A global review on ambient Limestone-Precipitating Springs (LPS): Hydrogeological setting, ecology, and conservation

Marco Cantonati, Stefano Segadelli, Kei Ogata, Ha Tran, Diethard Sanders, Reinhard Gerecke, Eugen Rott, Maria Filippini, Alessandro Gargini, Fulvio Celico

Museo delle Scienze - MUSE, Limnology and Phyecology Section, Corso del Lavoro e della Scienza 3, I-38123 Trento, Italy
Emilia-Romagna Region, Geological Seismic & Soil Survey, Bologna, Italy
University of Innsbruck, Faculty of Geo- and Atmospheric Sciences, Institute of Geology, Innrain 52f, A-6020 Innsbruck, Austria
University of Parma, Dept. Physics & Earth Sciences, Parma, Italy
University of Tübingen, Institute of Evolution and Ecology, Tübingen, Germany
University of Innsbruck, Faculty of Biology, Institute of Botany, Sternwartestrasse 15, Innsbruck A-6020, Austria
Alma Mater Studiorum University of Bologna, Dept. Biological, Geological & Environmental Sciences – BiGeA, Bologna, Italy

HIGHLIGHTS
• Limestone Precipitating Springs (LPS) are ideal to study biocalcification.
• Spring-habitat protection is limited globally; in Europe there is a focus on LPS.
• We present a conceptual model to predict LPS occurrence to meet EU directives.
• Main impacts on LPS are water overdraft and lacking appreciation of their relevance.
• LPS should be a flagship to achieve widespread conservation of springs in general.

GRAPHICAL ABSTRACT

Abstract
Springs are biodiversity hotspots and unique habitats that are threatened, especially by water overdraft. Here we review knowledge on ambient-temperature (non-geothermal) freshwater springs that achieve sufficient oversaturation for CaCO3 by physical CO2 degassing and activity of photoautotrophs to deposit limestone, locally resulting in scenic carbonate structures: Limestone-Precipitating Springs (LPS). The most characteristic organisms in these springs are those that contribute to carbonate precipitation, e.g.: the mosses Palustriella and Eucladium, the crenophilous desmid Oocardium stratum, and cyanobacteria (e.g., Rivularia). These organisms appear to be sensitive to phosphorus pollution. Invertebrate diversity is modest, and highest in pools with an aquatic-terrestrial interface. Internationally, comprehensive legislation for spring protection is still relatively scarce. Where available, it covers all spring types. The situation in Europe is peculiar: the only widespread spring type included in the EU Habitat Directive is LPS, mainly because of landscape aesthetics. To support LPS inventorying and management to meet conservation-legislation requirements we developed a general conceptual model to predict where LPS are more likely to occur. The model is based on the pre-requisites for LPS: an aquifer lithology that enables build-up of high bicarbonate and Ca2+ to sustain CaCO3 oversaturation after spring emergence, combined with intense groundwater percolation especially along structural discontinuities.
1. Introduction: What are Limestone-Precipitating Springs (LPS)?

Springs may represent or feed valuable GDE (Groundwater Dependent Ecosystems; e.g., Klose et al., 2011a, 2011b). Springs are unique habitats threatened by multiple impacts, either anthropogenic (water overdraft, e.g., Powell et al., 2015; contamination or drainage from subsurface excavations) or natural (e.g., the effects of climate change on the hydrologic cycle; Hartmann et al., 2014). One of the main reasons why springs are biodiversity hotspots (e.g., Cantonati et al., 2012a) is that they cover an extremely wide range of water chemistry, temperature, and environmental settings, and sustain a high within-habitat patchiness.

Spring types have been classified on the basis of diverse indicators (Alfar and Wallace, 1994; Kresic, 2010): hydrology (discharge rate, e.g., Meinzer, 1923; Netopil, 1971; recession coefficient, e.g., Gargini et al., 2008; active vs. inactive, Fensham et al., 2015), hydrogeology (e.g., Civita, 1973), geology and morphology (e.g., Springer and Stevens, 2009), physico-chemistry (e.g., electrical conductivity, Total Dissolved Solids, e.g., Clarke, 1924), temperature (e.g., Glazier, 2009, with a transition between cool and thermal groundwater between 30 and 40 °C), flow conditions at the spring head (Thienemann, 1924), and biological characteristics, in particular vegetation (bryophytes + vascular plants; e.g., Ellenberg, 2009) and invertebrate communities (e.g., Gerecke and Di Sabatino, 1996; Schröder et al., 2006; Martin and Brunke, 2012). Furthermore, biota-based spring types can be recognized by using benthic algae forming colourings and/or structures identifiable with the naked eye (Cantonati et al., 2012b), or their diatom microflora (Cantonati et al., 2012c). A comprehensive multi-taxon classification by “Procrustes” analysis showed that each group of organisms provides useful specific spring characters that however are related to other groups only at the level of broad ecological categories (e.g., photoautotrophs, meiofauna etc.; Spitale et al., 2012). In the USA, twelve spring types were distinguished by geomorphology and recurring species (Springer and Stevens, 2009).

Virtually all groundwater is subject to some amount of geothermal heating but this may be very small or negligible in the case of shallow, subsurface, very short recharge-discharge systems. When significant geothermal groundwater heating can be excluded, spring water will be near the mean annual air temperature (MAAT) of the recharge area (cf. Pentecost, 2005), and it was recommended that these be renamed ‘ambient springs’ (e.g., Glazier, 2009).

There is no universally accepted temperature limit for spring water to be designated as thermal, i.e., water that was substantially heated by geothermal energy. In Europe, a temperature of 20 °C at spring emergence is generally accepted (e.g., Boch et al., 2005). Other limits to thermal water have been proposed such as, for instance, 36.7 °C (mean core temperature of humans; Pentecost et al., 2003) and 21.1 °C (70 °F).

Over most of the Earth, the mean annual air temperature near ground is <20 °C (see, e.g., the Köppen modified scheme of world climates). In some areas located in the subtropical high-pressure cells, and over most of tropical lowlands, however, mean annual air temperature is above 20 °C; in consequence, there, ambient-temperature springs can also be warmer than 20 °C (e.g., Carthew et al., 2006). Therefore, we avoid the terms ‘cool’ and ‘hot’ or ‘warm’ to designate spring-water temperature, but prefer to speak of ‘ambient'-temperature springs that are dealt with herein.

