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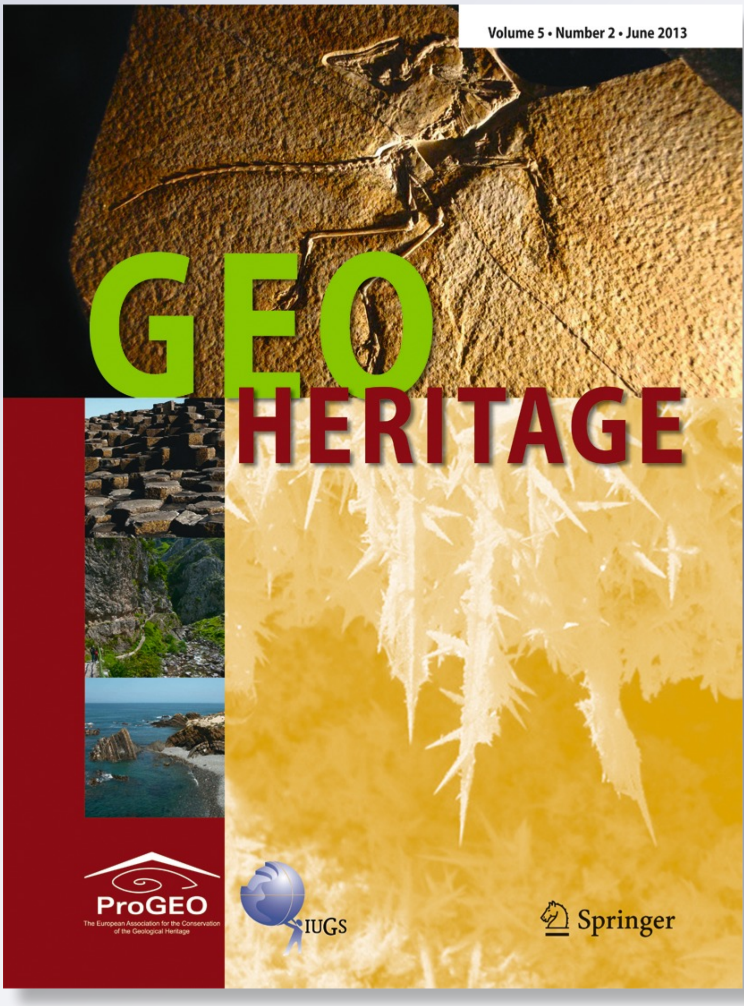

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ORIGINAL ARTICLE

Patch-Scale Relationships Between Geodiversity and Biodiversity in Hard Rock Quarries: Case Study from a Disused Quartzite Quarry in NW France

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Abstract While quarrying can cause significant negative impacts on geo- and biodiversity during the extractive operations, abandoned quarries can enhance biodiversity afterwards by acting as refuges for many plant and animal communities, including a range of rare and/or endangered species of high conservation value. Combination of exposed rock walls and bare surfaces, nutrient-poor soils, water bodies and associated wetlands are some of the abiotic factors that contribute to the wildlife potential of abandoned hard rock quarries. Focusing on the spatial relationships between geodiversity and biodiversity patterns, an eco-geomorphological survey carried out at a disused quartzite quarry, NW France, revealed a strong connection between quarrying landforms and biological assemblages at the patch scale. At this scale, geomorphological heterogeneity (or geomorphodiversity) induced by quarrying provides a diversity of ecological niches adapted to a wide range of plant and animal communities, including some rare taxa of high heritage value (rare, Red Data Book-listed and/or protected species, especially in vascular plant flora and invertebrate communities). Such dependence between geo- and biodiversity directly reflects the rapid adjustment of ecosystems—through primary ecological succession—to the new habitat conditions offered by individual quarrying landforms. This perspective deserves further attention in habitat conservation and landform replication strategies in other localities of hard rock disused quarries.

Keywords Quarrying · Anthropogenic landforms · Biological communities · Ecological succession · Armorican Massif

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Introduction

The extraction of building materials in open-pit quarries represents one of the major anthropogenic impacts on the Earth surface. The impacts of quarrying activities affect all aspects of the environment, including lithosphere (rock excavation and geomorphic changes of the landscape), atmosphere (dust and air pollution), hydrosphere (changes in ground- and surface water) and biosphere (destruction of habitats and loss of biodiversity). As a general rule, impacts of quarrying are classically regarded as threats and potentially damaging to the environment and, in particular, to biodiversity (e.g. Thornton 1996; Langer 2001; Lameed 2011): quarrying activities generally inflict heavy impact at both landscape and community levels, sometimes affecting habitats and species included in the European Habitat Directive (Martínez-Hernández et al 2011; Ballesteros et al 2012). Paradoxically, during the last decades, ecological and botanical studies of quarries in various geological and environmental settings have revealed the ecological potential and biological interest of post-quarrying sites after natural re-vegetation (e.g. Jefferson 1984; Frochot and Godreau 1995; Benes et al. 2003; UNICEM 2008). All these studies point to the positive effects of quarrying on biodiversity, because abandoned quarries act as refuges for many plant and animal communities, including a range of rare and/or endangered species of high heritage value.

The aim of this study is to analyse the relationships between geodiversity (i.e. diversity of exposed substrates, landforms and soils) and biodiversity (i.e. mosaic of plant and animal communities) at the patch scale of a quarry site. At this scale, geomorphological heterogeneity could be viewed as providing a diversity of potential niches for plants and animals (Burnett et al. 1998) that might explain biodiversity patterns and the bioheritage value of quarries. Following this perspective, an eco-geomorphological approach, integrating anthropogenic geomorphology and ecosystem ecology, was carried out at the Cheffois quarry site (Vendée, NW France; Fig. 1) serving as a 'natural laboratory'. Determination of the patch-scale relationships between geodiversity and biodiversity is a major issue with potential applications in quarry restoration and reclamation strategies. The main objectives of this study are: (1) to identify the different types of quarrying landforms and the patterns of geo(morpho)diversity at the site and (2) to characterize the biocenoses (i.e. plant and animal associations) occurring within them. A biocenotic analysis of Orthoptera communities serves as a special case study to illustrate the patch-scale relationships between biotic and abiotic components of the quarry. Including a comparative analysis of positive and negative effects of quarrying on biodiversity, this study finally proposes a discussion on the specific adaptation process of ecosystems to quarrying landforms and on the potential applications to restoration and landform replication within other disused quarries.

