Meteorites and craters found in Chile: a bridge to introduce the first attempt for geoheritage legal protection in the country.

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Abstract

This contribution presents a short historic review of meteorites and impact craters found in Chile, and how they were recently proposed to be protected as geological heritage, helping to introduce for the first time the concepts of geoheritage and geodiversity to a political level in the country. It includes a table with the percentages of the different type of meteorites found in Chile, for a total number of 1064 official meteorites declared to the Meteoritical Bulletin until July 2017.

1. Introduction

Chile has very particular geological characteristics, only partially shared with other countries: i) it is on a convergent margin zone, where two oceanic tectonic plates – Nazca and Antarctica – subduct under the South American continental plate. This configuration provokes important seismic activity and the development of a magmatic and tectonic setting that creates one of the largest active volcanic chains in the world, the Andes Mountains; ii) it has an abrupt relief which, in less than 200 km, rises from sea level to almost 7,000 m above sea level; (iii) it has more than 4,300 km of continental coastline; iv) it presents a latitudinal variation of approximately 38º which is reflected in a great climatic variety, including desertic regions in the north, mediterranean in the center, subpolar and oceanic conditions in the south and the extreme icy caps present at peninsular and continental Antarctica where Chile has many scientific-military bases.

The characteristics mentioned above, among many others, make Chile a territory with great comparative advantages in terms of geodiversity, and a world-renowned laboratory for the study of the Earth sciences.

One particular territory, the Atacama Desert, in northern Chile, has proved to be an excellent place to understand the effects of hyper arid climate regimes sustained in a long period of time, as i) the existence of the most clear skies on Earth, that have attracted the main astronomy observatories of the world to put their telescopes there; ii) the preservation of enriched mega porphyry copper deposits (Alpers and Brimhall, 1988), making the copper industry one of the main economical activities of the country; c) the existence of Mars-like-soils (Navarro-Gonzalez *et al*., 2003) and other extreme environments for the study of extremophile life (Azua-Bustos *et al*., 2012) as a planetary laboratory for the search of life; d) and recently, the discovery of the highest densities of meteorites per km^2 (Hutzler *et al.*, 2016) in some of its surfaces, due to their old ages and sustained stability over millions of years (Dunai *et al*., 2005), allowing the preservation of this rare material, as well as some impact structures.

However, at present the country does not have legislation specifically oriented to preserve its geodiversity, and the need to have an ethical behavior about it is not part of its present social and cultural values.

This paper describes a particular type of geological heritage: meteorites and impact craters found in Chile. It will be given a short historic review of their study in our country, discussing its main values and threats. In addition, it will be shown how these extraterrestrial geological materials and structures have helped to introduce the concepts of geoheritage in the country, allowing the proposal of the first legal request for protection of these materials in the Chilean history.

2. Extraterrestrial rocks and impact structures in Chile

Meteorites and micrometeorites (<2mm) are natural objects that survive their pass through Earth's atmosphere and succeed to arrive to the surface. They fall randomly all over the world, in the order of 10^4-10^5 tons per year (Hutchison, 2004), but only less than 1% of this amount has an appropriate mass to be recovered. They can accumulate in desertic areas (Bland *et al*., 1996) as Antarctica and hot deserts as North West Africa or Atacama (Chile), where the availability of liquid water – the major factor to destroy them – is restricted. Because they can fall everywhere, all countries can deal with the situation to witness a meteorite fall or report a find of these extraterrestrial rocks. However, there is little knowledge about the subject in most countries, and just a few of them have properly address the question of how to deal with this natural extraterrestrial material, and conduct protocols for doing so.

The importance of these rocks is given by the fact that they are the oldest solid remnants of the Solar System formation that scientist can access here on Earth. Most of them come from asteroids, but a few can also come from the differentiated crust of the Moon and Mars. Each of them represents a part of the puzzle which scientist from different research areas study in order to better understand how was form Earth, and how and where life started. So their protection should be considered a must, rather than only a need, because even if it can be of a national interest, it is, above everything, a world heritage natural object.