With respect to limestone deposition from springs, the temperature of the water at emergence was used for classification. Limestones deposited from thermal springs are commonly termed “travertine”, whereas limestones of ‘cool’ (non-thermal) springs are generally classified as tufa or calcareous tufa (e.g., Pentecost, 2005; Golubic et al., 2008). Both these terms, however, are problematic because they comprise an a priori interpretation of spring-water temperature (which may be difficult to deduce for fossil systems), and of the position of a given limestone within a spring depositional system (in fossil deposits, and even for parts of active spring-limestone deposystems, this may give rise to misinterpretations; see discussion in Sanders et al., 2011). The term tufa also cannot be reserved for highly porous (>10–15% porosity; see Ford and Pedley, 1996; Pedley, 2009) limestones from ‘cool’ springs, because similarly-high porosities are observed in actively-forming travertines of thermal springs. To avoid these confusions, we designate the deposits of Limestone-Precipitating Spring (LPS) neutrally as spring-associated limestones (SAL), irrespective of actual or interpreted water temperature, of derivation of spring waters (meteogene or thermogene), and irrespective of porosity (Sanders et al., 2011; Cantonati et al., 2012b, 2012c).

In general, composition and polymorphism of spring-related minerals are controlled by water chemistry rather than by the microbial communities mediating precipitation (Konhauser, 2007). Most SAL deposits consist of low-magnesian calcite (Table 1). This reflects the most widespread chemical composition of LPS, i.e., Ca2+-HCO3 waters with smaller amounts of other common ions (mainly sulphate, chloride, Mg, Na, K, and dissolved silica). Ambient-temperature LPS with a Mg/Ca molar ratio ≥2.5–3 are comparatively rare; these are characterized by precipitation of magnesian calcite and aragonite (Table 1). The precipitation of low-magnesian calcite is further impeded or modified by elevated concentrations of sulphate, orthophosphate, and some groups of organic substances (e.g., Bischoff and Fyfe, 1968; House, 1987; Plant and House, 2002; Lin et al., 2005; Fernández-Díaz et al., 2010). The impact of any of these compounds on crystal growth, however, seems to depend on many factors (e.g., concentration, pH, association with other ions or molecules), and details are far from resolved. In dysoxic to anoxic LPS, if present even in very low concentrations, Fe2+ can completely block CaCO3 precipitation (cf. Dromgoole and Walter, 1990). At spring emergence, thus, first the Fe2+ has to be removed by iron-bacterial oxidation (e.g., Gallionella, Leptothrix) into virtually-insoluble Fe3+-hydroxides (e.g., Sogaard et al., 2001; Chan et al., 2009). Only when the Fe2+ is exhausted, further downstream, CaCO3 precipitation can start, resulting in ‘mineralogically-zoned’ iron oxide/CaCO3 deposits (Sanders et al., 2011).

The crystal habit of pristine LMC precipitates (pristine = crystal precipitated from and still bathed in its parent solution) is extremely variable and ranges, for instance, from perfect ditrigonal scalenohedra to crystal skeletons to spheroids to needles, to name a few; similarly, crystal size ranges from nanometer- to millimeter scale (see, e.g., Freyted and Verrecchia, 1998; Pentecost, 2005; Turner and Jones, 2005; Shiraiishi et al., 2008). Whereas some correlation of crystal habit with water chemistry is obvious (see above), further influences most probably are degree of oversaturation and turbulence at microhabitat, rate of nucleation of crystals or subcrystals, fluctuations of water chemistry or water supply and, finally, biological mediation of precipitation.
Besides thermal/geochemo/mineralogical characteristics, other aspects of LPS are locally important around the world, e.g. the cultural, environmental, and societal significance of LPS. For instance, in Germany, a small LPS, deposited a large SAL over several thousands of years, known as the largest ‘channel on a stone ridge’ (Ger. Steinerne Rinne) in Germany (40 m long and 5 m high). The ‘Growing Rock’ (Ger. Wachsender Stein) of Usterling, also known as Johannes Rock after John the Baptist, is a natural monument in Usterling (Landau, Bavaria). Its oldest representation can be found on a late Gothic altar in the village church of St. John of Usterling: In one image, Christ’s baptism by John is relocated to this growing rock - a cultural-history curiosity. The illustration shows the natural monument as it should have looked in the 1500s. In 2006 it was admitted to the list of excellent National Geotopes of Germany. Over the rock stands St. John’s Chapel, and at its foot a chapel shrine with a wooden Johannes figure (Bauer et al., 2009). In Section 6 we discuss and even more striking example in Italy (Labante), where a scenic LPS is still active in spite of multiple impacts, it includes impressive fossil SAL extensively used since antiquity (Etruscan), and it is an emblematic example of the development of environmental policies on LPS in the last decades.

This review paper summarizes knowledge on freshwater, ambient-temperature LPS and their biota, on LPS distribution and conservation status worldwide, and on major impact types (e.g., water overdraft, P enrichment, lack of awareness) while providing management suggestions. At the same time the review paper presents a novel conceptual model to predict LPS occurrence from environmental settings, validated by its application to worldwide case studies (own + literature) and discussed illustrating a regional application. One emblematic case study will exemplify the main impact types.

2. Biota and biocalcification

Characteristic and common taxa of the flora and fauna found in LPS are summarized in Table 2, with indication of the microhabitat(s) they typically occupy within LPS systems, and shown in Fig. 1. Whereas elements of the flora can contribute to shape limestone deposition in springs, elements of the fauna of LPS are frequently hindered in their life functions by limestone deposition.

2.1. Flora

Besides the preponderant role of physical CO2 degassing by turbulence, pressure release, and temperature increase of waters from the spring origin to downstream that shifts water chemistry towards oversaturation for CaCO3 (Merz-Preiß and Riding, 1999; Chen et al., 2004), active biogenic processes can lead to deposition of low-magnesian calcite by photosynthetic withdrawal of HCO3- and CO2 (Schagerl and Wukovits, 2014). In addition, passive trapping and binding of particles and enrichment of HCO3- and Ca2+ on organic surfaces (polysaccharides or proteins) can take place (e.g., Merz-Preiß and Riding, 1999; Kowaguchi and Decho, 2002; Turner and Jones, 2005; Dittrich and Sibler, 2010). Downstream changes in oversaturation related to photosynthesis within spring streams may amount to a few percent only (Pentecost, 1992, 2005; Shiraishi et al., 2008), except for situations where Rivularia dominates and/or in larger spring-fed streams (e.g., Rott et al., 2000) where no inorganic limestone precipitation takes place (Shiraishi et al., 2008).