Materials and Methods

Study Site

The study site is a disused quartzite quarry within the commune of Cheffois (Vendée, NW France) in the southern

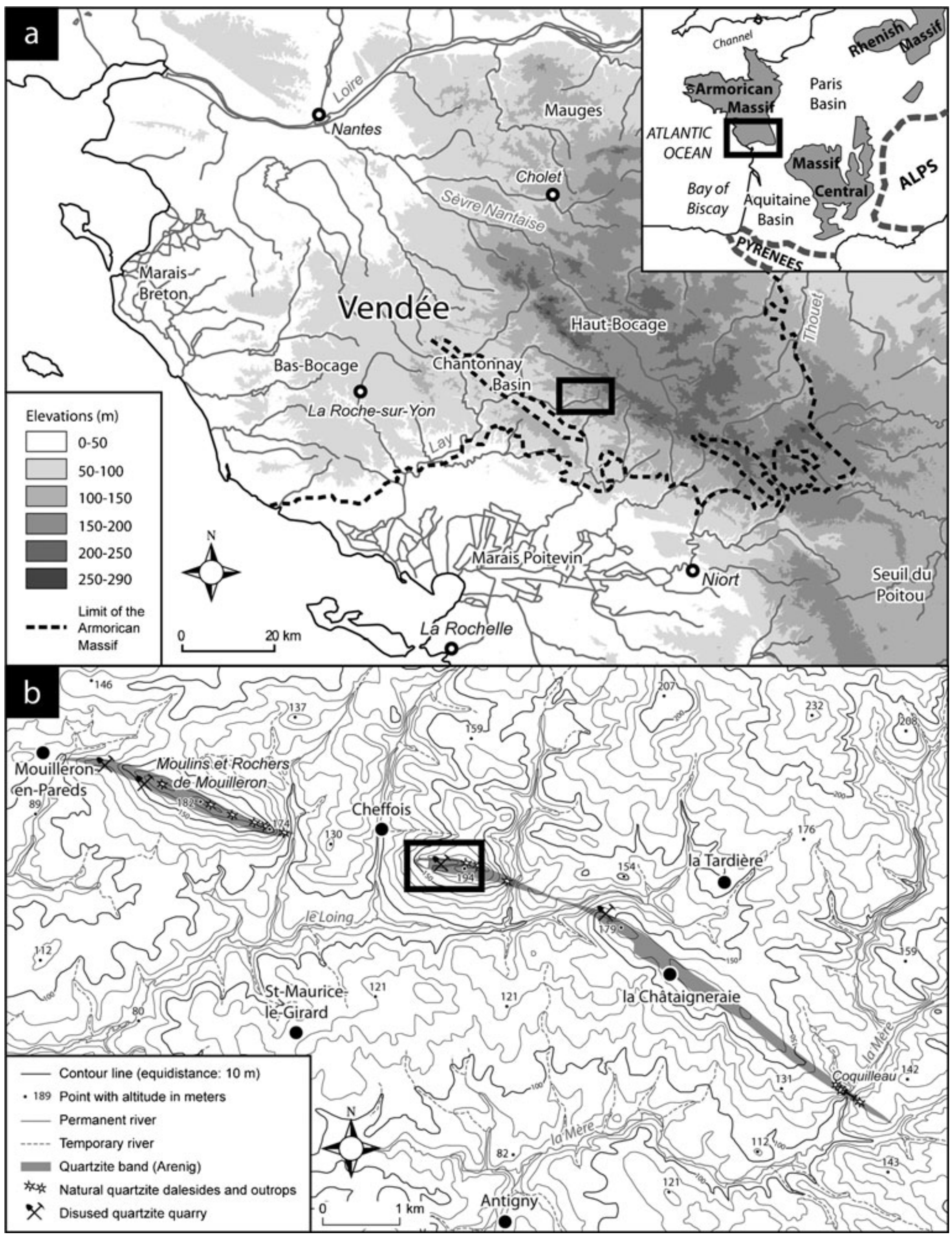


Fig. 1 **a** Location map of the study site in the southern Armorican Massif (Vendée, NW France); **b** simplified topographic map showing the situation of the studied quarry site along the Arenig quartzite band. The *rectangle* in **b** locates Fig. 2

Armorican Massif (coordinates, 46°39′50 N, 0°46′50 W; Fig. 1). The site occurs at the top of a quartzite butte culminating at 194 m above sea level, with a temperate oceanic climate. Rainfall is typically 800–850 mm/year, and mean annual temperature is ca. 13 °C. The quarry was developed in a ca. 100-m thick, Ordovician quartzite unit of Arenig age on the southern flank of a NW–SE-trending Variscan anticline. The extraction site is 600 m long with a maximum width of 100 m, covering a total surface area of ca. 8 ha. Outside the limits of the quarry pit, the surrounding ecosystems and land covers are represented by a grove landscape matrix (*bocage*) where cultivated lands are delineated by discontinuous hedges or tree lines, with small patches of woodlands and copses. In this agriculture-dominated landscape, the soil cover is composed of leached brown soils developed on grey and black schists contrasting with the lithic soils and rock outcrops of the quartzite butte.

During the nineteenth century, i.e. prior to quarrying, the butte of Cheffois was covered by a mosaic of dry heathlands (‘Atlantic moors’) and siliceous grasslands developed on natural dalesides of quartzite associated with lithic soils. This vegetation cover and associated components make up the reference ecosystem. The earliest quarrying activities began in the late nineteenth century, primarily to meet the important needs of building roads and railways at the time. After an initial stage of artisanal (manual) quarrying between 1896 and 1920, the Cheffois quarry site experienced a second stage of industrial development between 1920 and 1953, with the intensification of production means and modernization of facilities (establishment of a mechanical crusher in a raised position, construction of an aerial ropeway, etc.). The quarry site was closed in 1953, leaving a large excavated pit progressively re-vegetating by natural colonization and primary autogenic succession. In addition, as extraction had proceeded below the water table, a large water body, or pit pond, developed in the deepest excavations of the quarry site to the west (Fig. 2). Because of its ecological potential and high biological interest (the site is classified as ZNIEFF type 1: *Zone Naturelle d'Intérêt Ecologique, Floristique et Floristique*: MNHN 2003–2012), the disused quarry was partly acquired by the General Council of Vendée in 1993 for conversion as a protected natural area (ENS, *Espace Naturel Sensible*).

Methods and Data

To characterize landforms and patterns of geo(morpho)diversity in relation to quarrying features, a field-based geomorphological analysis was carried out in the study site, which included a systematic, multiscale description of quarrying landforms (macroforms, mesoforms and microforms), as well as observations on rockwall dynamics and evolution. The nomenclature used for quarrying landforms was adapted from the classification proposed by Dávid (2008). Descriptions of plant and animal communities are based partly on the author's own observations and partly on previous inventories of vegetation patterns (Dupont 1992) and the regional natural heritage (ZNIEFF inventory: MNHN 2003–2012). The compiled and added materials depicting the current state of biological assemblages in the quarry site provide the basis for analysing the patch-scale relations between geodiversity and biodiversity patterns. Special attention was drawn on the heritage value of habitats and biological species (e.g. habitat types of community interest in the European Natura 2000 network, species listed in Red Data Books and Protection Lists) in order to better appreciate the ecological value and the bioheritage of the site.