Today, due to the lack of legal protection in most countries, there is a meteorite market that operates in two modes as a formal and officially ruled market, and another that correspond to a black market. In the first one, most of the offers are private collectors grouped by the International Meteorite Collectors Association (IMCA). It operates guided by an ethic code that rules the behavior of any transaction, and respects the law and/or regulations for meteorites in different countries, most of them following the lineaments suggested by the Meteoritical Society.

The Meteoritical Society is an international scientific organization leading and promoting the research on Meteoritics, responsible for the record and authentication of new meteorites through the Meteoritical Bulletin periodic publication. This organization calls to donate at least the 20% of the meteorite to a scientific institution that can perform science with them – the type specimen –, but encouraging the donation of representative samples of meteorites to the local institutions where these meteorites were found, to promote education and research in meteoritics (http://www.meteoriticalsociety.org, accessed August 2017).

The fact that meteorite search expeditions are an expensive endeavor, difficult to address just by governmental institutions, add to the fact that ~90% of all the finds corresponds to a very well known type of meteorite, the ordinary chondrites (OCs), are the reasons why many countries have avoid to pass through an official legal protection of them, and only in special cases they have been protected (e.g. Argentina, Australia, Spain, among others) (Valenzuela, 2009).

By the other hand, impact structures are less evident on Earth than in the rest of the solid bodies of the Solar System, due to the effect of the recycling lithosphere process, add to the strong forces of superficial erosion driven by active atmosphere, hydrosphere and biosphere. In total there are ~190 proven impact structures in the world (http://www.passc.net/EarthImpactDatabase/ accessed August 2017), eleven of them located in South America, being one of them the Monturaqui impact crater, located in northern Chile, that is presented here, as well.

2.1. Meteorites found in Chile

Twelve years ago Chile had only ~60 official meteorites (Muñoz *et al*., 2007), some of them found by miners looking for ore deposits in the Atacama Desert from the early XIX century until the 1990's, as the historic meteorites Imilac, a pallasite found around 1820 and described in the treatise "*Viaje al desierto de Atacama*" (Phillippi, 1860), and the mesosiderite Vaca Muerta, discovered in 1861, one of the more massive meteorites found in Chile so far, with 3,8 tons, from which Domeyko and Sandt wrote reports (Pedersen *et al*., 1992). In 1983 private collectors – the brothers Rodrigo and Edmundo Martínez – restarted the search for meteorites in the Atacama Desert, rediscovering big mass fragments from Vaca Muerta and Imilac, and little craters associated to them (www.museodelmeteorito.cl accessed July 2017). They defined the first dense collection area (DCA) called Pampa (Zolensky *et al*., 1995), located in the flat lands of Mejillones Península, near the city of Antofagasta, with ~30 meteorites from different falls, collected in an area of 30x15 km^2 (Pampa and La Yesera meteorites), now renamed as Pampa de Mejillones and La Yesera DCAs.

Until those years Chile was still considered as a place with low potential to find more meteorites due to the difficulty given by the fact that most of the surface rocks were volcanic in origin, looking very alike the stony meteorites (Scherer and Delisle, 1992), very different to the perfect contrast displayed in other deserts, as Sahara and Nullarbor.

Other meteorite collections were at the Mineralogical Museum of Copiapó (at least 6 different meteorites, most of them irons), the Geological Museum Humberto Fuenzalida at Universidad Católica del Norte (Antofagasta), Geological Museum of the National Geological Survey (Santiago), and Chilean Natural History Museum (Santiago). Some important samples were robbed from these museums, other were not preserved in the right conditions, forming rust and breaking apart, and other just disappear for lack of a proper procedure to keep them well catalogued. Most of these issues could have been avoid with the good practices of a professional curator.

Little was done scientifically those years, and most geologists took it only as a hobby. Carlos Roeschmann, once the director of the National Geological Survey's Laboratory, was one of the only Chilean geologist that were interested to do research on meteorites, making connections with the national private collectors and other international museums, and teaching an elective course of Meteorites in the Geology Department at the Universidad de Chile in the years close to 2000.