Several phylogenetic lines among oxygenic photoautotrophs are supposed to contribute to biocalcification processes in LPS, including cyanobacteria, eucaryotic algae, and bryophytes (Fig. 1a-i).

Bryophytes (Fig. 1a-e) are the most characteristic organisms that contribute probably to a larger extent to carbonate precipitation in springs, and to the formation of pools and cascades by CO2 consumption in photosynthesis; this holds in particular for widespread (circumpolar and warm temperate) mosses, such as Palustriella commutata (Ger. Wachsender Stein) and warm temperate) mosses, such as Palustriella commutata (Ger. Wachsender Stein) and Palustriella commutata (Fig. 1a-b) Sanders and Rott, 2009; Rott et al., 2012; Linhart and Schagerl, 2015), which shows an almost any worldwide distribution (at least circumpolar, temperate, and tropical); it is documented for China, Cuba, India, North America, and a few locations all over Europe (see summary in Linhart and Schagerl, 2015).

Cyanobacteria are found widespread in both freshwater and marine carbonate depositional environments often related to aquatic in-transition-to terrestrial habitats (stones, soils). Rivularia is one of the most interesting in relation to LPS (Fig. 1g-i). This genus is represented in freshwater and marine habitats (Freytet and Verrecchia, 1998).

Diatoms (Fig. 1f) are seasonally abundant in LPS, mainly during the cold and low-illuminated season (e.g., Sanders and Rott, 2009; Linhart and Schagerl, 2015). Gomphonema calcareaum, in spite of its specific epithet, is usually not observed to form carbonate-encrusted colonies (Levkov et al., 2016). Other Gomphonema species are much more common in LPS (cf. Table 2), in particular Gomphonema latericolumnatum, an indicator species of the spring type carbonate hygropetric springs (= rock-face seepages) and LPS (Cantonati et al., 2012c). Macroscopic colonies of the hard-water diatom species Cymbella excisiformis were
observed in a LPS, however not encrusted with calcium carbonate (MC unpublished data.).

Bryophytes may calcify directly on their surface so that dead organic parts (e.g., stems) remain enclosed in the calcites and degrade gradually (Fig. 1e): in many cases, additional calcification of organisms living on the bryophyte plants, such as diatoms or Oocordium stratum plays a considerable role providing a large surface for smaller biota. Eucaryotic microalgae, such as Oocordium stratum, can precipitate low-magnesian calcite at vertical accumulation rates of up to 10 mm y \(^{-1}\) (Sanders and Rott, 2009); this alga seems to grow only in waters conducive to low-magnesian calcite precipitation (Rott et al., 2012). The initial calcification of O. stratum is highly variable with respect to basal crystallisate fabrics, so that several (at least three major within a cross section of the Alps and within the spring variability) of most probably biotic induced calcification types (calcites) were related to environmental variations in space and time of microhabitat conditions (e.g., pH, temperature, CO\(_2\) oversaturation; Rott et al., 2012).

Several cyanobacterial taxa show indeterminate calcification fabrics found also in LPS, although the precise mechanisms of cyanobacterial calcification are not yet clarified in detail (see e.g., Merz, 1992; Freytet and Verrecchia, 1998; Shiraishi et al., 2008). An interesting example of specific cyanobacterial calcites is known from the genus Rivularia (Fig. 1h-i) with a specific carbonate microfabric identifiable as of cyanobacterial origin (e.g., Flügel, 2004). Rivularia often forms primarily concentric layers within their young hemispheric colonies with calcite rhombs of micro- to orthospar size embedded in the mucilage layers between filament sheaths until finally the trichomes are completely fixed in calcite spar (Obenlüneschloss, 1991). Whereas early calcification is influenced by oversaturation for CaCO\(_3\), along spring streams other factors such as local current velocity and turbulence similarly are important (e.g., Freytet and Verrecchia, 1998; Sanders and Rott, 2009; Gradzinski, 2010).

Diatoms commonly are considered as non-influential with respect to spring calcification (Fig. 1f), yet they appear to contribute by inducing the formation mainly of loose, micritic to sparitic carbonate sediment not firmly bound into specific calcification fabrics (Sanders and Rott, 2009). Detailed microscopic and SEM studies show that diatom frustules associated with CaCO\(_3\) are widespread. In the mucilage of diatom mats, calcite crystals of micro- to orthospar size are common. In addition, diatom frustules and also their stalks are frequently embedded in calcite crystals, and loose aggregates of frustules embedded in clumps of micrite to microsparite are common (Wallner, 1935; Sanders and Rott, 2009). Whether the diatom frustules and their stalks are just passively trapped within the crystals or crystal clusters, or to what extent they took an active role in inducing CaCO\(_3\) precipitation, however, is unknown. In mid-latitudes with a distinct climatic seasonality, the seasonal changes of spring biota associated with changes of water chemistry, temperature and illumination typically impart annual or seasonal laminations to SAL deposits (e.g., Kano et al., 2003; Kawai et al., 2006; Shiraishi et al., 2008; Sanders and Rott, 2009; Arenas et al., 2010).