To complete the analysis of patch-scale relationships between landform heterogeneity and biodiversity patterns, a biocenotic analysis of orthopteran communities (Caelifera: grasshoppers; Ensifera: crickets and bush crickets and the allied Orders: Mantoptera, Phasmoptera) serves as a special case study. Orthopteran communities were chosen because this faunal group presents several advantages and interests, as advocated by some authors (Andersen et al. 2001; Picaud and Petit 2007): (1) abundance and diversity, particularly in open landscapes such as quarries; (2) presence of functional groups and typical species assemblages, favouring the assessment of ecosystem complexity; (3) ease and reliability of sampling and identification; (4) sensitivity to environmental changes and anthropogenic disturbance (orthopteran communities are composed of pioneer species which closely follow plant succession during the natural re-vegetation process). In the study site, a survey of Orthoptera was conducted between 2010 and 2012, mainly during spring and summer months, focusing on the hottest hours of the day, between 1100 and 1800 hours GMT. This study was supplemented by crepuscular and nocturnal surveys that were useful to detect several species of Ensifera (e.g. *Oecanthus pellucens*). For each habitat with homogenous vegetation structure, adult individuals were sampled and identified *in natura* or after capture, using the determination key of Defaut (2001). For the smallest species (e.g. Tetrigidae), determination was verified in laboratory by examination under a ×30 stereo-binocular microscope. Species of the genera *Phaneroptera* and *Calliptamus* were identified only from male specimens. In order to prevent the insects from escaping, the sampling strategy in the field was to move from the periphery toward the centre of each plot. An abundance index was assigned to each species encountered during field surveys in the different habitat types, using the following classes: (+) one to three individuals recorded after a half hour of survey (scarce species), (++) four to ten individuals recorded (fairly abundant species), (+++) more than ten individuals recorded (very abundant, dominant species). The species were finally grouped into synthetic records for each landform/habitat type, with reference to the syntaxonomic system developed by Defaut (1999).

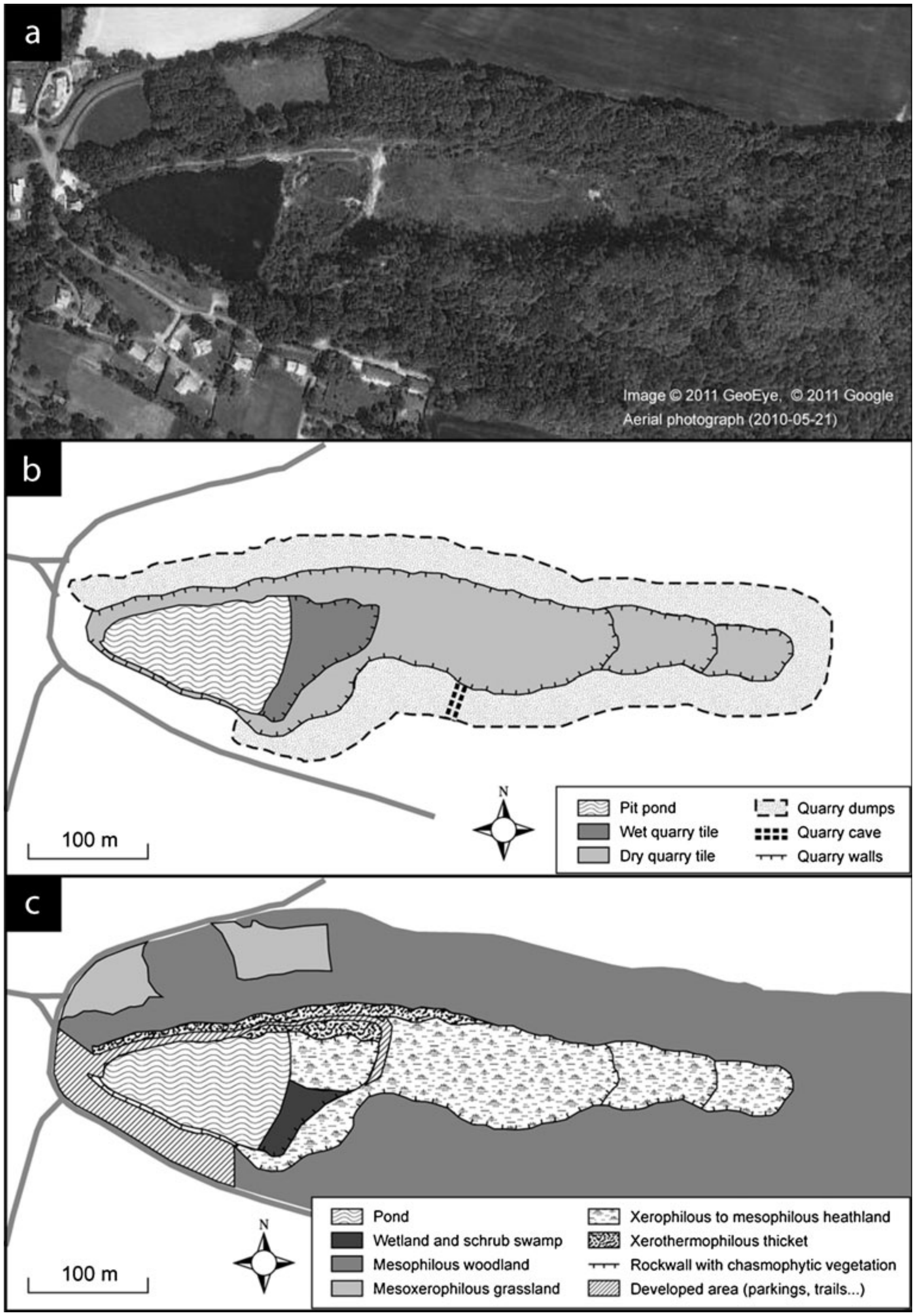


Fig. 2 Environmental setting of the Cheffois quarry site. **a** Aerial view (Google Earth) of the study site; **b** simplified landform map, showing the distribution of the main quarrying features; **c** present-day habitat and vegetation patterns in and around the quarry site

Typology of Quarrying Landforms and Patterns of Geo(morpho)diversity

From a general perspective and as a parallel to biodiversity, geodiversity is defined as 'the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms and processes) and soil features, including their assemblages, relationships, properties and systems' (Gray 2004). Focusing on the geomorphic component of the abiotic nature, the term *geomorphodiversity* is 'a critical and specific assessment of the geomorphological features of a territory, by comparing them in an extrinsic and in intrinsic way, taking into account the scale of investigation, the purpose of the research and the level of scientific quality' (Panizza 2009).

Here, we describe the distribution pattern of geomorphodiversity at the Cheffois quarry site as a direct consequence of extraction activities. Indeed, the extraction of raw materials, or quarrying, may be considered as a geomorphic process since it produces an impact on geomorphological landscapes which undergo fundamental and visible changes (Dávid 2008; Prikryl 2009). Thus, involving artificial erosion (excavation of rocks) and subsequent deposition (accumulation of waste material), quarrying results in a range of new landforms that may be classified into two main categories: (1) excavated landforms, created by artificial erosion, and (2) accumulated landforms, originated by artificial deposition. Within these two categories, quarrying landforms are highly diversified as a function of size and origin, highlighting high levels of geomorphodiversity on a local scale.

Excavated Landforms

Quarry Tiles and Ponds The Cheffois quarry site belongs to a 'complex excavated type' (*sensu* Dávid 2008) resulting from multi-levelled horizon mining. The present-day multi-storeyed scenery is composed of four levels of quarry platforms—or tiles (Fig. 2)—each level representing an approximately flat ground surface, surrounded by quarry walls on three sides and including a range of microforms (sparse accumulations of quarry material in alternation with bare rock surfaces and associated protosoils). In the deeper excavations, a large pit pond occupies the western part of the quarry floor (Fig. 3a). It is ca. 1 ha in surface area and 9 m in mean depth (up to 12–13 m at maximum). The water level of the lake drops ca. 1 m during warm and drier summer months. The water body is bordered by steep rocky banks (5 to 10 m high), with the exception of its eastern shore which forms a smooth transition with a wet quarry level (Fig. 3b). The latter is occupied by small pools and temporary puddles caused by seasonal flooding, in relation to a rise in water table and pond level during winter months. The upper quarry levels are characterized by dry edaphic conditions (Fig. 3c), due to their position well above the water table and to the high permeability of quartzite.

