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THE CAMPO DE CALATRAVA VOLCANIC FIELD: GEOLOGY AND RESOURCES

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Abstract. The volcanic region of Campo de Calatrava, located in South-Central Spain, and in particular in the Ciudad Real Province (Castilla-La Mancha region) is one of the three most important areas with recent volcanic activity in the Iberian Peninsula, together with those of Olot (Gerona, in Catalonia) and Cabo de Gata (Almeria, in Andalucía). In this work we describe succinctly the characteristics of this volcanism, as well as the related iron and manganese (plus minor cobalt) oxides mineralizations. Finally, an also brief description of the legal measures implemented to protect the local volcanic buildings is included.

1. INTRODUCTION

The volcanic region of Campo de Calatrava (Fig. 1) is one of the three most important areas with recent volcanic activity in the Iberian Peninsula, together with those of Olot (Gerona, in Catalonia) and Cabo de Gata (Almeria, in Andalucía). Eruptive activity took place between 0.7 and 8.7 million years ago, ie during Pliocene and Quaternary. It is therefore a rather recent activity, which has allowed the volcanic edifices largely retain their original morphology, and their products have been relatively well preserved until today, despite modern mining activity to exploit the volcanic materials as aggregates and for concrete (puzzolan) production.

The volcanic region has a total area of about 5000 km^2, and includes some 240 different volcanic edifices. Some of the main towns of the Ciudad Real province are included within the area: Ciudad Real, Almagro, Daimiel and Bolaños. Puertollano is placed close to the extreme South, while the volcanic edifices located closest to Almadén are those of La Bienvenida and Cabezarados.

2. MORPHOLOGICAL AND GENETIC ASPECTS

The geomorphology of the Campo de Calatrava region is conditioned by the existence of a series of Pliocene-Quaternary basins, which are bounded by sierras constituted by Paleozoic quartzite rocks. Within the basins the landscape is very smooth, and it is only modified by the presence of the volcanic edifices, which produce very striking features and morphologies (Fig. 2), which traduces in also characteristic place names, so that these volcanic edifices are named as "Negrizal de las Casas", "Cabeza Parda", "Cerro Moreno", etc. Also to note is the presence of *"lagunas"* (small lakes, or wetlands), corresponding to the sites of hydromagmatic activity (see below).

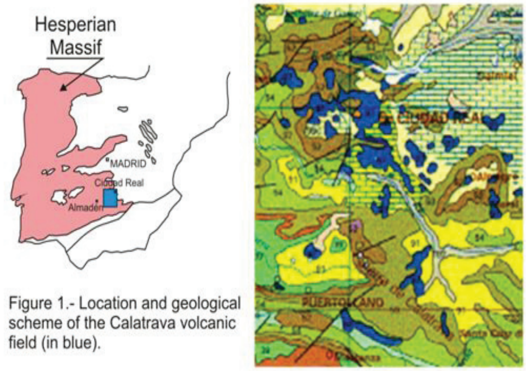

Figure 1. Location and geological scheme of the Calatrava Volcanic field (in blue).

Figure 2. Castillejo de La Bienvenida, one of the characteristic volcanic edifices dominating the almost plain landscape of the area.

Figure 3. La Yezosa volcanic edifice, affected by quarry activity.

The conservation of individual volcanic edifices depends on several factors:

—Eruption age (the latest are better preserved).
—Original edifice morphology.
—Volume of erupted materials.
—Nature of eruption products.
—Geological location (basins or quartzite reliefs).
—Modern mining activity.

This means that in each case it may be more or less complicated the identification of the volcanic nature of the edifice concerned.

Eruptive mechanisms responsible for these morphologies have been essentially of two types: Strombolian and Hydromagmatic. There are no edifices that could correspond to Hawaiian-type eruptions, but there are lava flows of a certain volume issued by Strombolian volcanoes.

