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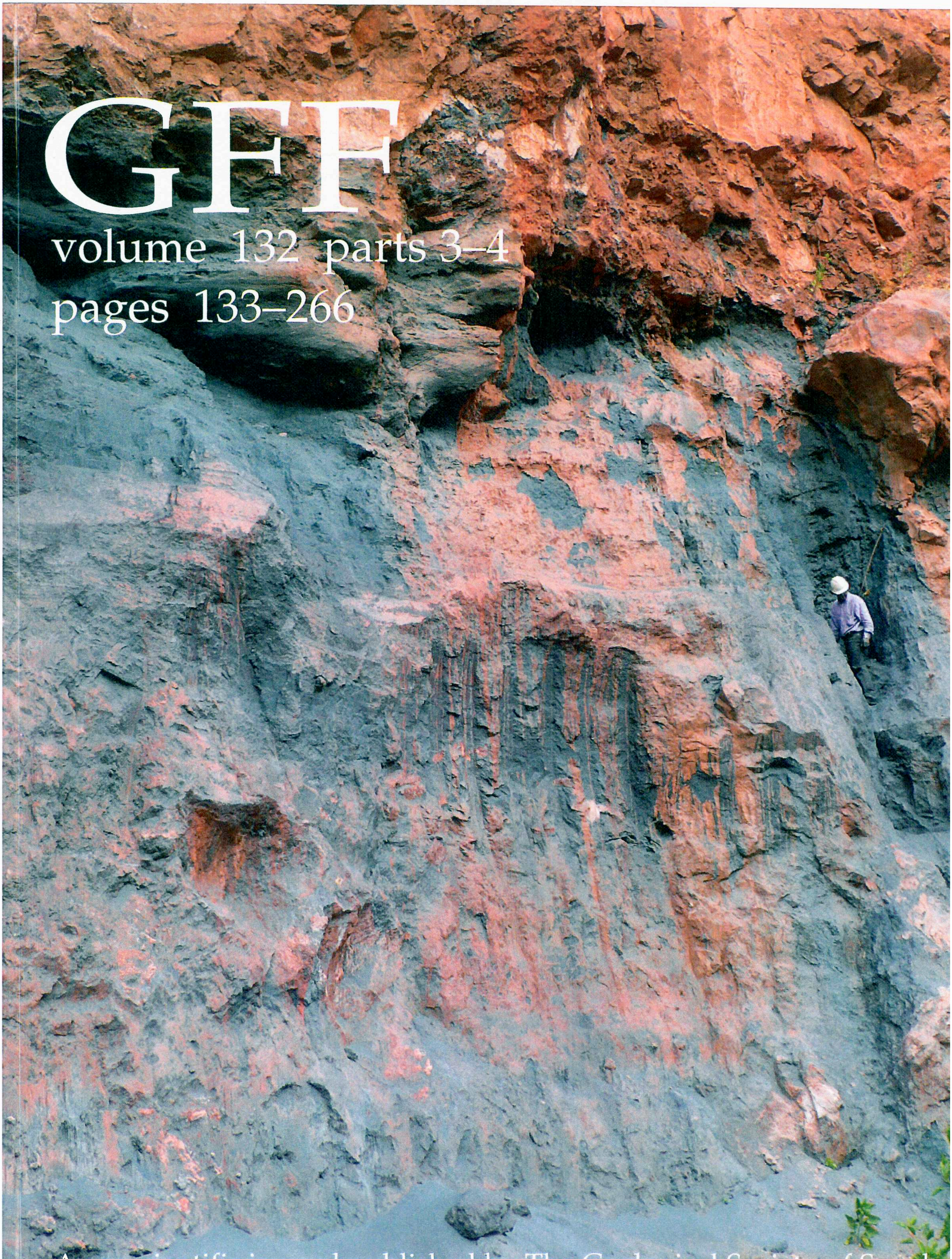

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About this journal
GFF was founded in 1872 by the then "Geologiska Föreningen i Stockholm" under the name of *Geologiska Föreningens i Stockholm Förhandlingar* ['Transactions of the Geological Society in Stockholm']. It was issued under that name for 122 years, i.e. 1872-1993, volumes 1–115 (ISSN 0016-786X). As of 1994, vol. 116, the journal was formally renamed *GFF*, its nickname since 1963 (being an acronym of its original name).

On the cover: A section through a thick bed of powdery apatite iron ore of Kiruna type overlain by rhyodacite at La Perla in Chihuahua, northern Mexico. The ore is a poorly consolidated aggregate of hematite (locally magnetite) crystals. It is stratified, siz[illegible] sorted, and contains a thermally unaltered fossil flora of pollen grains and fungal spores of Oligocene or Miocene minimum age a[illegible] the level marked by the person. Several lines of evidence suggest that the iron oxide was deposited as volcanic ash that captured wind-blown pollen (see Corona-Esquivel et al., pp. 133–213). Photograph by Rodolfo Corona-Esquivel.