### Table 2

<table>
<thead>
<tr>
<th>Taxon</th>
<th>LPS formation</th>
<th>LPS-associated ecological niches</th>
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<tr>
<td><strong>PHOTOAUTOTROPHS</strong></td>
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<td>Cyanobacteria</td>
<td>Eu-LPS</td>
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<td><em>Rivularia</em> spp.</td>
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<td><em>Homoerichia crustacea</em></td>
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<td><em>Phormidiun incrustatum</em></td>
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<td><em>Tolyphryx</em> sp.</td>
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<td><em>Scytonema</em> (Myochrotes) spp.</td>
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<td>Hy</td>
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<td><strong>Diatoms</strong></td>
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<tr>
<td><em>Achnanthes trinodus</em></td>
<td>Eu-LPS</td>
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<td><em>Brachysira calcicola</em></td>
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<td><em>Gomphonema lateripunctatum</em></td>
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<td><em>Fregilaria distans</em></td>
<td>Eu-LPS</td>
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<td><em>Denticula elegance</em></td>
<td>Eu-LPS</td>
<td>Hy</td>
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<td><em>Cymbella diminuta</em></td>
<td>Eu-LPS</td>
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<td><em>Cymbella euxiformis</em> (macroscopic colonies)</td>
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<td><strong>Mesophytes</strong></td>
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<td><em>Oocordium stratum</em></td>
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<td><em>Yellow-green algae</em></td>
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<td><em>Vaucheria</em> sp.</td>
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<td><strong>Mosses</strong></td>
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<td><em>Palustriella commutata</em></td>
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<td><em>Esulaudum lenticulatum</em></td>
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<tr>
<td><em>Cyanoprothrix filicium</em></td>
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<tr>
<td><strong>Vascular plants (Brassicaceae)</strong></td>
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<tr>
<td><em>Cochlearia bavarica</em></td>
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<tr>
<td><strong>INVERTEBRATES</strong></td>
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<td>Caddisflies</td>
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<td><em>Rhyacophila pubescens</em></td>
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<td><em>Moth flies (Diptera Psychodidae)</em></td>
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<td><em>Pericoma infasciata gr.</em></td>
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<td><em>Midges (Diptera Chironomidae)</em></td>
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<td><em>Tanytarsus emarginatus</em></td>
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<td><em>Rheotanytarsus reissi</em></td>
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<td><strong>Gammaries (Crustacea, Amphipoda, Gammariidae)</strong></td>
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<tr>
<td><em>Gammarius fossatum</em></td>
<td>Eu-LPS, Lc, Ls</td>
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<td><strong>Salamanders (Caudata, Salamandridae)</strong></td>
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<tr>
<td><em>Salamandra salamandra</em></td>
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<td>Lc</td>
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| Eu-LPS = Eucrenal of LPS, Lc = Liminocrenic, Hy = Hygropetric, Ls = Lotic sectors, Br = Bryophytes & fine-grained sediments. |  |

LPS typically show low faunal diversity. Most animals adapted to this habitat live in pool areas below cascades or in the aquatic-terrestrial interface where allochthonous organic matter accumulates (Table 2). The proportion of specialized spring-dwellers is low, and the fauna of LPS is very poor in character species (Zolliöhöfer, 1997; Martin and Wischniowsky, 2014). In general, faunal richness in springs is found to be directly influenced by microhabitat diversity, in particular by the availability of stable transition-habitats in the aquatic-terrestrial eco-tone. Since the limestone cover produced by CaCO\(_3\) deposition imparts homogenization of microstructures and reduction of microhabitat richness, a low animal diversity is typical for LPS (Dürrenfeldt, 1978; Martin and Wischniowsky, 2014).

Animal species able to persist in the petrified channels are mostly rathrobiotic generalists which migrate from their preferred habitat (mountain streams) into spring brooks (in lotic sectors; gammaries, in pools: salamander larvae and some taxa of Trichoptera).

An exception is the case-less larva of the caddisfly *Rhyacophila pubescens*, which can be considered an outstanding example of LPS in Europe. It is strictly bound to springs and low order stream sectors rich in calcium-carbonate deposits. A genetic analysis showed a rather high isolation of local populations, probably due to habitat fragmentation combined with a low dispersal rate of adults (Engelhardt et al., 2011). With regard to other genera and families, the trichopteran fauna, usually very diversified in springs, is uniform and poor in LPS. Kühn (1940) reports an extreme example of case-building caddisflies literally “caught” and immobilized by quickly growing calcium-carbonate crusts. Most probably, the involved specimens were at a late nymphal stage, at the beginning of pupal quiescence.

Two phenomena observed among Diptera larvae may be mentioned in this context: At oversaturation for CaCO\(_3\), larvae of *Pericoma* species (Psychodidae) tend to become encrusted by calcium carbonate.
The CaCO₃ precipitates preferably around the long dorsal setae which take the appearance of horn-like appendages, but also on other integument structures (Fig. 1j). The animals are obviously not hampered in their lifestyle, and even have advantages such as mechanical body protection and camouflage. Larvae of the non-biting midges (Chironomidae) Tanytarsus emarginatus and Rheotanytarsus reissi normally live in self-produced silk tubes covered by fine sand. In springs and streams with rapid CaCO₃ precipitation they form dense populations associated with Fissidens spp. moss and cyanobacteria of the genus Rivularia in biohermal structures. This so-called “chironomid tufa” (Fig. 1k-l) grows passively without active contribution to CaCO₃ precipitation by the dwelling animals. The abundance of such populations, however, suggests that they profit from this lifestyle (Thienemann, 1934; Kühn, 1940; Burmeister and Reiss, 2003).

As a general rule, decreased faunal diversity correlates with rate of carbonate precipitation in LPS. In “moderate-rate LPS”, formation of riparian transition zones with organic debris and moss/macrophyte...
vegetation may allow for the formation of pools with a typical crenobiotic fauna. In Central Europe, the water mite *Lebertia heloerecnic* is a potential character species of such habitats. The species, however, is known from three sites only (in the Southern and Northern Alps and Prealps; Gerecke, 2009); this highlights the need for more faunistic research dedicated to “moderate-rate LPS”.

3. Worldwide conservation status of Limestone-Precipitating Springs

In Europe, the conservation legislation of LPS is based on the Annex I of the Habitat Directive (EU-HD, 1992) in which LPS are listed as “Petriﬁying springs with tufa formation (Cratoneuron)” (EU-Code 7220). Among spring habitats mentioned in the Habitat Directive, LPS are by far the most widespread. However, for the sake of completeness, we note that the Habitat Directive Annex I includes also two very special and geographically-localized types of springs: “Inland salt meadows” (*Puccinellietalia distantis*, EU-Code 1340, including some inland saline springs), and “Fennoscandian mineral-rich springs and spring fens” (EU-Code 7160).

Inclusion in the Habitat Directive allows designated LPS to be preserved in the frame of the Natura 2000 coordinated network of protected areas. Furthermore, some LPS sites are protected as National Parks or UNESCO World Heritage sites, such as the Plitvice Lakes National Park in Croatia.

In connection to LPS and spring protection, it might be also worth mentioning that downstream and in close proximity to SAL, “springs with iron precipitates” can occasionally be found in form of “mineralogically-zoned” iron oxide/calcium-carbonate depositing streams. This relatively-rare type of spring requires anoxic to dysoxic groundwater conditions, and is remarkable from a mineralogical and biological point of view (cf. Sanders et al., 2011).