Strombolian volcanism originated small conical volcanoes, now downgraded to rounded hills, with tapered hemispherical forms, depending on the degree of erosion. Their diameters range from 100 m to 2 km, and their heights, from 20 to 120 m. Crater-like depressions can occasionally be identified. Lava flows are occasionally emitted from these volcanoes, which can lead to achieving the 6-7 km long. Some of the best examples of this type of volcano are the La Yezosa in Almagro (Fig. 3), and Cerro Gordo in Valenzuela de Calatrava (Fig. 4).

Hydromagmatic volcanism is the most common in the region and gives rise to some very distinctive volcanic edifices, but often difficult to identify as such in the field: the so called "maars", depressions surrounded by a ring of pyroclastic products, which can reach diameters of 1-1,5 km. Most of these maars are occupied by wetlands. One of the most representative examples might be the small lakes or wetlands of Caracuel and La Posadilla (Fig. 5), or Hoya del Mortero depression (Fig. 6) in Poblete.

3. PETROGRAPHY

The volcanic rocks emitted by these volcanoes co-

Figure 4. Cerro Gordo, with a lower layer of porphyritic materials and a top layer of pyroclasts.

Figure 5. Partial view of the *Laguna de Fuentillejo*, also known as La Posadilla, maar-type wetlands declared as Natural Heritage by Act 207/1999.

Figure 6. Hoya del Mortero, a deep endorreic basin also of mar typology.

Figure 7. Macroscopic aspect of a local basalt sample.

rrespond to basalts in broad sense; they can be differentiated a number of varieties, both i) compositional: olivine melilitites, limburgites, olivine nephelinites, basanites and olivine leucitites, and ii) textural: massive porphyritic rocks, scoriaceous pyroclastics (tepha) and hydromagmatic deposits, constituted by heterometric mélanges of host rocks and volcanic fragments.

Massive porphyritic varieties have porphyritic texture, and consist of phenocrysts of olivine or olivine and pyroxene in a microcrystalline to glassy matrix formed by crystallites of augite, iron and titanium oxides (magnetite-ilmenite) and olivine. They can also contain plagioclase, feldspathoids, melilite and glass, in varying proportions, allowing finer petrographic classification as above indicated. Figures 7 and 8 show the macroscopic aspect of two of these varieties.

In regard to their applications, massive porphyritic varieties have been used until recently in obtaining cobblestones for paving streets. Its main current application is to obtain crushing aggregates, and especially for obtaining ballast for high-speed train (AVE) crossing the volcanic area. One of the main existing quarries on such materials is that of Morrón de Villamayor. They also have utility as building stones.

Tepha-type varieties are very vacuolar, of "pumice" type, and they form masses constituted by rocks fragments of widely varying sizes: from clusters of very fine grained material, (ash) to accumulations of large blocks, passing through very heterometric accumulations of medium-sized fragments centi-to decimeter (lapilli), with occasional presence of much larger fragments (bombs). Figures 10 to 13 show illustrations of some examples from these rocks types.

These materials are mined in several quarries in the region to obtain pozzolan concrete (Figure 14), which is its main industrial application. It should be noted, moreover, that have also been used as building stone, in monuments such as the Calatrava La Nueva Castle, and the Visigothic shrine of Virgen de Zuqueca in Oreto (Granátula de Calatrava).

Hydromagmatic deposits are usually well-strat-

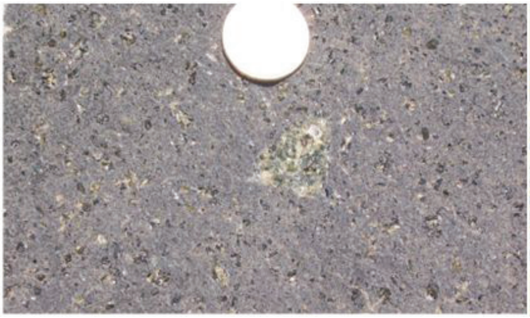

Figure 8. Macroscopic aspect of an olivine leucitite, from Morrón de Villamayor. It constitutes the only outcrop of this type of rocks in Europe.

Figure 9. Basaltic ballast at the AVE railway.

Figure 10. "Bomb sag" structure in pyroclasts from the Cerro Gordo volcano.