Quarry Walls and Debris Aprons In the study site, quarry walls are steep rocky scarps, or subvertical quarry faces, shaped into steeply dipping quartzite. According to their orientation (E–W dominant) and slope exposition, they are characterized by contrasting microclimatic conditions (wet and shaded north-facing vs. dry and warm south-facing quarry walls). Artificial rockwalls include numerous microforms, such as rock counterforts, rock benches and weathered-out rocks. At the foot of the quarry walls, debris cones and debris aprons have accumulated with smaller angles as talus slopes (Fig. 3d), partly derived from extraction activities and partly from natural processes (rockfalls, dry debris flows). Although they may represent accumulated landforms, their origin is strictly connected to the formation and evolution of quarry walls classified as excavated landforms. Two modes of rockwall dynamics were recognized in the study site: (1) a rockfall-dominated mode, in quarry faces shaped into compact quartzite beds (Fig. 3e), and (2) a debris-dominated mode, in quarry faces shaped into triturated quartzite facies (Fig. 3f).

Quarry Caves Quarry caves are artificial underground landforms or cavities that have been created by excavation during extraction activities. Several underground cavities of different sizes and origins were identified in the quarry site; some of them are old explosive warehouses or compartments. The main quarry cave at the site is a ca. 20-m-long subterranean gallery, located halfway up on the main north-facing quarry wall, 50 m east of the ruins of the crusher (Fig. 3g). It is characterized by a quasi-absence of light, a relatively stable temperature (10 to 15 °C all throughout the year) and high hygrometry levels (>80 %). This type of underground landform is almost unique in the non-karstic environment of Western France, where geological bedrock is dominated by Proterozoic–Paleozoic basement rocks of the Variscan belt (Armorican Massif). Public access to the main subterranean gallery has been prohibited since April 2010 on order of the Prefect, to avoid any disturbance to bats and to promote their conservation at the site.

Accumulated Landforms: Quarry Dumps

As opposed to excavated landforms carved by artificial erosion of quarrying origin, accumulated or depositional landforms can be distinguished in almost every extraction site. Often known as quarry dumps, they are built up by the movement and accumulation of waste materials which had no value from an economic viewpoint during extraction activities (Dávid 2008). In the study site, quarry dumps are distributed all around the excavation pit (Fig. 2b). Accumulation of waste was originated from the removal of overburden from above the fresh rock to be excavated, but also from the processing of the extractive material during grinding and crushing operations. The shape of the dumped material arranged in disordered groups defines here 'a complex accumulated type' (*sensu* Dávid 2008). As a consequence, chaotic topography formed by waste heaps predominates in the landscape (Fig. 3h). Shallow rills and gullies, formed by natural processes, are common microforms on spoil dumps, but the efficiency of linear erosion is today limited by forest vegetation developed on the soft soils of the dumps.

In summary, all these landforms contribute to the high level of *geomorphodiversity* of the quarry at different scales, both in *extrinsic* (rare landforms at the regional scale of the Armorican Massif) and *intrinsic* ways (varied landforms at the local scale of the quarry site).

Biodiversity Patterns in Relation to Quarrying Landforms

According to the 'Convention on Biological Diversity' (accepted during the 1992 United Nations Earth Summit in Rio de Janeiro), biodiversity is defined as 'the variability among living organisms from all sources, including terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems'. One textbook's definition proposes a simplified definition where biodiversity is the 'variation of life at all levels of biological organization' (Gaston and Spicer 2004).

Here, we describe the biodiversity patterns of the Cheffois quarry site in a qualitative way, with reference to typical plant and animal associations in relation with the distribution pattern of quarrying landforms. Special attention is drawn on the heritage value of the habitats and biological species occurring within this pattern of geomorphodiversity. A measure of the health of ecosystems of the quarry is provided by the biocenotic study of Orthoptera communities, serving as potential bioindicators of landform heterogeneity at the patch scale.

Plant Communities

Due to the rich landform assemblage responsible for a mosaic of extremely diversified habitats, high diversity and richness of plant species occur in the quarry site. Vascular plant flora includes some rare taxa of high conservation value which found suitable ecological niches in the areas transformed by excavation activities. The plant communities occurring in the extraction site have very different ecological exigencies in relation to landform and habitat heterogeneity, depending on the nature of the exposed substrate (i.e. from compact rocks on quarry walls and tiles to soft soils on quarry dumps) and the hydro-edaphic conditions (i.e. from wet areas to dry conditions related to different levels of soil humidity or slope exposition) (Fig. 4).

In the lower parts of the quarry site, the pit pond has a poor and low diversified flora, due to the significant water depth and the steepness of the banks. However, in the immediate vicinity of the pit pond to the east, wet areas of the quarry floor are home to swamp hygrophilous species that contribute to the general increase in biodiversity of the area investigated. Annual–perennial herb communities (e.g. *Juncus effusus*, *Juncus bulbosus*, *Agrostis canina*, *Gnaphalium luteo-album*, *Holcus lanatus*, *Molinia caerulea*) develop in the periodically flooded area due to annual fluctuations of water table height.

At higher elevations in the multi-levelled quarry landscape, the plant associations of the dry quarry tile belong to European dry heaths, i.e. a habitat type of community interest that is very scarce and declining in northwestern France (European Commission 2007). More specifically, they correspond to dry Atlantic moors rich in Fabaceae (*Ulex europaeus*, *Cytisus scoparius*) and Ericaceae (*Erica cinerea*, *Erica scoparia*, *Calluna vulgaris*) and include patches of lichenic (*Cladonia* sp.) and bryophytic (*Polytrichum* sp., *Hypnum* sp.) communities of great biological interest (Fig. 3c).

