystems and geotopes.

Psiloritis Geopark

The assessment of Psiloritis Natural Park's geotopes was undertaken several years ago as a prerequisite for the development of the geopark's management and action plan. An ongoing inventory study initiated in 2001 has resulted to date in the recognition of 63 individual sites. An early qualitative assessment was undertaken in order to identify the most important values of these geotopes with respect to their local or international significance (Fassoulas and Skoula 2006), as well as their significance within the national framework (Fassoulas et al. 2007). In the present study, these geotopes were used both for the development of the proposed assessment methodology and for the quantitative evaluation of their touristic, educational and protection necessity values.

Psiloritis Natural Park is located in central Crete covering an area of about 1100 km^2, which includes the main part of Psiloritis Mountains and its northwards extension to Cretan Sea (Fig. 1). Psiloritis is not only the highest mountain on the island but also a place of high environmental variety and wealth. Intense geological processes have sculpted over millions of years a unique and complicated bedrock over which life migrated and developed, adapting its features and behaviours to the changes of surface and landscape. Most of the mountainous area is thus included in the NATURA 2000 list (Fig. 2), mainly due to the high endemism of local flora and fauna and the variety of natural habitats that have to be conserved. In 2001 the Psiloritis Natural Park became a full member of the European Geoparks Network mainly due to its rich geodiversity, and its cultural and ecological beauty as well. The majority of geotopes identified in the geopark consist of karstic features, geomorphological landscapes, fossils sites and tectonic features (Fassoulas 2008).

The geotopes selected for this study (Table 3; Fig. 3) represent major tourist attractions in the area, such as the Idaion Andro cave (which is the place according to mythology where Zeus, the king of the ancient Greek gods, grew up), the beautiful Sfentoni showcave (that receives more than 25,000 visitors per year) and the Zaros springs and artificial lake (a marvellous recreation area); areas important for educational and research activities like the Rouvas Forest and Petradolakia Plateaus (both of high ecological and geological value), the Gonies stratigraphical section (a mile-long section with five different nappes) and the Grandma's Pies (geomorphologic features with plenty of wild flowers); as well as other areas scientifically important but not suitable for geotourism or educational activities, such as the Fodele Permian fossils (the oldest fossils on the island, exposed near the highway) or the Kourouna dolines (a typical karstic but isolated landscape).

The implementation and resulting scoring values of these geotopes can be seen in Table 3. The best geotopes for educational activities are Idaion Andro and Sfentoni caves, Gonies stratigraphical section, Rouvas Forest and Petradolakia areas, where several educational activities and projects are already implemented by the Geopark and the Educational centres of the area. The highest potential for tourism development appears for the Gonies stratigraphical section, Grandma's Pies, Vossakos folds, and Rouvas Forest where the Geopark has recently developed trails and visitor's information facilities. It is worth mentioning that popular tourist attractions like Idaion Andro or Sfentoni cave scored lower values due to the limitations in the number of visitors imposed either due to the fragility of the site (Sfentoni cave) or the ongoing excavations (Idaion Andro cave). The highest protection need values appear for Talea Ori and Gonies stratigraphical sections, as well as for Stefana sinkholes, as a result of intense human activities (traffic, quarrying and waste disposal) and high scientific value. It should also be mentioned that the site of the Fodele Permian fossils, which has one of the highest scientific values and could be used for touristic or educational activities, scored low tourist values mainly due to its location at the sides of the highway and the visitor's safety problems that may appear (Fassoulas 2008).

For visualisation purposes we have developed the map shown in Fig. 4, where the derived indexes values are presented as a series of bars in front of a white square scaled to the maximum score of 10.