On the basis of an international consultation from all continents (see Acknowledgements), it can be stated that the situation in Europe (i.e. spring protection focused on LPS) is very peculiar, and cannot be found anywhere else in the world. Internationally, comprehensive legislation for the protection of spring habitats in general is still relatively rare. In countries where it is available, it covers all spring types, or broad categories of spring habitats (e.g., two categories are considered in Australia: Tertiary springs fed by localized aquifers, and Discharge springs fed by the Great Artesian Basin; Renee Rossini, University of Queensland, St. Lucia, Australia, personal comm.).

However, there are some interesting local situations that combine approaches, or partly differ from the situation as described above.

In Finland, there is no special legislation for LPS but the EU Habitat Directive applies. Interestingly, in addition, at the national level, Finland has the ‘Water Act’ which protects all pristine or close-to-pristine springs as habitats from damaging, and the ‘Forest Act’ which protects the forested marginal surroundings of all pristine/close-to-pristine springs from excess forestry (Jari Ilmonen, Biodiversity Research Programme, Finnish Environment Institute, Helsinki, Finland, personal comm.).

The USA have no protection for LPS (Larry Stevens, MNA Springs Stewardship Institute, Flagstaff, AZ, personal comm.) but there is a very peculiar situation in the State of Minnesota that has undertaken a specific conservation step in favour of LPS.

In Minnesota, there is a state law and associated rules (Minnesota Statutes 103G.223 Calcareous Fens; Minnesota Rules Chapter 8420.0935 Standards and Criteria for Identification, Protection, and Management of Calcareous Fens) aimed specifically at protecting what are defined as calcareous fens, which are peat-accumulating wetland areas supported by upwelling calcium/magnesium-carbonate rich groundwater, often having carbonate precipitates (tufa or marl). This law does not apply to other types of springs, nor are there any other regulations specifically focused on springs (Doug Norris, Wetlands Program Coordinator, Minnesota Dept. of Natural Resources, Division of Ecological and Water Resources, St. Paul, MN, USA, personal comm.).

At worldwide scale water has since long been treated as an economic good. The “sanitary revolution” of the 19th century saw the demand for public ownership and management. This determined an emphasis on the public-good nature of water and led to the development of strongly-subsidized public systems. In the late 1980s, however, there was diffuse “privatization” of public services with all related problems of setting tariffs and prices (Rogers et al., 2002). As a consequence, springs are even more threatened since disregarded as natural habitats, with a strong tendency to consider them exclusively as a source of primarily (economically) precious water resources.

As other freshwater environments, LPS are also threatened by nutrient enrichment. Recent findings of *Ocardium stratum* in 8 springs and spring complexes within a N-S transect across the Alps were mostly from sites with low TP (<10 μg L−1) but variable nitrate concentrations (>2000 μg L−1 in 3 out of 5 sites). This could be an indication that this biocalciﬁer is impeded by excess phosphates (House, 1987; Rott et al., 2012).

4. A conceptual model on ambient-temperature Limestone-Precipitating Springs distribution

Based on direct observations and revision of available published and unpublished datasets, we here present a conceptual model on the formation of LPS, with a focus on geological structure. The main aim of this model is to highlight how the structural-stratigraphic framework controls the hydrologic system in creating compart-ments, bafﬁles, barriers and preferential groundwater ﬂow pathways. In this framework, the proposed classiﬁcation speciﬁcally provides insights on the subsurface structural architecture and physiography of the geological setting, which have been often overlooked in the concerning literature so far, and thus intended to integrate and complement the other widely used classiﬁcations based on different approaches considering the surface expressions of such deposits (see e.g. Pedley, 1990; Ford and Pedley, 1996; Pentecost, 2005; Pedley, 2009; Jones and Renaut, 2010).

Our database also includes those comparatively rare situations in which carbon dioxide is not derived from the atmosphere and/or the soil cover (e.g., Celico et al., 2010), but from deep sources related to hypogenic processes such as anaerobic degradation of hydrocarbons (e.g., Chakraborty and Coates, 2004) and metamorphism of carbonate rocks (e.g., Glassley, 1983; Ague, 2000; Bissig et al., 2006). We however exclude those cases in which “warm” water (compared to the environmental temperature; see above) is involved, and in which CO₂ derivation is directly related to magmatic and hydrothermal processes.

4.1. LPS structural background: types and signiﬁcance

The model proposed focuses on structural heterogeneities and the related distribution of groundwater ﬂow paths, assuming favourable biologi-cal, physical, and chemical conditions for LPS formation at the surface, already described in the classically used schemes deposits (see e.g. Pedley, 1990; Ford and Pedley, 1996; Pentecost, 2005; Pedley, 2009; Jones and Renaut, 2010). The model encompasses six (6) LPS types (Fig. 2) representing different associations of interacting and overlapping processes and products.

Type 1 LPS develops from well to partly consolidated lithologies, where the aquifer is deﬁned by primary (e.g., depositional) and secondary (e.g., diagenetic) matrix permeability due to porosity (e.g., Becker and Shapiro, 2000). The groundwater flow is funnelled and/or vertically compartmentalized. Eventual emergence as an LPS is mainly controlled by depositional-diagenetic discontinuities (e.g., stratigraphic surfaces, diagenetic fronts; Mayo et al., 2003).

Type 2 LPS encompasses situations where the contribution from the matrix is negligible, and the overall bulk permeability of the hydrologic
system is provided by fracturing (Motyka, 1998). In carbonate rocks, bulk permeability can be enhanced by meteoric dissolution, eventually leading to karst systems; these are not specifically discussed herein.

Type 3 LPS refers to Earth-surface processes resulting in un lithi fied to partly lithi fied, mostly coarse-grained sediment bodies with different fabrics, such as talus, alluvial fans, glacial deposits, as well as rock slides and rock avalanches. LPS are concentrated at the margins of the highly porous and permeable sediment bodies, or where the groundwater level intersects the surface of a thicker deposit (e.g., rockslide masses) (e.g., Sanders et al., 2011). Locally, LPS discharge to the surface is associated with significant cementation within the permeated sediment bodies.

Type 4 LPS is associated with shallow- to deep-seated gravitational slope deformations. This type of LPS is typical for mountainous areas with high-gradient streams and steep relief. In the Apennines, slope gravity movements of km-scale slabs (mainly calciturbidite successions and ophiolites) within shale-rich chaotic complexes act as perched isolated aquifers that are effective in producing LPS (Chelli et al., 2013; Gargini et al., 2014; Carlini et al., 2015; Segadelli et al., submitted).