Valenzuela (2003) and Valenzuela (2011) were the first scientific works done in Meteoritics in Chile, that created the base of fruitful collaborations that started the expeditions to Atacama Desert to search for meteorites and study the population of ordinary chondrites (OCs) found there. Valenzuela *et al*. (2008) describe and quantify the weathering products found in Atacama OCs for the first time, using Mössbauer spectroscopy, while Munayco *et al*. (2013) continue the characterization of the weathering mineralogy for new samples discovered in other DCAs. The study of the flux of meteorites was addressed in Gattacceca *et al*. (2011) and Hutzler *et al*. (2016a), where densities of meteorite per km^2 were calculated for San Juan and El Medano DCAs, respectively, demonstrating an amazing concentration in certain surfaces, as at El Medano DCA, with more than 150 meteorites/km^2, due to the old and stable surfaces of the desert and the existence of meteorites with terrestrial ages reaching 2 My (Hutzler *et al*., 2016b).

Knowing that a few private collectors were operating in a permanent way in the Atacama desert, most of them working under the procedures established by the IMCA and the Meteoritical Society, the scientific team responsible of the Atacama Meteorite Search Expeditions – lead by Gattacceca and Valenzuela – contact them to offer the possibility of a collaboration. In this way it was improved the information about all the recoveries, a percentage of the meteorites was kept in a scientific institution, and the new discoveries were quickly notified, not only of meteorites, but also of the first tektites found by them, now known as Atacamaites (Devouard *et al*., 2014). By their side, they could save time, having an authenticated official meteorite in approx. six months, in contrast with the year they had to wait when they send their samples to American institutions.

At present, the number of official Chilean meteorites is 1064 (https://www.lpi.usra.edu/meteor/metbull.php accessed in July 2017), and is dominated by OCs by far, corresponding to the 92% of the total amount (Table 1). As pointed by Gattacceca *et al*. (2011), the recovery of other kind of stony meteorites in Atacama, beside OCs, is quite difficult as the surfaces are dominated by volcanic rocks of different types, and without the fusion crust, an achondrite, for example, will appear very similar to the most abundant rocks in the desert.

As is shown in Table 1, there are some scarcer meteorite types in the Chilean collection, as carbonaceous chondrites (18), the meteorite El Medano 301 that corresponds to an ungrouped reduced chondrite (Pourkhorsandi *et al*., 2017), and 46 irons.

2.2. Craters

Along with research studies relevant to the previously described meteorites in Chile, there have also been reports and studies of extraterrestrial impact craters. The Vaca Muerta set of holes, the Imilac small crater, and the Monturaqui explosion crater are examples of such cases, all of which are located within the Atacama Desert.

The Monturaqui impact crater is a paradigmatic case in terms of conservation because it presents a set of antecedents (Table 2) that, according to the Chilean Geological Society (SGCH), elevate it to the category of geological heritage of national relevance (http://sociedadgeologica.cl/crater-de-impacto-monturaqui/ accessed in July 2017). However, it does not count with any legal standing that may protect it, although there are a number of present and potential factors that threaten to damage it (Table 2).

The crater is approximately 3000 m above sea level and is located in the Andean foothills, south of the Atacama Salt Flat. It has an almost circular structure, ~350 m in diameter and ~34 m deep (Figure 1). The target rocks of the impact are composed of Ordovician granite basement cut by various small mafic dikes (1-2 m wide) and covered by a thin (0-5 m) discontinuous layer of Pliocene ignimbrite (Rathbun *et al*., 2016). Along with the structure some fragments of the remains of the impacting meteorite were found, a thick group I octahedrite as determined by Buchwald (1975), as well as many impactites.

Table 1. Number of meteorites found in Chile, per types, present in the official list of the Meteoritical Bulletin (July 2017), compared with the total amount of meteorites (total falls and finds of the world), and their percentages.