Lassithi Mountains

Lassithi Mountains in eastern Crete (Fig. 2) consist of similar rocks to Psiloritis area but differing in the variety of rocks and the number of nappes. More sedimentary rocks and schist occur in the lowlands resulting in the development of many streams and larger forested or cultivated areas. The largest plateau on the island, Lassithi Plateau, with the famous windmills that attract thousands of tourists every year, dominates the landscape. The smaller Katharo Plateau on the eastern side hosts a great variety of rocks, as well as Pleistocene fossils. Many important ecotopes and ecosystems can be found in the general area resulting in the inclusion of the majority of the mountains in the NATURA 2000 list (Fig. 2). Additionally, cultural and historical sites, traditional villages and other natural resources are widespread.

In this study we recognised and considered 21 geotopes (Table 4; Fig. 5) that include five caves (among them the famous Diktaion Andro, the mythological birthplace of Zeus), five karstic structures (Omalos Viannou plateau, Chonos sinkhole, Favetoprinos landforms as well as Havga and Avdou gorges), two geomorphological structures (the Kastellos and Kalamafka Meteora stone towers), three fossil sites (among them the important Katharo Pleistocene mammal site), one tectonic structure (Armacha fold), two water resources sites (Kastamonitsa and Krassi springs), two stone-constructed sites (Littos aqueduct and Seli windmills) and the Talc deposits (Fig. 6). The majority of these, especially the caves and fossil sites, have no protection or are not protected in an appropriate manner, as there is no central management. Thus, these sites face serious risks and threats. Many of these geotopes have strong connections with the history of Crete and local culture. Additionally, some of them are important for the

Fig. 3 Geotopes from Psiloritis Geopark. **a.** Grandma's Pies. **b.** Petradolakia sinkholes and at the background Psiloritis' summit. **c.** Vossakos folds. **d.** Idaion Andro cave

economy of the local population, as many of their economic activities are connected to them (like the Lassithi and Katharo plateau areas).

Lassithi Mountains geotopes were mainly used to test and evaluate the formulae for quantitative assessment developed in Psiloritis Geopark (Mouriki and Fassoulas 2009), as well as for the recognition of their individual values. Their assessment identified some very important sites for both educational and tourism activities, such as the Meteora of Kalamafka and Avdou gorge, and sites which are important either for educational or tourism activities, like Diktaion Andro cave and Kastelos Hills respectively. This assessment also revealed sites that need protection, like the Avdou and Havga gorges, Omalos Vianou and the Talc outcrop (Table 4; Fig. 6). It is noticeable in this case that Diktaion Andro cave, which is the biggest attraction in the area (around 70,000 visitors per year), only receives a score of 4.8 for tourism value which is due to the serious problems of colour degradation of the stalagmites and stalactites resulting from the inappropriate lighting used for many decades.

The most important result of testing the assessment formulae in Lassithi area was the correction (addition of value {11—*Integrity*}) of the *Protection-need* formula that was proposed by Mouriki and Fassoulas (2009). In the latter study, the V_{prot} index was estimated only as the average of the scientific criteria and ecological risk factor (F_{ecol}) scoring. That formula, however, failed to recognise the high protection need for the Talc geotope where an off-road driving field is seriously damaging the outcrop (3.1 old scoring compared to 5.4 using the revised formula). Similarly, underestimated values appeared for the Katharo fossil site (4.25 old scoring as compared with 5.7) that is exposed to risks of weathering and poor protection, the Trapeza cave (2.75 old scoring compared with 4.7) and Diktaion Andro cave (3.63 old scoring compared with 4.7) which is facing threats as a result of insufficient management in former years (Dimitriou-Nikolakis and Fassoulas 2010). The correction of the formula resulted also in more balanced values for some remote and rigid geotopes in Psiloritis Geopark that, in reality, were not facing serious threats, like the