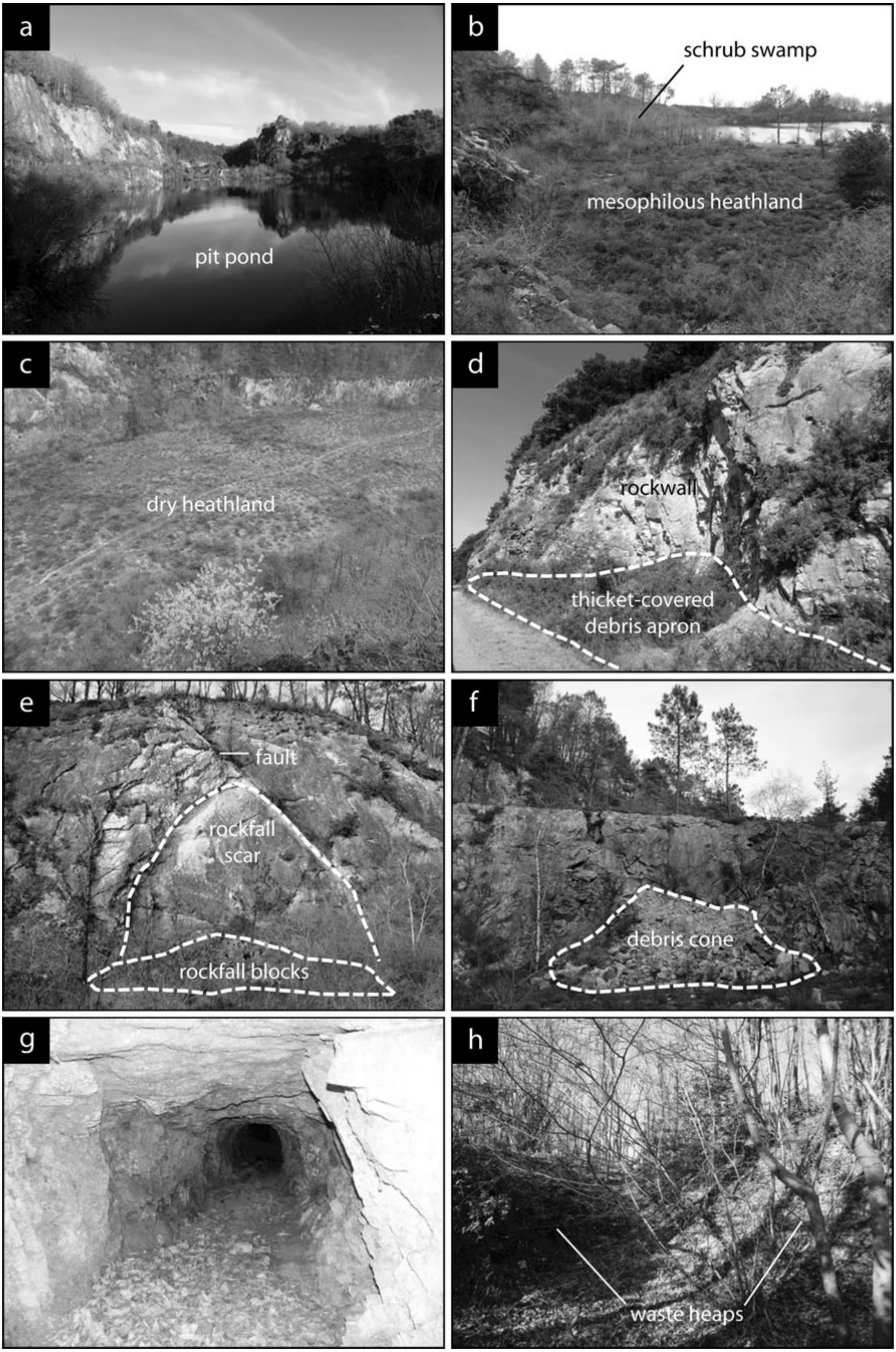
Fig. 3 Photographs of the Cheffois quarry site, showing the main quarrying features and landforms. **a** Overall view of the quarry site, with the pit pond at the foreground and multi-levelled quarry tiles at the background; **b** view of the wet quarry tile; **c** view of the dry quarry tile; **d** quarry wall and thicket-covered debris apron; **e** quarry face with traces of major rockfall and associated block fields; **f** quarry face with traces of dry debris flow accumulated in the form of debris cone; **g** entrance of the main quarry cave; **h** quarry dumps; Photos: F. Bétard

The exposed quartzite walls in the artificial scarps have the highest conservation value in terms of vascular plant flora and high species richness, despite the poorly developed soils and the sub-verticality of landforms. The great majority of these plants grow on microforms such as rock benches and ledges in sun-lit places, but also in the cracks and on the shaded walls, promoting the development of a chasmophytic vegetation typical of siliceous rocky slopes—another habitat type of community importance in the European Ecological Network, Natura 2000 (European Commission 2007). The community of *Asplenio billotti–Umbilicion rupestris* appears typical for the rockwalls of the quartzite quarry. In the south-facing quarry walls, rare or uncommon heliophilous, xerothermic plants develop on the rocky scarps: *Hypericum linariifolium*, *Micropyrum tenellum*, *Anthoxanthum aristatum*, *Sedum anglicum* and, very exceptionally, *Silene vulgaris* subsp. *bastardii*—this last being a subendemic taxa listed in the Red Book of French endangered flora as a species of special concern (Olivier et al. 1995). In the north-facing shaded walls, moss species and ferns (*Polypodium vulgare*, *Pteridium aquilinum*) appear and coexist with *Umbilicus rupestris*, a typical chasmophytic species colonising the cracks and fissures of rock faces.

Contrary to habitats on compact rocks in the quarry floor and walls, quarry dumps are represented by forest communities developed on soft soils. An acidiphilic oak forest of high species diversity, in which *Quercus robur* dominates the tree layer, covers the waste heaps all around the quarry pit (Fig. 2c). The pedunculate oak species is accompanied by significant populations of *Castanea sativa*, *Pinus pinaster* and *Fraxinus excelsior* in places. The undergrowth layer is dominated by *Ilex aquifolium*, *Lonicera periclymenum* and *Ruscus aculeatus*, but contains a very high diversity of shrub and herbaceous species. Two plants of higher conservation value were observed in the lower parts of the spoil dumps, to the north of the quarry: *Mycelis muralis* and *Orchis mascula* (Dupont 1992).

Animal Communities

Given that human pressure is lower than in surrounding cultivated and inhabited lands, abandoned or disused quarries


a
pit pond
b
schrub swamp
mesophilous heathland
c
dry heathland
d
rockwall
thicket-covered debris apron
e
fault
rockfall scar
rockfall blocks
f
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waste heaps

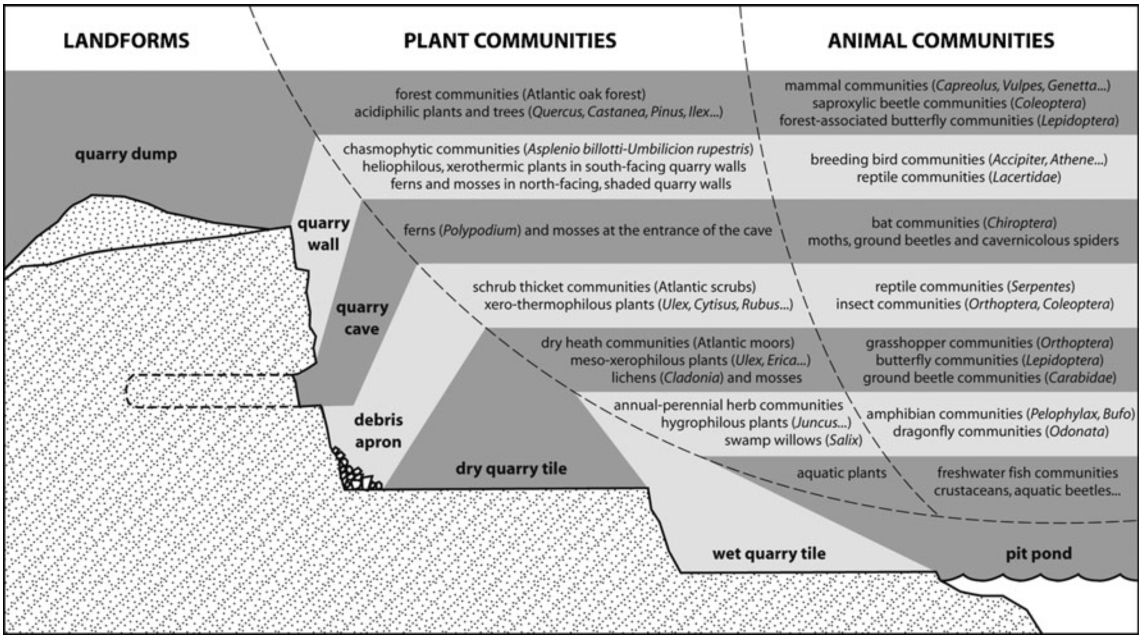

Fig. 4 Synthetic, schematic cross section of the quarry site, showing the distribution of landforms in relation to typical plant and animal communities