Meteorites	Chile	(%)*	(%)**	Total***	(%)*
STONES					
Chondrites					
Carbonaceous	**18**	**0**	**2**	**2162**	**4**
CB	1	0	0	20	0
CH	0	0	0	24	0
CI	0	0	0	9	0
CK	1	0	0	346	1
CM	0	0	0	545	1
CO	10	0	1	558	1
CR	3	0	0	178	0
CV	0	0	0	426	1
Ungrouped	3	0	0	43	0
Ordinary	**981**	**2**	**92**	**49015**	**83**
Petrologic type 3	67	0	6	2809	5
H	547	1	51	22157	38
L	383	1	36	19614	33
LL	51	0	5	7244	12
Other chondrites	0	0	0	1113	2
Enstatite	0	0	0	599	1
Rumuruti	0	0	0	183	0
Kakangari	0	0	0	4	0
Ungrouped chondrites	1	0	0	19	0
Melt (impact)	4	0	0	308	1
TOTAL CHONDRITES	**1004**	**2**	**94**	**52290**	**89**
Achondrites					
Primitives achondrites					
Acapulcoites-lodranites	1	0	0	148	0
Brachinites	0	0	0	41	0
Winonaites	0	0	0	30	0
SUBTOTAL	**1**	**0**	**0**	**219**	**0**
Differentiated achondrites					
Aubrites	0	0	0	74	0
Ureilites	3	0	0	451	1
HED's	4	0	0	1893	3
Howardites	0	0	0	341	1
Eucrites	3	0	0	1112	2
Diogenites	1	0	0	440	1
Lunar meteorites	0	0	0	306	1
Martian meteorites	0	0	0	198	0
Angrites	0	0	0	28	0
Ungrouped	0	0	0	80	0
Enstatite achondrite				13	0
SUBTOTAL	**7**	**0**	**1**	**3043**	**5**
TOTAL ACHONDRITES	**8**	**0**	**1**	**3262**	**6**
Unclassified stony	0	0	0	1888	3
TOTAL STONES	**1012**	**2**	**95**	**57440**	**97**

Table 1. Cont.

Meteorites	Chile	(%)*	(%)**	Total***	(%)*
STONY IRONS					
Pallasites	1	0	0	114	0
Mesosiderites	5	0	0	235	0
TOTAL STONY IRONS	**6**	**0**	**1**	**349**	**1**
IRONS					
Magmatic					
IC	0	0	0	12	0
IIAB	6	0	1	129	0
IIC	0	0	0	8	0
IID	1	0	0	24	0
IIF	0	0	0	6	0
IIG	2	0	0	6	0
IIIAB	16	0	2	309	1
IIIE	1	0	0	18	0
IIIF	1	0	0	9	0
IVA	5	0	0	84	0
IVB	3	0	0	15	0
SUBTOTAL	**35**	**0**	**3**	**620**	**1**
Non-magmatic					
IAB Complex	9	0	1	300	1
IIE	1	0	0	22	0
SUBTOTAL	**10**	**0**	**1**	**322**	**1**
Iron-Ungrouped	1	0	0	121	0
Iron (not classified further)				97	0
TOTAL IRONS	**46**	**0**	**4**	**1160**	**2**
TOTAL METEORITES	**1064**	**2**	**100**	**58949**	**100**

* percentage calculated from the same category
** percentage from the total amount of meteorites
*** Total = world falls + finds

Based on the paleomagnetic measurements on rocks inside the crater and the use of cosmogenic isotopes to constrain the terrestrial age of the impactor meteorite, the age of the crater was estimated to be 500-600 ky (Valenzuela *et al.*, 2008). Through microscopic study of the minerals that composed the impactites, Roeschmann and Rada (2000) estimated that the heating effect produced during the collision exceeded 1400ºC and dissipated an amount of energy similar to the explosive impact produced by ~2.2 atomic bombs such as those used in Hiroshima.

The crater have been visited extensively along the years by scientific and non-scientific expeditions, both of them damaging the edges of the crater due to the entrance of motor vehicles inside the structure. The place has been cleaned out of all the remaining impactites and iron shales, but its shape and ejecta deposits still remain, along with its scenic beauty, making it a special place to come to observe and learn about one of the most important geological processes occurring in the Solar System, craterization, and its consequences in the origin and evolution of life on Earth.