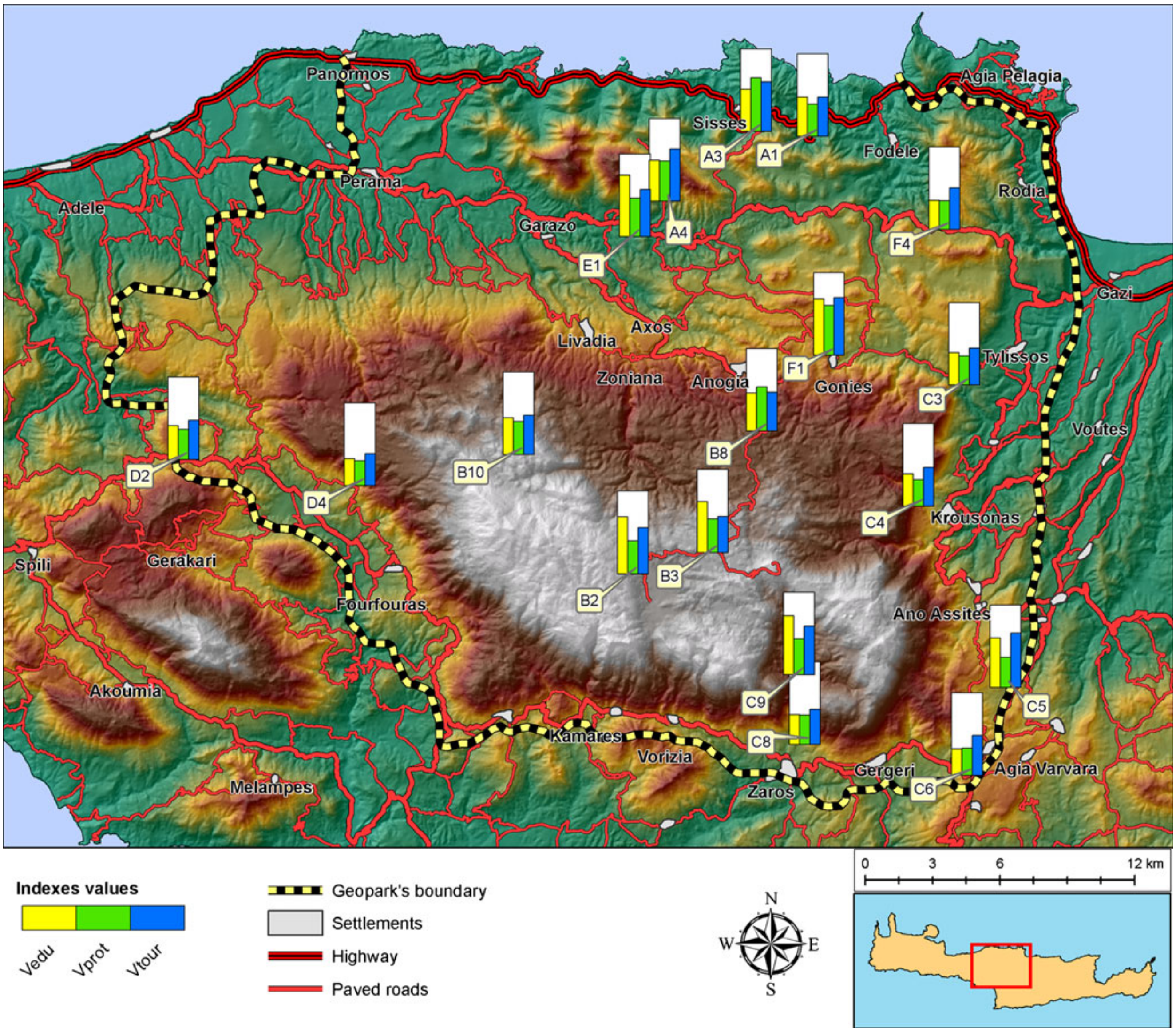

Fig. 4 Results of quantitative assessment of Psiloritis geotopes. Note that the background *white box* in each geotope represents the optimum score of 10. For labels refer to Table 3

Kourouna dolines (5.5 old scoring compared to 4 now) and Grandma's Pies area (5 old scoring compared to 3.7 now).

Discussion

The purpose of this study was to develop a methodology for a quantitative assessment of geotopes capable of demonstrating in a comparable and unbiased manner the tourist, educational and protection-need values. Such an evaluation is currently of the highest priority, not only for scientific purposes but mainly for the management and conservation of geological heritage.