appear as areas of relative quiescence for wild animals after cessation of excavation activities. The varied landforms of the Cheffois quarry site, and the mosaic arrangement of biotopes occurring within them, constitute convenient living conditions for a wide range of animal communities (Fig. 4). In the area investigated, many endangered and/or protected species find shelter and ecological niches suitable to their maintenance and development within the quarry.

In the pit pond, aquatic fauna is still poorly known but probably highly diversified, including crustaceans, aquatic beetles and other limnophilous hexapods. A community of freshwater fishes, mainly introduced by man, inhabit the pond, with two species listed in national and international Red Data Books and Protection Lists: *Esox lucius* and *Anguilla anguilla*—this last being considered at the risk of extinction by IUCN. The edges of the lake are breeding sites for amphibian communities, mainly represented by *Pelophylax kl. esculentus*, *Rana dalmatina* and *Bufo bufo*. Close to the pit pond, various insect species occupy the wet quarry tile, especially dragonflies (Odonata). The Cheffois quarry site is notably known to house the rare orange-spotted emerald *Oxygastra curtisii*, a nationally protected species of dragonfly also listed in Annex II of the EU's Habitat Directive.

Within the dry quarry tile, diversified insect communities occupy the miscellaneous micro-habitats and plants of the Atlantic moors, especially grasshoppers (Orthoptera), butterflies (Lepidoptera) and ground beetles (Coleoptera), with some species of high conservation value. Subservient to gorses (e.g. *U. europaeus*) represented in the moors and thickets of the quarry, the green head grasshopper *Chorthippus binotatus* is an endangered species at risk of becoming extinct in the national territory (Sardet and Defaut 2004). Mammal communities are also well represented, with the notable presence of *Genetta genetta*.

Rocky environments of the quarry walls provide conducive niches for a wide range of animal communities, especially breeding birds. Avifauna species include raptors (*Accipiter gentilis*, *Accipiter nisus*, *Athene noctua*) as well as more common species (e.g. *Columba palumbus*) which find favourable conditions to nest in the rocky scarps. At the foot of quarry walls, thicket-covered debris aprons provide refuge for various reptile species (e.g. *Coluber viridiflavus*, *Lacerta bilineata*, *Podarcis muralis*) and diversified insect communities (Coleoptera, Orthoptera).

In the quarry caves, environmental conditions are highly favourable to bats (Chiroptera), which are largely classified as endangered species in Red Data Books. The main subterranean gallery of the quarry site serves as a hibernaculum for several species of Europe's protected bats (listed in Annex II of the EU's Habitat Directive): *Rhinolophus ferrumequinum*, *Rhinolophus hipposideros*, *Myotis mystacinus*, *Myotis nattereri*. A diversified 'cave' microfauna is also represented, including moths (e.g. *Mormo maura*, *Scoliopteryx libatrix*), ground beetles and cavernicolous spiders. In winter, some amphibian and butterfly species find shelter within the gallery, such as the European peacock, *Inachis io*.

On the unexploited quarry dumps, various groups of wildlife species today colonise the forest ecosystem, including mammals (e.g. *Caproleus caproleus*, *Vulpes vulpes*) and a wide range of insect communities. Among the numerous saproxylic beetles recorded at the site, *Cerambyx cerdo*, *Rosalia alpina* and *Lucanus cervus* are probably the most emblematic, because of their high conservation value and protection status in France and Europe. During the spring and summer months, the undergrowth is home to a diversified community of forest-associated butterfly species and to various arboricolous insects (Hemiptera, Coleoptera, Orthoptera).

Case Study: Orthoptera Communities in Relation to Quarrying Landforms

Orthoptera communities (bush crickets, crickets and grasshoppers) are very sensitive to environmental change and anthropogenic disturbance, and are therefore useful bioindicators of landform heterogeneity and ecosystem health in post-mining areas and quarries (Andersen et al. 2001; Picaud and Petit 2007). A total number of 27 species of Orthoptera were recorded at the Cheffois quarry site (Table 1). This total species richness (γ-diversity) for the whole quarry landscape is relatively high when reported from the small area of the study site (8 ha in total) and when compared to the 60 species currently listed for the whole Vendée department (Defaut et al. 2009). The Orthoptera community was divided into four distinct groups corresponding to four types of quarrying landforms with different vegetal structure and levels of soil humidity (Table 1).

Table 1 Systematic list of Orthoptera species inventoried at the Cheffois quarry site

Family	Species	Abundance				Status		
		WQT	DQT	QW	QD	CI	RVI	NRL
Tettigoniidae	*Phaneroptera nana* (Fieber, 1853)		+	++	+	MA	NT	
	Leptophyes punctatissima (Bosc d'A., 1792)			++	++	EU	NT	
	Meconema thalassinum (De Geer, 1773)				+++	EU	NT	
	Cyrtaspis scutata (Charpentier, 1825)				+	EM	RA/𝔑	
	Tettigonia viridissima (Linné, 1758)			++	++	EA	NT	
	Platycleis albopunctata (Goeze, 1778)		++			EU	NT	
	Platycleis tessellata (Charpentier, 1825)		+			EA	NT	
	Pholidoptera griseoaptera (De Geer, 1773)			+	+	EU	NT	
	Ephippiger diurnus (Dufour, 1841)		+			HM	NT	
	Uromenus rugosicollis (Serville, 1839)		++	++	+	EUm	RA/𝔑	
Gryllidae	*Nemobius sylvestris* (Bosc d'A., 1792)			++	+++	EM	NT	
Oecanthidae	*Oecanthus pellucens* (Scopoli,, 1763)		++	++		EA	NT	
Tetrigidae	*Paratettix meridionalis* (Rambur, 1838)	+				EUm	RA/𝔑	
	Tetrix ceperoi (Bolivar, 1887)	+++				EU	RA/𝔑	
	Tetrix undulata (Sowerby, 1806)	++	++			EU	NT	
Acrididae	*Calliptamus barbarus* (Costa, 1836)		+++			EM	NT	
	Oedipoda caerulescens (Linné, 1758)		+++			EA	NT	
	Aiolopus strepens (Latreille, 1804)			+		MA	EN/𝔑	
	Omocestus rufipes (Zetterstedt, 1821)		++	++		ES	NT	
	Chorthippus albomarginatus (De Geer, 1773)	++				ES	NT	
	Chorthippus vagans (Eversmann, 1848)		++	++		MA	NT	
	Chorthippus brunneus (Thunberg, 1815)		++			ES	NT	
	Chorthippus biguttulus (Linné, 1758)		++			EA	NT	
	Chorthippus binotatus (Charpentier, 1825)		++	++		EUm	VU/𝔑	P2
	Euchorthippus declivus (Brisout de B., 1848)	++	+++	++		EUm	NT	
Mantidae	*Mantis religiosa* (Linné, 1758)	+	+	+		MA	NT	
Phyllidae	*Clonopsis gallica* (Pantel, 1915)			+		Eum	RA/𝔑	
	Species richness per habitat (α-diversity)	6	16	14	8			