Table 2. Values and threats of the Monturaqui impact crater.

VALUES	
Type	**Description**
Scientific	It is the only confirmed impact structure from explosion of an asteroid in Chile and one of the few recognized in South America. It is a simple crater (< 1km in diameter), relatively well conserved for its age and, as such, a one-of-a-kind natural laboratory for the morphological study of these type of craters and their processes.
Cultural	It posses an exceptional historical value since it was part of the Qhapaq Ñan or "Inca Trail" (Hyslop, 1984), which was recognized in 2014 as a World Heritage Site by the UN.
Scenic	It has a great scenic value (Figure 1), being part of the Atacama Desert and the Andean Precordillera, offering a privileged view of the Andean massif to the East and the Atacama Salt Flat, to the North. The gullies next to the crater, also, grow a variety of native high Andean plateau flora adding beauty to its surroundings.
THREATS	
Type	**Description**
Legal	Chilean law has not yet legislated on any sort of specific protection for impact craters.
Collecting	Collection and sales of impactites and specimens from the crater is common and have been performed by both touristic and scientific expeditions. An iconic example of this threat occurred when the television show Meteorite Men, from the Science Channel, visited and camped inside the crater, collected and later sold the specimens they had gathered[1].
Erosion	Erosion inside the crater is common due to the flux of vehicles that enter and exit it.
Mining	The entire area is surrounded by mining concessions for both exploration and exploitation purposes.

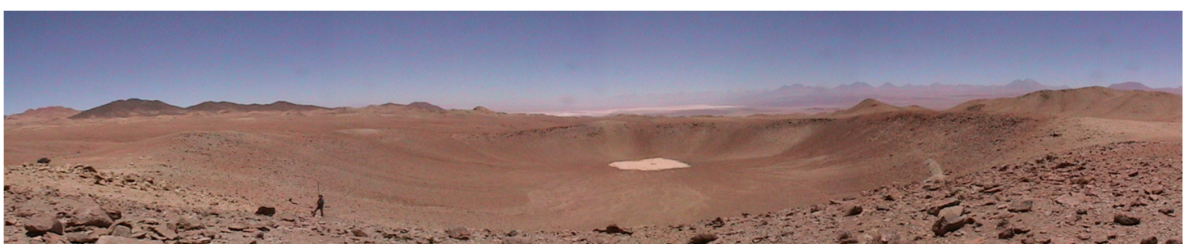

Figure 1. Monturaqui impact crater. View to the North. Photo by Hernan Ugalde (in Ugalde et al., 2007)

Efforts have been done to raise concern about this situation among the atacameñan community of Peine that own these lands. At present the SGCH, the Millennium Institute of Astrophysics and the Centro de Estudios de Montaña foundation, along with the Peine community, are trying to declare the Monturaqui crater as a Historic Monument to protect it, presenting the first formal request to the Chilean Government during 2017.

3. Law Proposal for Meteorite Protection

It has been a long way to build Meteoritics in Chile. The steps have included a continuous

[1] The Monturaqui episode is available at: https://www.youtube.com/watch?v=giZU9mlEMAM

effort to participate in the annual expeditions organized by the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE, France), lead by Dr. Jérôme Gattacceca, in a frame project associated to the study of hot desert meteorites, not only in Chile, but also at Algeria, Tunisia, Morocco and Iran deserts.

The number of Chilean scientists working in meteorites over time have been almost none, but the actions taken by Valenzuela in different national scientific meetings (Valenzuela 2009, 2015, 2016) to raise awareness about the situation of Chilean meteorites, specially after the publication of the high densities discovered at Atacama (Hutzler *et al.*, 2016), have made a positive response in the geological community.