It is the case for any conservation action that funding should be secured not only in the short term but on a longer and constant base. Economic benefits should thus always be considered either for the area's management authority for geoheritage or for the local communities in order to sustain funding for conservation. Consequently, geoconservation should be considered under a broader framework that combines sustainable development and protection of geological heritage, similar to the model of the European Geoparks Network or IUCN's recent initiatives.

Quantitative assessment of geoheritage is thus a useful tool that serves the needs for site management and protection as it can reveal priorities for sustainable tourism development, including geotourism and educational tourism

Table 4 Results of Lassithi Mountains' geotope assessment (for discussion see text)

Code	Name	LON	LAT	Scientific score	Ecology score	Cultural score	Aesthetic score	Economic score	Potential use score	F_{ecol}	V_{edu}	V_{prot}	V_{tour}
L 01	Chonos Lassithiou	25.42778	35.19167	5.7	6.3	2.6	6.3	3.7	3.7	1.5	5.3	3.6	4.5
L 02	Diktaion Andro	25.44500	35.16278	6.5	8.8	7.5	2.5	8.3	3.1	1.5	5.9	4.7	4.8
L 03	Gaidourotrypa cave	25.61882	35.15860	3.5	3.8	1.4	1.8	3.7	4.0	2.0	2.8	3.0	2.5
L 04	Havga gorge	25.52556	35.16444	6.5	3.0	1.8	10.0	5.3	4.5	5.0	5.6	5.0	6.3
L 05	Meteora Kalamafka	25.63722	35.06639	9.0	1.8	10.0	8.8	5.3	6.5	2.5	7.7	4.2	7.9
L 06	Kastelos Hill	25.65756	35.07367	5.5	3.0	5.3	8.8	5.8	5.5	5.0	5.6	3.8	6.8
L 07	Katharo fossils	25.56688	35.14107	8.0	3.8	1.4	1.8	3.7	4.5	0.5	4.6	5.7	2.6
L 08	Kritsa fossil beds	25.59389	35.15333	3.5	1.0	1.0	2.5	4.0	3.7	1.0	2.3	4.3	2.7
L 09	Littos aquaduct	25.38169	35.19876	5.9	4.3	4.0	5.0	2.0	5.0	0.1	5.0	3.2	4.2
L 10	Favetoprinos	25.59700	35.15605	4.5	3.0	1.0	3.8	4.0	7.5	5.0	3.4	4.3	4.0
L 11	Kroustas corals	25.59604	35.11296	5.0	1.0	1.0	2.5	4.0	4.0	1.0	2.9	4.8	2.8
L 12	Talc	25.57941	35.12892	5.2	1.0	1.4	2.5	4.0	2.2	1.0	3.1	5.4	2.5
L 13	Peristera cave	25.45674	35.20182	4.5	5.0	2.0	2.5	3.7	3.7	3.0	3.7	3.7	2.9
L 14	Seli windmiles	25.45469	35.20452	4.4	3.0	4.3	7.5	5.0	7.0	0.2	4.7	3.5	6.3
L 15	Trapeza cave	25.49359	35.19789	3.5	3.8	3.4	2.5	5.8	3.7	2.0	3.3	4.7	3.6
L 16	Agia Foreini cave	25.42353	35.19789	5.0	5.0	8.1	3.8	5.0	1.9	3.0	5.4	4.7	4.5
L 17	Avdou gorge	25.44512	35.22315	7.5	4.3	1.8	10.0	5.8	6.0	7.5	6.2	6.2	6.7
L 18	Krassi spring	25.46750	35.23306	3.7	3.0	4.6	3.8	5.0	4.5	0.2	3.8	2.5	4.3
L 19	Omalos Vianou	25.45300	35.07152	6.0	4.3	4.0	8.8	5.3	5.5	7.5	5.8	5.7	6.5
L 20	Kastamonitsa spring	25.38445	35.19528	5.0	3.8	1.4	5.0	3.2	5.5	2.0	4.0	3.5	4.0
L 21	Armacha fold	25.36715	35.16281	8.0	1.0	1.0	8.8	4.8	7.2	1.0	5.4	3.3	6.1