Figure 11. Lapilli pyroclasts, La Atalaya volcano (Ballesteros de Calatrava).

Figure 12. Scoriaceous aspect of pyroclasts products, La Atalaya volcano (Ballesteros de Calatrava).

Figure 13. Heterometric pyroclast material with large bomb. Quarry at Almodovar del campo volcano.

Figure 14. Puzzolan quarry. Ballesteros de Calatrava.

ified, alternatively with planar or cross-stratified facies. In addition, they contain large bombs, usually constituted by non-volcanic material (quartzite, basically).

They correspond to unconsolidated heterometric lithic and crystal-lithic tuffs, consisting largely of fragments of Paleozoic rocks (quartzite, shale), with minor co-genetic volcanic components (basaltic fragments, crystals of olivine, pyroxene, etc.).

These rocks do not have industrial utility, rather than to obtain low quality classified aggregates.

4. GEOCHEMISTRY

From the geochemical point of view, the volcanic rocks from the Campo de Calatrava field correspond to an intraplate alkaline magmatism, generated from low rates of upper mantle partial melting. Magmas would be primary liquids, as indicated by high contents of Ni and the high value of #Mg parameter (MgO/MgO + FeO). Table 1 shows the average chemical composition and CIPW Norm calculated from the porphyritic varieties.

These geochemical characteristics, as well as data from the study of its evolution in time and space, allow a genetic interpretation related to the existence of a hot spot associated with a process of cortical lifting and possibly of aborted rifting for the magmatic activity present at the Campo de Calatrava volcanic field.

5. RELATED ORE DEPOSITS

Associated with this magmatism there are a number of minor mineral deposits, usually with low tonnage, but constituting a worldwide singularity. They correspond to Fe and Mn oxides, the latter with the added interest of showing relatively high Co content, and have been the subject of prospection in the 90's, aimed to identify larger deposits with these high Co contents.

The mineralizations have been characterized by Crespo et al. (1995) as of exhalative-sedimentary origin, appearing in the form of stratabound lenses within the Pliocene and Quaternary sequences, forming lenticular masses of up to several meters thickness and up to several hundred meters of lateral extent. Its origin seems to be related to other characteristics and much more common events of the area: the so called "hervideros" (boilers) and "agua agria" (sour water) springs, the best known of which could be the *"Fuente Agria"* in Puertollano. The genetic link would be that both mineralization and springs would be posthumous manifestations of hydrothermal activity linked to this magmatic activity.

Following Crespo et al. (1995), two major types of mineralizations can be differentiated in the area (Fig. 15):

— Proximal mineralizations, with respect to hydrothermal sources. Two subtypes can be stablished:

Fe-Mn oxides crusts.

Layers of "*canutillos*" (small spliffs) of Mn-(Co) oxides.

	Basalts	**Basanites**	**Olivine nefelinites**	**Olivine melilitites**	**Olivine leucitites**
SiO_2	44.32	43.01	40.14	37.29	44.40
Al_2O_3	12.06	11.94	11.67	10.44	10.93
Fe_2O_3	4.88	5.54	5.50	5.58	5.36
FeO	6.37	5.85	5.92	6.00	3.98
MgO	10.33	10.74	11.86	13.25	11.79
CaO	11.43	11.87	13.44	15.37	12.33
Na_2O	2.63	3.26	3.23	2.87	2.42
K_2O	1.18	1.08	1.02	1.37	3.73
MnO	0.16	0.18	0.18	0.21	0.16
TiO_2	3.04	3.09	3.35	3.06	2.27
P_2O_5	0.73	0.78	1.02	1.34	1.14
H_2O	2.45	2.21	2.49	2.49	1.52
Total	99.58	99.55	99.82	99.27	100.03
Ba	737	752	826	831	1154
Ce	77	95	111	137	133
Co	45	43	47	46	56
Cr	416	401	472	492	924
La	66	67	80	96	80
Ni	205	183	212	235	213
Rb	37	39	38	34	257
Sr	918	870	1047	1583	1057
Y	27	26	29	34	8
Zr	247	261	278	292	396
CIPW Norm					
Or	7.0	6.4	3.2	--	6.6
Ab	17.1	11.5	2.1	--	--
An	17.6	14.8	713.5	11.6	5.1
Lc	--	--	4.5	6.3	9.8
Ne	3.1	8.8	13.4	13.2	10.3
Di	26.2	29.9	35.7	25.1	31.0
Ol	11.7	10.1	11.5	16.77	22.3
Ln	--	--	--	6.8	--

Table 1. Chemical composition and calculated CIPW Norm for prophiritic rocks from the Campos de Calatrava volcanic field.