Fig. 2. Diagram illustrating the conceptual model. A. Schematic 2D representation of the 6 type-cases. B. Summary of the occurrence of the type-cases in an hypothetical 3D environment.
Type 5 LPS indicates situations where LPS development is due to fracture corridors arrays related to folding and bending of the hydrogeological formations. The classical recurrent example comprises a topographic-scale antiform breached by upward-fanning, along- and cross-fold fracture sets, representing preferential fluid escape pathways to the surface (e.g., Evans and Fischer, 2012; Ogata et al., 2014). It is important to stress that in this particular case the upward migration of cool water is not driven by temperature but overpressure, due to hypogenic (see below) CO₂ degassing in shallow, compartmentalized aquifers (e.g., Dockrill and Shipton, 2010).

Type 6 LPS comprises aquifers partitioned into highly permeable fault damage zones and low permeability fault cores (e.g., Bense et al., 2013). In these cases, LPS occurrence is related to fault pattern. The sub-groups 6a, 6b, and 6c are differentiated according to fault character: normal, reverse, or strike-slip. The permeability of fault zones is controlled by the degree of cementation of fracture porosity, and therefore related to depth of deformation, strain type and rate. Along with the fracture network sustaining effective rock leaching in the subsurface, associated morphological relief is an additional factor in providing a structurally controlled pressure gradient for meteoric water percolation.

Among the cases in which the fracture-related contribution to permeability prevails, there is a gradual transition from purely gravitational (Type 4 LPS) to entirely tectonic (Type 6 LPS) processes (see Fig. 1a). Deep-reaching fault systems (Type 6) and large-scale fracture corridors' arrays (Type 5) may promote ascend of hypogenic CO₂-rich waters, not necessarily hot, and unrelated to magmatic/hydrothermal activity. In these cases, the CO₂ can be provided by i) oxidation of thermogenic methane, and ii) metamorphism of deeply buried carbonates rocks (e.g., Frey et al., 2015).

The concepts introduced above are similar to those commonly used in the oil and gas industry for the characterization of dual porosity-permeability reservoir systems (e.g., Spence et al., 2014), here adapted to conditions where groundwater is the permeating fluid.

4.2. Worldwide occurrence of LPS types

Through a careful and detailed review of the inherent literature we compiled a database of recognized LPS types and their locations worldwide. As already pointed out above, warm-water-related LPS strictly associated to hydrothermal and magmatic/volcanic processes are excluded. The entire data collection is represented and summarized in Table 3 and Fig. 3.

This compilation, which is function of data availability/quality and intensity of studies in the related regions, is not intended as an exhaustive database for LPS occurrence, but a geographical distribution of examples used to validate the model. The importance of a robust global database, which is beyond the scope of this work, and the general guidelines to a shared workflow are pointed out in the next section. Nonetheless a general overlap with the distribution of carbonate rock outcrops exists, LPS appear unrelated to specific environments or lithologies, being by far apparently and relatively underrepresented in karst systems. This suggests that favourable physical-chemical boundary conditions to LPS development might be achieved by different means and interactions, and that the structural control exerted by the geological framework appear to play a fundamental role.

5. Model application: Limestone-Precipitating Springs territorial information system of the Emilia-Romagna Region (Italy)

Extended inventories on the LPS distribution are often missing or incomplete, mostly because thoroughly field searches of entire geographic areas would be extremely expensive and time-energy-consuming. Information on their occurrence and conservation status is thus absent or poor.

To overcome this limitation, since 2010, the Geological, Seismic and Soil Survey of Emilia-Romagna has activated:

1) the inventoring and cataloguing program of exploited springs (http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/sorgenti-unita-geologiche-sede-acquiferi-appennino. Italian version only);
2) the mapping of the main host hydrogeological complexes;
3) the “Habitat map” cartography within Natura 2000 network and regional Parks (http://ambiente.regione.emilia-romagna.it/parchi-natura2000/consultazione/cartografia-interattiva. Italian version only).

The typical aquifers of the Northern Apennines are silicilastic-calcareous turbidites and ophiolites, and the major perennial springs suffer the impacts of a variety of anthropic activities (e.g., mining, drinking water withdrawal, as for the Labante spring, see below). Few major springs contribute also to the maintenance of environmental flows in streams of the higher mountain range. Another significant threat to these important groundwater resources and related biota is the forced drainage induced by tunnelling for transport infrastructures and/or water-abstraction purposes; relevant are the impacts induced by the drilling of the High Speed Railway connection between Bologna and Florence (Gargini et al., 2008; Vincenzi et al., 2014) that caused the permanent vanishing of natural environmental flows during the dry season (summer) and the complete desiccation of major springs.

The inventoring program of the Emilia-Romagna Region pointed out the existence of 185 LPS (Fig. 4). These initiatives are promoted to abide by the requests of the Groundwater directive (GWD-European Commission, 2006).

Comparing the location of LPS with the distribution of the main hydrogeological complexes in the Emilia Romagna Region, it can be noticed that they preferentially occur near perennial springs fed by groundwater circulation inside carbonate dominated rock aquifers.

The map shown in Fig. 4 represents a first evaluation of the potential LPS-prone areas. In particular, from a first screening, the LPS appear to occur mainly within or along the perimeter of the major hydrogeological complexes. Such areas are the starting targets for dedicated investigation strategies aimed to evaluate the true potential for LPS occurrence.

Given the importance of these habitats, any decision-making policy aimed at protecting and managing LPS requires the prompt availability and consultation of geographic information stored in a comprehensive database accessible to the public. This kind of Territorial Information System represents the most simple and suitable mean to accomplish this task.

6. Case study and suggestions for management

We provide suggestions for an effective and sustainable management discussing a case study in which LPS are left in poor condition because of marked water diversion (total during long drought periods), and because of limited awareness of the conservation value of these fragile environments.

The Labante spring (Fig. 5; Table 4) is a LPS located in the northern Apennines (Castel d’Aiano, Bologna). The spring is an important source of drinking water and a site of high environmental and touristic value. It arises at the southern boundary of a large sandstone plate (Pantano Formation, lower Miocene). The aquifer permeability is given by pervasive fracturing related to high-angle normal faults. A ranking methodology proposed by Gargini et al. (2008) for Apenninic springs was applied to the spring. In the ranking method, S (Slope) type and T (Trans-watershed) type springs are differentiated according to differential elevation of the spring above the local base level, recession coefficient α and average base flow discharge. Labante is classified as T-type spring and therefore has the potential to sustain drinking water supply for local communities and to host freshwater habitats (Bertrand et al., 2012). A
recharge area of 2.61 km² was determined for the spring via numerical
modeling (Gargani et al., 2014; Piccinini et al., 2014).
Carbonate-rich groundwater arising from the spring allows the de-
position of SAL, which occurs in correspondence of a morphologic
drop able to produce a spring-waterfall. SAL deposits grow at the water-
fall front with the formation of a prograding flat surface. An important
system of primary caves (the biggest in Italy) is hosted in these deposits.
The caves and the waterfall represent the main touristic attractions of
the site, while at least three different habitats hosted in the SAL (follow-
ing the EU Habitats directive; EU-HD, 1992) are main grounds for its nat-
uralistic and environmental interest as a Groundwater Dependent
Ecosystem (GDE).