LON longitude, *LAT* latitude

Fig. 5 Geotopes from Lassithi Mountains. **a.** Seli windmills. **b.** Diktaion Andro cave. **c.** Krassi spring. **d.** the Talc outcrop

activities, and for the conservation of geotopes. As has been documented by the implementation used in this study, our methodology performs very well both in a geopark territory and a non-managed area. It has proved successful in recognising the tourism, educational and protection-need values both in the Psiloritis Natural Park area, which has been a member of the EGN since 2001, as well as in the nearby Lassithi Mountains. The selection of criteria, as well as the scoring system which is focused on regional and national levels, helps in the identification of local priorities, which are very important for the management and protection of geological heritage, either within a geopark or for regional and national planning. Geotopes that have the highest potential for tourism or environmental education development can be easily recognised and can become the focus for such actions. Similarly, the protection need value identifies those geotopes that are facing the highest risks, indicating the priorities for geoconservation in a certain area. Charts and visualisation maps can thus be presented to the decision makers who can decide on the allocation of funding for development and conservation based on unbiased and numerical data.

We have to stress, however, that the qualitative criteria and some quantitative too are assessed in respect to the area of the geopark, in accordance with the purpose of this study to evaluate geoparks' geodiversity. Thus, the overall or net value of geotopes on a national or global scale cannot be achieved directly by applying the proposed methodology; however, the individual scores of the criteria groups can contribute to an evaluation on a national and global level. This means that in order to evaluate geotopes at a national or international level, this scoring should be compared with the overall national or international geodiversity. In a national inventory assessment, the scientific, ecological, cultural, aesthetic and economic criteria can be implied using the correct reference framework, resulting in a quantitative evaluation of each geotope's national importance. On the other hand, the recognition of the global value of a geotope needs further study on the basis proposed by Dingwall et al. (2005), undertaken by an international organisation or group.

It is very important to stress here that for a successful and reliable implementation of the proposed methodology, a multidisciplinary group of scientists has to be established. Earth scientists alone cannot cover the broader topics