GFF volume 132 (2010), pp. 173–181. Article

Palynologic evidence for iron-oxide ash fall at La Perla, an Oligocene Kiruna-type iron ore deposit in northern Mexico

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Corona-Esquivel, R., Martínez-Hernández, E., Henríquez, F., Nyström, J.O. & Tritlla, J., 2010: Palynologic evidence for iron-oxide ash fall at La Perla, an Oligocene Kiruna-type iron ore deposit in northern Mexico. *GFF*, Vol. 132 (Pt. 3–4, September–December), pp. 173–181. Stockholm. ISSN 1103-5897.

Abstract: La Perla is an Oligocene deposit of apatite iron ore located in northern Mexico. The main ore types are massive ore, ore breccia and powdery ore. The latter is of special genetic interest because it contains well-preserved palynomorphs; fossil pollen representing several plant families growing in the region of investigation during the late Paleogene-Neogene; the assemblages include angiosperm and gymnosperm pollen grains, and also fossil fungal spores from two genera, *Frasnacritetrus* and *Dyctiosporites*, indicative of Eocene to Miocene age. The beds of powdery ore are stratified and size-sorted, but in some places there is no discernible stratification. The ore consists of a friable open framework of anhedral to euhedral hematite plates, or less commonly, martitized magnetite octahedra. Locally, the ore is even unconsolidated. The ore minerals show no abrasive rounding or other epiclastic features, and the high porosity of the iron-oxide crystal aggregate embedding the palynomorphs rules out formation by hydrothermal deposition or replacement. The exines of the palynomorphs have a light yellow color which demonstrates that they are unaffected by thermal alteration. This shows that the pollen-bearing powdery ore was deposited at a temperature below 150°C, probably as volcanic ash that captured wind-blown pollen.

Keywords: Pollen, fungal spores, apatite iron ore, Kiruna-type, hematite, magnetite, ash fall, Oligocene, Paleogene, Neogene, Mexico.

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Introduction

La Perla is an Oligocene iron ore deposit of Kiruna-type situated in northern Mexico. Kiruna-type ores consist of magnetite, or less commonly hematite, and small amounts of apatite and silicate gangue minerals. These ores are associated with volcanic and subvolcanic rocks of intermediate to moderately silicic composition. Ore districts with deposits unaffected by deformation and strong metamorphism contain orebodies of different primary structure and texture. Such variation is found at La Perla, where one variety of ore is of special genetic interest: powdery iron oxide with small amounts of pollen.

The origin of magnetite-apatite deposits of Kiruna-type has been controversial for more than a century. At present the discussion is focused on El Laco, a Pliocene volcanic complex in the Chilean Andes where the best preserved deposit of this ore type is found. The traditional interpretation is that the orebodies at El Laco formed from extremely iron-rich magmas erupted onto the surface or crystallized at shallow depth (Park 1961; Henríquez & Martin 1978; Nyström & Henríquez 1994; Naslund et al. 2002; Henríquez et al. 2003). Other authors argue that the ore was deposited from hydrothermal-metasomatic fluids that replaced preexisting silicate rocks (Rhodes et al. 1999; Rhodes & Oreskes 1999; Sillitoe & Burrows 2002).

Magmatic and hydrothermal processes have also been proposed for the formation of the La Perla deposit. Cárdenas-Vargas & Del Castillo-García (1964) concluded that the iron ore originated from iron-rich liquids derived by liquid immiscibility; a gaseous phase generated the powdery ore. Van Allen (1978) suggested a hydrothermal replacement model for the ore: fluids rich in Fe, F and P reacted with and dissolved glassy volcanic rock, depositing iron oxide; the highly porous nature of the powdery ore is attributed to loss of volume during the replacement.

The purpose of this paper is to describe an extensive, many meters thick, partly stratified bed of friable hematite-magnetite ore at La Perla that contains well-preserved fossil palynomorphs (pollen and fungal spores), and to discuss how the character of the powdery ore and the palynomorphs constrain the depositional environment and formation of the ore.

La Perla iron ore deposit

The La Perla ore deposit is located in the state of Chihuahua (Fig. 1; coordinates 28°18′51″ N, 104°33′46″ W). It is situated in a broad valley within Sierra de Mesteñas, at an altitude of ca. 1550 m above sea level. The iron ore is hosted by a 250 m thick sequence of rhyodacitic lavas called the La Perla Formation, that constitutes the lower part of a 560 m thick pile of Oligocene volcanic rocks, mainly lavas of rhyolitic to dacitic and trachytic compositions (Campbell 1977; Van Allen 1978; Corona-Esquivel et al. 2003). The rocks are subalkaline to alkaline with geochemical features reflecting slight crustal contamination that suggest formation during extension in an intraplate setting (Jacinto-Estanes 2005).