WQT wet quarry tile, *DQT* dry quarry tile, *QW* quarry walls and associated debris aprons, *QD* quarry dumps, + 1 to 3 individuals recorded after a half hour of survey (scarce species), ++ 4 to 10 individuals recorded after a half hour of survey (fairly abundant species), +++ more than 10 individuals recorded after a half hour of survey (very abundant, dominant species), *CI* chorological index, *EA* Eurasiatic, *ES* Eurosiberian, *EU* European (*EUm* south European), *EM* Euromaghreban, *MA* Mediteranneo–Asian, *HM* Holomediterranean, *RVI* regional vulnerability index, *EN* endangered, *VU* vulnerable, *RA* rare, *NT* non-threatened, 𝔑 striking species (ZNIEFF species), *NRL* national red list (Sardet and Defaut 2004), *P2* priority 2 (at risk of becoming extinct in the national territory)

In the wet quarry tile bordering the pit pond, the species group is typified by the exclusive presence of *Tetrix ceperoi* and *Paratettix meridionalis*, associated with *Tetrix undulata* during the spring season. This association of hygrophilous Tetrigidae is completed during summer months by the dictyopteran *Mantis religiosa* and by mesophilic species of Acrididae, especially *Chorthippus albomarginatus* and *Euchorthippus declivus* that benefit from morpho-edaphic conditions of moderate humidity. In the syntaxonomic system developed by Defaut (1999), the group identified here belongs to hygrophilous synusiae of the *Tetricion undulatae* alliance, in which *T. ceperoi*, *T. undulata* and *C. albomarginatus* are characteristic species.

The dry quarry tile has the highest species richness per habitat (α-diversity) in Orthoptera at the study site, with 16 different species recorded. The group is characterized by the exclusive presence of *Calliptamus barbarus* and *Oedipoda caerulescens*—two xerothermophilous species which are co-dominant in this biotope. They are completed at the shrub layer with abundant populations of *C. binotatus*, *Chorthippus vagans*, *Uromenus rugosicollis* and, more occasionally, *Platycleis albopunctata*, *Platycleis tessellata*, *Ephippiger diurnus* and *M. religiosa*. Given its faunal and synecological characteristics, this group unequivocally belongs to the *Chorthippion vagantis* alliance (Defaut 1999), bringing together the xerophilous synusiae of heaths and thickets in Western France.

At the foot of quarry walls, thicket-covered debris aprons are home to an orthopteran community substantially modified from that of the neighbouring heathlands. This group is characterized by the appearance of partial shade species, such as *Leptophyes punctatissima*, *Phaneroptera nana*, *Pholidoptera griseoaptera*, *Nemobius sylvestris* and *Clonopsis gallica*. In addition to this community, a new species of grasshopper from Vendée—*Aiolopus strepens*—was discovered at the foot of quarry walls in February 2012 (Bétard 2012). From a synsystematic standpoint, this group also belongs to the *Chorthippion vagantis* alliance typical of woody xeric environments in Western France (at the exclusion of dense forests).

Behind the quarry faces, forested dumps are typified by a species group dominated by *N. sylvestris* in the soil litter. Frondicolous species are also well represented with *Meconema thalassinum* and *Cyrtaspis scutata*. Other Ensifera were regularly found at the schrub and tree layers, such as *Tettigonia viridissima*, *L. punctatissima* and *P. nana*. *P. griseoaptera* is scarce in this habitat where it preferentially frequents forest edges. With the presence of characteristic species with southern affinities, this group belongs to submediterranean synusiae of the *Yersinelletali raymondii* alliance.

Discussion

Negative vs. Positive Effects of Quarrying on Biodiversity: a Preliminary Assessment

Like other man-made activities, quarrying originally causes significant impacts on the environment (noise, dust and air pollution, slope instability, changes in ground- and surface water, etc.). One of the biggest negative effects of quarrying is the potential damage to biodiversity. In the study site, the opening of the quarry led to the destruction of rare habitats of high ecological interest (natural dalesides of quartzite associated with dry siliceous grasslands). Consequently, one direct effect is a loss of biodiversity, particularly in vascular plant flora which contained some vulnerable species of high heritage value. Among these species, the rare *Romulea bulbocodium* was described in the late nineteenth century in the site which was at the time the only known location in the Armorican Massif (Marais 1891), before quarrying probably caused its regional extinction, as assumed by several authors (Abraham 1987; Dupont 1992). Since the end of quarrying activities, the plant has never been found and is now listed in Red Data Books as a 'species presumed extinct' in the Armorican Massif and in the Pays de la Loire region. In a similar way, the *Silene vulgaris* subsp. *bastardii*—a subendemic taxon of France with a few stations restricted to the southern Armorican Massif—was removed from the major part of the quartzite butte, with the exception of its central part where a small area of natural quartzite outcrops has been preserved. In combination with *Umbiculus rupestris*, it forms a rare plant community considered as a synendemic association of the Armorican Massif: *Umbilico rupestris-Silenetum vulgaris* subsp. *bastardii*. This plant community has never been observed in the quarry tiles and walls, with the exception of a unique quarry face located in the vicinity of relict natural dalesides.

While quarries can cause significant negative impacts on biodiversity, many positive effects can be observed and measured after cessation of quarrying activities, with the primary colonization of original plant and animal communities in relation to new landforms and habitats. Of particular relevance to the aim of this study, the results showed that the varied landforms of the disused quarry today act as refuges for many plant and animal species, some of which having high conservation value. The ecological gain is especially important since it occurs in a grove landscape matrix (*bocage*) where biodiversity is low and has been declining for several decades because of the intensification of agricultural practices (use of pesticides, removal of hedges, etc.). In detail, the ecological gain seems to be more important for fauna than flora: the diverse landforms of the quarry site, and the mosaic arrangement of new biotopes occurring within them (wetlands, dry heathlands, rockwalls and associated debris aprons, etc.), constitute suitable living conditions for a wide range of animal communities, especially insects, breeding birds, amphibians and reptiles. The presence of underground cavities also allowed the establishment of bat communities, which was not possible in the original geomorphic environment. Furthermore, much of the flora specific to natural quartzite dalesides retrieved the conditions of its original habitat on the quarry tiles and faces, except for a few more vulnerable species, such as *R. bulbocodium* and *S. vulgaris* subsp. *bastardii*. Finally, the structure and diversity of Orthoptera communities well reflect landform heterogeneity in the quarry site, as well as development and recovery of ecosystems after anthropogenic disturbance and cessation of extraction activities. As such, Orthoptera communities are good bioindicators of the overall biodiversity and ecosystem integrity at the study site. All things considered, the estimated biodiversity budget (gain–loss) at the site seems highly positive.