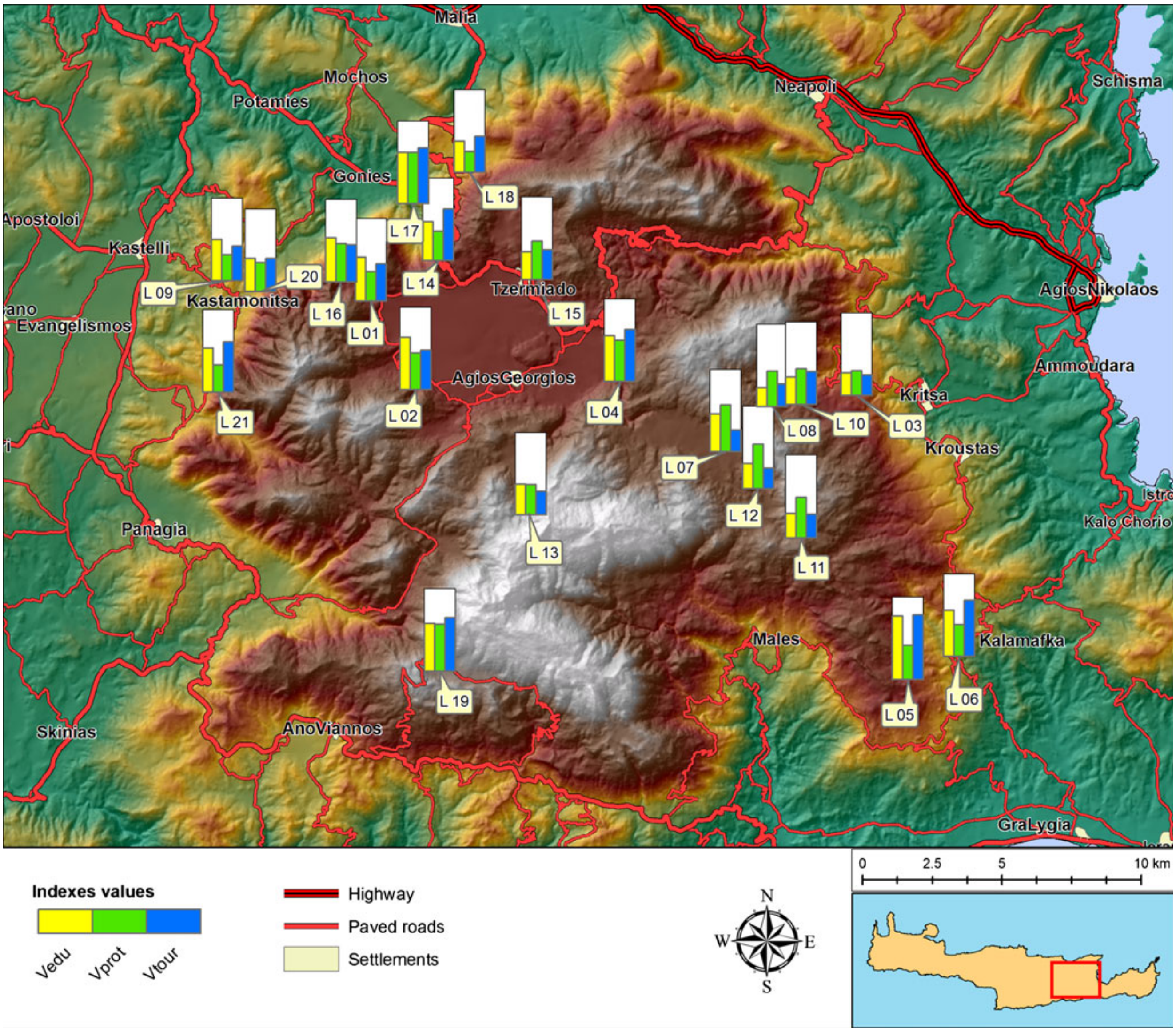

Fig. 6 Results of quantitative assessment of Lassithi Mountains' geotopes. Note that the background *white box* in each geotope represents the optimum score of 10. For labels refer to Table 4

necessary for the complete evaluation of geotopes. Ecological, cultural, historical and economic data have to be analysed together with the geological and geographical information in order to reveal the relations and links between the abiotic and natural heritage and thus to define the real value of each geotope.

Conclusions

This study aims to develop a methodology for the quantitative evaluation of geotopes that can be used for the sustainable management and conservation of the geological heritage of an area. The proposed methodology incorporates the knowledge developed for the evaluation of geomorphosites, and earlier procedures for evaluating all types of geotopes. Our evaluation, however, is based on a series of criteria that cover not only the geological and geographical importance of geotopes but also the ecological, cultural, aesthetic, economic and exploitation factors within the area of a geopark. A common scoring system has been developed based on both qualitative and quantitative measures that indicate the total *scientific*, *ecological*, *cultural*, *aesthetic*, *economic* and *potential for use* value of each geotope.

By identifying conservation and sustainable development actions as the core issues of geoheritage management, we developed three indexes that can present the *touristic*, *educational* and *protection-need* values of each geotope on the scale of 1–10. These indexes come from formulae that combine the scores of the individual criteria groups, using different weighting coefficients for each case. The methodology was implemented in two areas of the island of Crete, the Psiloritis Natural Park, a European and Global Geopark and the Lassithi Mountains, leading to very reliable values which are in accord with the Geopark's activities.

The proposed quantitative assessment method is, therefore, a useful tool which serves the needs for appropriate management and protection of geoheritage in a certain territory as it can reveal priorities for sustainable tourism development, including geotourism, educational tourism activities and conservation of geotopes. In addition, it can also be applied on a larger scale in evaluation studies using the scientific, ecological, cultural, aesthetic and economic criteria scoring to identify the regional or national importance of geotopes.

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