The main collection of meteorites recovered from Atacama in the last expeditions (2004 – 2016) is in the French repository of the Group of Planetology, Inner Earth and Meteorites at CEREGE, in charge of the curator Dr. Jérôme Gattacceca. From 2016 a national repository with a few number of meteorites from expeditions was created at the Astro Engineering Center of the Universidad Católica de Chile (AIUC-PUC) in Santiago. A private collector, Dr. Holger Pedersen, donated pieces of the historic Chilean meteorites Vaca Muerta and Imilac. Some of them are on a permanent display at AIUC, along with other ones collected in Chile. Figure 2 show the detail of two ordinary chondrites from Atacama displayed there.

Figure 2. Detail of two ordinary chondrites shown at the permanent exhibition of meteorites and impact materials at the Astro Engineering Center of the Pontificia Universidad Católica de Chile, Santiago. Photos by John Clews (2016). The samples show preserved fusion crust. Shiny metal grains of kamacite as well as dark shock veins are visible in the polished cut surface shown in the image to the right.

During 2017 the International Astronomical Union gave the name Millarca to the main belt asteroid Nº 11819, as a recognition to the Chilean geologist Millarca Valenzuela for her work done with the meteorites from Atacama Desert, the development of the Chilean Allsky Camera Network for Astro-geosciences (CHACANA) project (Valenzuela *et al.*, 2017), and for her efforts to raise Meteoritics and Planetary Sciences in the country and South America.

The award had great media coverage that helped to install the subject of Meteoritics and Planetary Sciences in the public domain. As a consequence, one senator, Mr. Guido Girardi, part of the governmental initiative called Congreso Futuro, decided to present a proposal for the meteorite protection.

The proposal norm the exploration and exploitation of meteorites in the country, as it recognize the fact that most of them are ordinary chondrites, the most common type of meteorite, very well known, and promote the protection of part of the material for scientific research. The law does not consider to penalize the use of the material for commercial purposes as tourism and/or jewelry, if they are declared, and norm that at least 20% of each rock must be donated to the institution that will act as the national repository.

Some important points that the law will consider include:

1) Any meteorite found in Chile will be declared as a geological heritage natural object.
2) The proposed public institution for the implementation of the protocols established by the law is the Chilean Geological Survey (Sernageomin). This institution will hold the official meteorite repository as well.
3) The protocol will include the requirement of an official permission to conduct search of meteorites, for any kind of national or foreign missions, as well as for the possession of them. There will be fines for people found with meteorites without the correspondent permission.
4) Illicit traffic will be penalized with prison and fines.
5) For meteorites of a special value (for its rarity or size) the donation to the official repository will be of 50% of each rock.
6) The research done with the Chilean meteorites will have to be communicated before 2 years after the findings.

4. Final considerations

The Chilean Geological Society, through its Geoheritage Group of Specialist, has raised the list of sites considered of geological relevance – known as geosites – to ~70 by now (http://sociedadgeologica.cl/category/geositios/ accessed in July 2017), and has presented to the national authorities a proposal to include the concepts of **geodiversity** and **geological heritage** in the context of a new law that propose the creation of the Service of Biodiversity and Protected Areas, and the National System of Protected Areas of the Ministry of Environment, that will rule and norm the relationship with natural environments in Chile. The first attempt did not succeed, but the reference to the same concepts in the law for the protection of meteorites will open a new way to reach the authorities to try in the future to include them.

The method to create consciousness about this subject in the country is to improve and extend the interactions with the community at different levels. For that, the authors think the Chilean geological community – including students, professionals and scientist – should incorporate into their normal activities the ones related with outreach and education, giving them an equal importance as other professional and academic practices, as it is the only way to create a proper culture of respect and responsibility about nature.

In this context the creation of geoparks as Kütralcura (Schilling, 2009), in the Araucania region, and the miner geopark of the Bio-Bio's litoral, among others, are excellent initiatives to promote the protection of geological, cultural and historic heritage, as well as contributing to social, cultural and economic development of the territory where they are emplaced.

The XV Chilean Geological Congress, which will be held in Concepción in November 2018, will include a session dedicated to discuss this and other issues related with any of the ethical aspects related with our professional practice, to trace the next steps to conquer in our community.

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