Adjustment of Ecosystems to the Neoformed Pattern of Quarrying Landforms

The process by which new biotopes and ecosystems are connected with the neoformation of quarrying landforms can be regarded as a remarkable example of adaptation of ecosystems to changing landforms (Corenblit et al. 2008; Reinhardt et al. 2010), where biological communities have adjusted to the new habitat conditions offered by the individual landforms produced by quarrying. The adjustment process by which biocenoses adapt to the new quarrying landforms is determined by primary ecological succession, i.e. successional dynamics beginning with the colonization of a newly exposed rock surface created by the excavation. In the study area, plant succession was naturally influenced by anteriority and the proximity of conservation-valuable habitats, e.g. dry siliceous heaths and grasslands which make up the reference ecosystem. In the quarry tiles and walls, the plant succession logically began with the colonization of newly exposed rocks by mosses, lichens and herbaceous plants typical of the above-mentioned dry siliceous grasslands. Since 1953 when the extraction site was closed and abandoned, natural plant succession in the quarry floor evolved toward a dynamics of progressive closing of the vegetation cover, with the development of heaths and thickets, and finally the installation of pioneer tree species (e.g. *Pinus sylvestris*, *Betula verrucosa*, *Populus tremula*). However, the capacity of wildlife to be adaptive to such environmental change varies within biological communities and individual species. Rare and endemic plants are poorly or non-adaptive, as shown by the locally extinct *R. bulbocodium* and the endangered, subendemic *S. vulgaris* subsp. *bastardii*. More common and highly productive species with high fecundity and/or dispersion potential are more adaptive; examples of such species are found within the pioneer Orthoptera community colonising the quarry tile.

During extraction activities, the perpetual adjustment of biological communities to evolving, quarrying landforms is especially relevant. Constantly newly emerging succession zones due to the spatial and temporal changes of quarrying sections constitute typical 'wanderbiotopes' (Rademacher and Tränkle 2010). During excavation operations, quarrying landforms—especially quarry tiles and walls in large and complex sites—are continually renewed, promoting the 'wandering' or displacement of plants and animals from one part of the extraction site to another. Consequently, neoformed habitats of various age and structure coexist in the quarry site and are closely connected via ecological succession process: this is notably the case in the multi-stage quarry tiles of the study site. A typical example of autogenic succession in quarries and mines is also provided by Orthoptera communities which closely follow plant changes during succession process (Picaud and Petit 2007). Furthermore, wet areas occupied by ponds and temporary pools, which can appear within a short time during the extraction process, are often species-rich wanderbiotopes that are colonised very quickly by a range of plant and animal communities (e.g. amphibians, dragonflies). The same process occurs on spoil dumps that are constantly renewed by waste accumulation. All these wanderbiotopes and associated succession zones finally promote the development of high structural diversity, thus enabling rare plant and animal species to settle in the quarry.

Implications for Habitat and Nature Conservation in Hard Rock Quarries

The high conservation potential of the studied quarry site is illustrated by a high proportion of rare, red-listed or protected species among plant and animal communities. In our study, results showed that the neoformed pattern of quarrying landforms acts as refuges for many plant and animal species of high heritage value, especially among vascular plant flora and invertebrate communities. Here, as in other quarry and post-mining sites (Prach and Hobbs 2008; Takeuchi and Shimano 2009; Rufaut and Craw 2010; Tropek et al. 2010), spontaneous succession proves to be an effective restoration tool that enhances biodiversity and promotes the settlement of specialized and/or endangered species. In many cases, this restoration strategy should be preferred to technical reclamation, consisting of covering sites by topsoil or overburden, with the consequence of eliminating the original landforms created by quarrying. In addition to these biodiversity and conservation benefits, spontaneous succession is considerably cheaper and less restrictive, only involving minimal mechanical intervention and maintenance of early successional stages. Obviously, each case is unique, and the best solution to recover a disused quarry depends on several variables related to the characteristics of the site and its surroundings. One alternative could consider that natural plant succession would be accelerated by human intervention, which must set a reference ecosystem in accordance with the ecological profile of the site. In addition, mining companies are today responsible for the restoration planning of disused quarries and mines. Compensatory measures are usually demanded, depending on the law in the country. In that context, planning authorities should also take into consideration the temporary habitats (wanderbiotopes) formed during the extraction process, because of the numerous endangered species that are able to adapt to these ephemeral environments. This confirms the need to manage biodiversity in relation to changing landforms and habitats in quarries, both during and after extraction activities.

One restoration technique in disused quarry sites, named 'landform replication', consists of creating landforms and ecosystems similar to those found on natural dalesides (Gagen et al. 1993). Reconciling anthropogenic landforms with their natural analogues is one of the objectives of this restoration technique that could enhance biodiversity conservation and ecosystem services in disused or abandoned quarries (Lundholm and Richardson 2010). For example, in the studied quarry site, artificial rockwalls mimic the natural dalesides of siliceous rocky slopes with chasmophytic vegetation found in the reference ecosystem—and classified as a habitat type of community importance in the European Ecological Network, Natura 2000 (European Commission 2007). Given the biodiversity patterns and conservation potential associated to quarrying landforms in the Cheffois quarry site, an alternative strategy of landform replication might consist of replicating the recognized anthropogenic landforms and habitats in other quartzite quarries characterized by lower geomorphological heterogeneity and biodiversity. In particular, special attention should be drawn to quarry walls and associated scree slope deposits (talus cones, debris aprons) whose ecological interest has been often neglected (Raska et al. 2011). Such uncommon habitats in non-mountainous regions are home to xerothermic stenoecious species, both in flora and fauna, which can find convenient refuges for living or breeding.

Conclusion

In the broader scope of studying relationships between geodiversity and biodiversity in anthropogenic environments, the Cheffois quarry site serves as an ideal laboratory for integrating anthropogenic geomorphology and ecosystem ecology. From a methodological viewpoint, this study points out the valuable contribution of an eco-geomorphological approach to analyse landform–ecosystem relations in hard rock quarries, whereas most studies in ecogeomorphology—or biogeomorphology—deal with the interactions between fluvial or tidal landforms and ecosystems in active sedimentary environments (e.g. Wheaton et al. 2011; Reinhardt et al. 2010; Corenblit et al. 2008; Fisher et al. 2007; Renschler et al. 2007). Of particular relevance to the aims of this study, the results showed that the diversified patterns of quarrying landforms strongly influenced the biological assemblages at the patch scale of the quarry site. In this case, quarrying acted as a geomorphic process responsible for creating a mosaic of new landforms and habitats, providing a diversity of ecological niches adapted to a wide range of plant and animal communities that enhance biodiversity. Such dependence between geo- and biodiversity directly reflects the rapid adjustment of biological communities to the new habitat conditions offered by individual quarrying landforms. As an environmental paradox, while quarrying activities have a negative effect on the conservation of ecologically valuable habitats and communities in Europe (Mota et al 1996; Thornton 1996; Ballesteros et al 2012), this man-made process of degradation can stimulate biodiversity at disused extractive sites owing to diversified landforms and habitats, as demonstrated with this case study of a quartzite quarry site. Comprehensive research in connecting geo- and biodiversity deserves further attention in habitat conservation and restoration strategies in post-quarrying sites, with the potential application of landform replication to enhance biodiversity in other disused hard rock quarries.

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