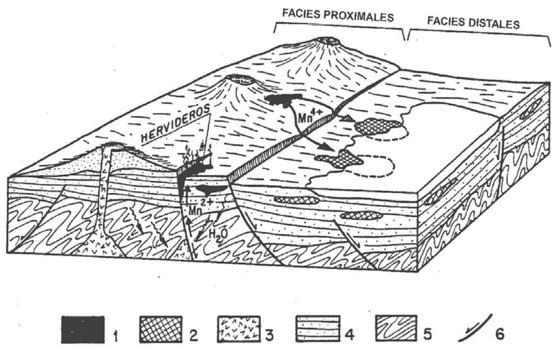

Figure 15. Geologic scheme of the Calatrava volcanic field Fe-Mn-(Co) deposits. 1: Proximal deposits. 2: Distal deposits. 3: Volcanic rocks. 4: Pliocene and quaternary detritic sequence. 5: Hercynian basement. 6: Fault.Photo 14.- Mn nodules (black) covered by an iron oxides crust (reddish). La Zarza mine.

Figure 16. Mn nodules (black) covered by an iron oxides crust (reddish). La Zarza mine.

—Distal mineralizations, with respect to hydrothermal sources: pisolithic layers with Mn-(Co) oxides.

Ore mineralogy includes complex manganese oxides and hydroxides: cryptomelane (KMn_8O_{16}) and lithiophorite ($(Al, Li)MnO_2(OH)_2$) are the main ores, and they appear in the form of earthy micro-or cryptocrystalline aggregates.

The Fe-Mn oxides crusts are lenticular formations of a few meters thickness and several hundred square meters in extension, generally associated with the "*agua agria*" springs, and are constituted by nodules of Co-rich Mn oxides covered with a crust of iron oxides and hydroxides some 1-1,5 cm. thick (Fig. 16). The mine of La Zarza, located some 2 km SSW from Pozuelo de Calatrava, is one of the most representative mineralization of this typology.

"Canutillos" layers are accumulations of Co-rich Mn oxides replacing vegetal structures, constituting which appear to form levels up to 2-3 m. thickness between alluvial materials. Mine Chorrillo, located in the vicinity of the La Zarza, is one of the best examples of this type of mineralization (Figs. 17 and 18).

Pisolithic layers with Mn oxide correspond to mineralizations that have suffered some transport for the hydrothermal sources. They consist of lenticular concentrations of Mn oxides and hydroxides pisolithic structures, centimetric in diameter. Los Ardales mineralization can be considered representative of this typology.

6. LEGAL PROTECTION

As stated in the preamble of the Spanish Law 42/2007 of Natural Heritage and Biodiversity: "In today's society has significantly increased concern with issues relating to the conservation of our natural heritage and biodiversity..." "... and degradation of natural areas of interest has become a serious concern for citizens, claiming their right to a quality environment adequate for their health and welfare". This law has established that public autho-