The Labante site (i.e. caves and waterfall) has been affected by
human activities since the ancient age (e.g., exploitation of SAL as build-
ing materials in the Etruscan age, cave frequention). Until a decade
ago the site was in a general state of abandon and decadence, due to
lack of guidelines and regulations for its preservation. Since 1993 the
spring is exploited to gain drinking water. The water diversion occurs
up-gradient from the SAL deposits (Fig. 5), causing a significant de-
crease of flow rate at the waterfall (up to 85% during the dry season).
This produced a significant decrease in the progradation rate of the
SAL front during the last two decades (Piccinini et al., 2014).

Despite the significant impact of water diversion, a biological survey
based on sampling performed in 2011 revealed the occurrence of one
of the most characteristic SAL species: the microalga *Oocardium stratum*
(ER, unpublished data). Moreover, the typical LPS mosses *Palusstriella
commutata* and *Eucladium verticillatum* were found to be dominant
among bryophytes (Daniel Spitale, unpublished data). Among the
diatom microalgae several species characteristic of LPS springs includ-
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*diatom microalgae several species characteristic of LPS springs includ-

Table 3 Worldwide distribution of recognized LPS used to validate the conceptual model. The characteristic type-cases, geographic location, bibliographic reference, and host lithologies are indicated.

<table>
<thead>
<tr>
<th>Conceptual LPS type</th>
<th>Location</th>
<th>Lithology</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mt. Caramato, Mt. Pelpi, Mt. Caio, Mt. Carpegna (northern Apennines, Italy)</td>
<td>Interbedded calcarenites and calcareous mudstones</td>
<td>Chelli et al. (2013), Carlini et al. (2015)</td>
</tr>
<tr>
<td>6</td>
<td>Val Pessola (northern Apennines, Italy)</td>
<td>Coarse- to medium-grained sandstones</td>
<td>KO pers. Comm.</td>
</tr>
<tr>
<td>3, 1, 2</td>
<td>Eastern Alps</td>
<td>Interbedded sandstones and shales</td>
<td>Linhart and Schugel (2015)</td>
</tr>
<tr>
<td>3, 1, 2</td>
<td>East African Rift System</td>
<td>Interbedded sandstones and shales</td>
<td>Ashley et al. (2014)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Colorado Plateau (SE Utah, USA)</td>
<td>Interbedded sandstones-mudstones</td>
<td>Gratier et al. (2012), Frey et al. (2015), Priewisch et al. (2014); Ricketts et al. (2014)</td>
</tr>
<tr>
<td>1, 2, 3</td>
<td>Western Alps (Central Switserland)</td>
<td>Different lithologies</td>
<td>Wehrli et al. (2010)</td>
</tr>
<tr>
<td>5, 6</td>
<td>SE Utah (USA)</td>
<td>Interbedded sandstones-mudstones</td>
<td>Dockrill and Shipton (2010), Ogata et al. (2014)</td>
</tr>
<tr>
<td>5, 6</td>
<td>New Mexico (USA)</td>
<td>Interbedded sandstones-mudstones</td>
<td>Crumpler (2005)</td>
</tr>
<tr>
<td>6</td>
<td>East-central Utah</td>
<td>Interbedded sandstones-mudstones</td>
<td>Jung et al. (2014)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Eastern Tunisia</td>
<td>Different lithologies</td>
<td>Essell et al. (2014)</td>
</tr>
<tr>
<td>4</td>
<td>Sierra del Montsec (Pyreenees, Spain)</td>
<td>Biothermal limestones</td>
<td>Rosell and Linares (2001)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Italoral basin (Southeastern Brazil)</td>
<td>Basement rocks with sedimentary cover</td>
<td>Sant’Anna et al. (2004)</td>
</tr>
<tr>
<td>1, 2, 3, 4, 6</td>
<td>Eastern Alps (Europe)</td>
<td>Carbonate and calcilastic deposits</td>
<td>Sanders et al. (2010a, 2010b), Sanders and Rott (2009), Sanders et al. (2011)</td>
</tr>
<tr>
<td>6</td>
<td>Labante (northern apennines, Italy)</td>
<td>Medium- to fine-grained calcarenites</td>
<td>Gargini et al. (2012)</td>
</tr>
<tr>
<td>2, 6</td>
<td>South Tibet</td>
<td>Metamorphosed carbonate and siliciclastic, and crystalline rocks</td>
<td>Zentmyer et al. (2008)</td>
</tr>
<tr>
<td>2, 4, 6</td>
<td>Southern Apennines (Italy)</td>
<td>Carbonate and calcilastic deposits</td>
<td>Asciene et al. (2013)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Kerch Peninsula (Crimea, Russia/Ukraine)</td>
<td>Layered limestones</td>
<td>Kohl et al. (2015)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Fossil Creek (Arizona, USA)</td>
<td>Mainly aeolian sandstones</td>
<td>Schleicher (2011)</td>
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<tr>
<td>1, 2, 6</td>
<td>Dalhouse Springs (Australia)</td>
<td>Mainly silicilastic deposits</td>
<td>Clarke and Bourke (2011)</td>
</tr>
<tr>
<td>5, 6</td>
<td>Poland, central and western Carpathians</td>
<td>Biothermal limestones</td>
<td>Mastella and Rybak-Ostrowska (2012)</td>
</tr>
<tr>
<td>6</td>
<td>South Australia</td>
<td>Different lithologies</td>
<td>Koppel et al. (2011)</td>
</tr>
<tr>
<td>2, 5, 6</td>
<td>Oman</td>
<td>Ophiolites</td>
<td>Olsson et al. (2014)</td>
</tr>
<tr>
<td>2, 5, 6</td>
<td>Sierra de Alflaguara (Granada, southern Spain)</td>
<td>Calcarenites, limestones, gypsum, marls, sandstones and claystones</td>
<td>Martin-Algarra et al. (2003), Andreo et al. (1999), Prado-Pérez et al. (2013)</td>
</tr>
<tr>
<td>2, 5, 6</td>
<td>Northern Australia, Barkly karst</td>
<td>Limestones and dolomites</td>
<td>Carthew et al. (2006)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Expedition Fjord, Canadian High Arctic</td>
<td>Gypsum-anhydrite</td>
<td>Onelos et al. (2000)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Santa Barbara, California (USA)</td>
<td>Limestones and calcareous mudstones</td>
<td>Ibrra et al. (2014)</td>
</tr>
<tr>
<td>5, 6</td>
<td>Longmenshan, southwestern China</td>
<td>Mixed with dominant carbonates</td>
<td>Shi et al. (2014)</td>
</tr>
<tr>
<td>2, 5, 6</td>
<td>Plitvice, Croatia</td>
<td>Limestones and dolomites</td>
<td>Golubić et al. (2008)</td>
</tr>
<tr>
<td>2, 6</td>
<td>Sleeve Bloom, Ireland</td>
<td>Limestones and dolomites</td>
<td>Heery (2007)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>High Andes, Argentina</td>
<td>Conglomerates, sandstones, and intraclastic limestones</td>
<td>Valero-Garcés et al. (2001)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Taung, South Africa</td>
<td>Limestones and clastic-soil cover</td>
<td>McKee (2010)</td>
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<tr>
<td>1, 2, 6</td>
<td>Sears Lake, California (USA)</td>
<td>Conglomerates, sandstones, and intraclastic limestones</td>
<td>Guo and Chafetz (2012)</td>
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<tr>
<td>1, 2, 6</td>
<td>High Andes, Peru</td>
<td>Different lithologies</td>
<td>Acosta and Prat (2011)</td>
</tr>
<tr>
<td>2, 5, 6</td>
<td>Paris Basin, France</td>
<td>Limestones and clastic-soil cover</td>
<td>Freyset and Piet (1996)</td>
</tr>
<tr>
<td>1, 2, 6</td>
<td>Pyramid Lake, Nevada</td>
<td>Un lithified lithologies</td>
<td>Benson (2004)</td>
</tr>
<tr>
<td>1, 3</td>
<td>Guadalandara, Spain</td>
<td>Un lithified lithologies</td>
<td>Pedley et al. (2003)</td>
</tr>
</tbody>
</table>