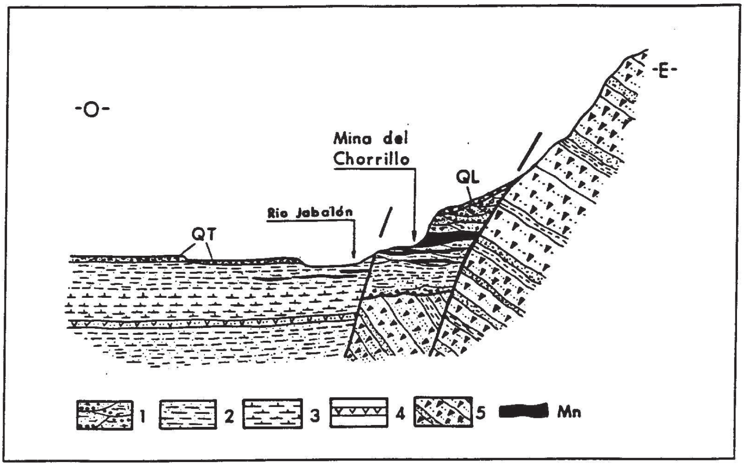

Figure 17. Geologic scheme of El Chorrillo mine. 1-4: Plio-Quaternary sediments. 5: Hercynian basement. Mn: *"Capas de canutillos"*.

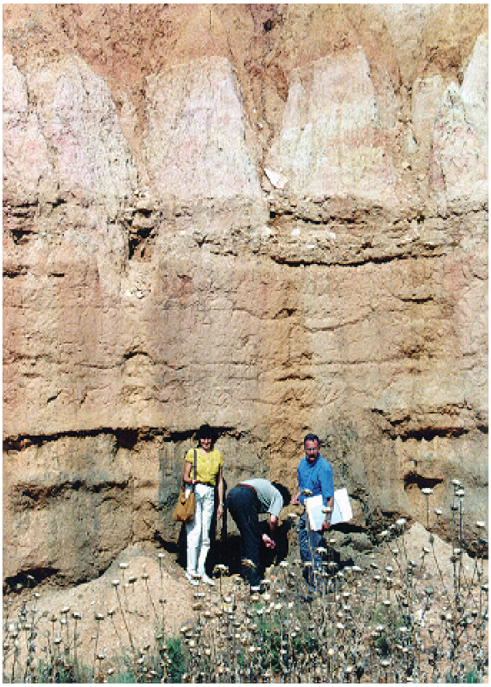

Figure 18. El Chorrillo mine. The dark level, coinciding with the person's highness, corresponds to the orebody thickness.

rities must be equipped with tools to know the state of conservation of Spanish natural heritage and biodiversity and the causes that determine their changes.

On the other hand, in the Region of Castilla-La Mancha has been considered, among other objectives for the development of the Law 9/1999 of 26 May of Nature Conservation: "to establish a protection framework, today inexistent, for certain geological and geomorphological features especially valuable".

This Law let to establish as Natural Monuments geological formations that after typology, development and extension, may be considered be representative of the geomorphologic domain where they are located. This has been the approach followed to estimate the protection needs of the recent volcanic manifestations of Campo de Calatrava as geological and geomorphologic features, and it is expressed as: "Because they can be considered as geological or geomorphologic features of special interest, either because they represent unique geomorphologic processes, ... characterize remarkable landscapes or possess special interest from the scientific or educational points of view".

As a result, and up to date, the Regional Government of Castilla-La Mancha has declared as Natural Monuments the volcanoes that are listed in Table 2.

Area Name	Location	Total declared area (ha)	Declaration date
Michos volcanic wetland	Abenojar, Luciana	218.00	5/10/1999
La Alberquilla volcanic wetland	Mestanza	111.00	5/10/1999
Hoya de Cervera Maar	Aldea del Rey, Almagro	284.00	5/10/1999
La Posadilla wetland and volcano	Alcolea de Cva.	296.00	5/10/1999
Los Castillejos de la Bienvenida	Almodóvar del Campo	197.00	5/10/1999
Peñarroya wetland and volcano	Alcolea de Cva. Corral de Cva.	544.00	5/12/2000
Hoya del Mortero Maar	Ciudad Real	124.00	5/12/2000
Cerro de los Santos volcano	Porzuna	120.00	27/09/2001
Calatrava volcanic massifs	Aldea del Rey, Almagro, Argamasilla de Cva., Ballesteros de Cva., Pozuelo de Cva.	3,763.00	24/06/2008
Piedrabuena volcano	Piedrabuena	480.30	31/03/2009

Table 2. List of volcanoes declared as Natural Monuments.

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