4334
compiled to address the management of the drinking-water exploitation (minimum sustainable flow) and the site conservation (sustainable tourism, e.g.: proper access ways, monitoring of human activities potentially negative for the GDE).

7. Conclusions

Springs and spring-associated limestones have been classified before with highly different perspectives (e.g., according to types of...
sedimentary facies, geomorphology, or botany) (see also review in Ford and Pedley, 1996). Our classification presented herein emphasizes the combined structural–geomorphological–hydrogeological aspect of LPS, so it seems best suited for regions of differented relief, such as highlands and mountain ranges. Our concept is not explicit on the type, facies architecture or size of spring-limestone deposystems; these features can be categorized in classification schemes presented previously (e.g., Pedley, 1990; Ford and Pedley, 1996; Carthew et al., 2003; Capezzuoli and Gandin, 2004; Jones and Renault, 2010; Keppel et al., 2011). In mountain ranges, because of topographic relief and steep slopes, by far most spring limestone deposystems may pertain to the ‘perched springline (slope system)’ type of Ford and Pedley (1996, p. 123 f.). To achieve a more distinguishing characterization, depending on area, it may be desirable to further divide the perched-springline type into subgroups (e.g., Sanders et al., 2010a, 2010b). Travertines or hot-spring limestones are commonly associated with volcanism and/or with active faults guiding fluid ascend; therefore, travertines can be recorders of neotectonic deformation (e.g., Hancock et al., 1999; Minissale et al., 2002; Capezzuoli and Sandrelli, 2006; Zentmyer et al., 2008; De Filippis and Billi, 2012). With respect to the association of travertines with faults, mainly the structural aspects of our concept also are applicable to hot LPS.

Herein, Limestone Precipitating Springs (LPS) are understood as springs of ambient-temperature waters (no geothermal contribution) that achieve sufficient oversaturation for CaCO₃—mainly by physical CO₂-degassing and photosynthetic activity— to deposit limestone.

LPS support specific calcifying organisms, mainly cyanobacteria, algae, and mosses. The invertebrate fauna is of low diversity, and is limited to a very few adapted specialists coexisting with several generalists tolerating the permanent environmental stress by carbonate precipitation.

LPS are found on all continents but do not have a special protection status in most countries yet. This contrasts with the current situation in Europe where LPS are the most protected spring type (listed in Annex I of the Habitat Directive). Special protection status is primarily due to aesthetic, cultural and touristic reasons, and only secondarily to the scientific interest as key sites for ongoing geogenic processes including biocalcification.

To support mapping of LPS in fulfilment of the Habitat Directive, we developed a conceptual model based on fundamental stratigraphic and structural conditions to predict where LPS are more likely to occur in a particular region, with a focus on the geologic structure. This should facilitate an integrated view on spring phenomena and help optimizing management. The main impacts on LPS are due to inappropriate management underlain by missing awareness. It is thus important to disseminate knowledge on spring habitats, and to urge the application of flow splitters to sustain long-term persistence of key biota.

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References


Arenas, C., Óskar, C., Sanchez, C., Vázquez-Urbé, M., Auque, L., Pardo, G., 2010. Seasonal record from recent fluvial tufa deposits (Monasterio de Piedra, Spain): sedimentological and stable isotope data. In: Pedley, H.M., Rogerson, M. (Eds.), Tufas and Speleothems: Unravelling the Microbial and Physical Controls Geologic of

Table 4

<table>
<thead>
<tr>
<th>Hydrodynamic, physical, chemical, and topographic features of the Labante spring. Data obtained from a continuous monitoring performed at spring 2003 and in 2010–2011.</th>
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<tr>
<td><strong>Altitude (m a.s.l.)</strong></td>
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<td><strong>min</strong></td>
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<td>612</td>
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Fig. 5. View from above (left; summer; aerial view) and from the side (right; winter) of the Labante SAL. The SAL outcrop is outlined in both views (red line). The man-made channelization of water towards the waterfall is highlighted on the aerial view (yellow line).