Before mining started at La Perla in 1953, the deposit was known as "Cerro del Fierro" (Iron Mountain). It was a hill rising 70 m above the surrounding alluvial plain. The original ore deposit was 1200 m long, 700 m wide and 180 m thick in its central part, and the total reserves were estimated at 87 million metric tons of iron ore with 57.2 wt.% equivalent Fe (Ramirez-Lara 1973). The exploitable reserves remaining at present exceed 5 million tons. Open-pit mining and diamond drilling revealed that the original deposit was composed of many subhorizontal to gently dipping lenticular orebodies, the largest being more than 400 m long and 50 m thick (Fig. 2). Individual orebodies were dipping away from the central part of the deposit, accounting for the morphology of the hill. There is no evidence that the structural pattern is caused by doming.

The orebodies occur intercalated in the upper part of the La Perla Formation. No radiometric age determination has been reported for the mineralization. The La Perla rhyodacite has been dated to between 31.5 ± 0.7 and 31.8 ± 0.5 Ma using the K/Ar method (Campbell 1977), i.e. it is early Oligocene in age. The intercalation of the ore in the lava sequence suggests that they are coeval and that, therefore, this age is also valid for the ore.

The main ore types at La Perla are massive ore, ore breccia and powdery ore (Fig. 2), the latter being the topic of this study. The massive ore that made up the predominant part of the unexploited deposit has been removed by mining. It is reported to have had sharp contacts with the underlying and overlying rhyodacites. The massive ore was largely composed of fine-grained hematite, but widespread relicts suggest that magnetite was the main primary phase. Part of the ore was scoriaceous and looked like a vesicular basalt, according to Cárdenas-Vargas & Del Castillo-García (1964); they also documented a columnar texture later found to be common at El Laco (Henríquez & Martin 1978). Van Allen (1978) reported flow banding in the massive ore. Apatite visible to the unaided eye was scarce, and only found as light yellow to white prisms up to a few millimeters long. The ore breccia consists of similar iron oxide, scarce apatite, and varying amounts of angular rhyodacite fragments. Pyroxene has been reported as a rare mineral. Quartz, calcite and fluorite are seemingly late phases.

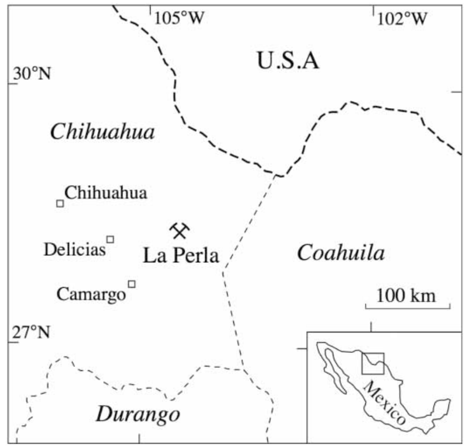

Fig. 1. Location of the La Perla iron ore deposit in Chihuahua, northern Mexico.

The powdery ore occurs as at least three horizontal to gently dipping beds of stratified, friable iron oxide (Fig. 3) that are thickest in the northern and southern parts of the deposit. The most extensive bed is more than 300 m long. In the north, the powdery ore forms a thick bed (> 10 m) at the bottom of the open pit (Fig. 4). Continued mining has shown that the lower part of this ore bed is a breccia very rich in unmineralized fragments and blocks of rhyodacite. The proportion of rhyodacite in the ore increases irregularly with depth. The contact between the ore breccia and underlying rhyodacite of the La Perla Formation is unexposed.

Methods

This study is based on 20 samples of powdery ore collected during November 2005 in the cross section depicted in Fig. 4, and 15 additional samples from 2008. Special care was taken to avoid contamination of the unconsolidated and friable ore by material introduced during mining. The idea to search for pollen in the ore came after the first samples had been collected. Palynological processing of these samples at Instituto de Geología de la Universidad Nacional Autónoma de México resulted in the discovery of pollen. In June 2008, the pollen-bearing sampled section (Fig. 4) had been removed by mining. Pollen was found again in powdery ore from a new section about 40 m east of the original sampling site, in the inferred continuation of the pollen-bearing strata.

Palynological processing

An extraction procedure was necessary due to the scarceness of pollen in the ore. 250 g of sample was added to distilled water with a detergent. After vigorous stirring and sedimentation for 24 hours, still floating fine material was removed and new water was added. After stirring, the water and suspended fine particles were decanted into another beaker, discarding the heavy residue on the bottom. This procedure was repeated several times until only clay- and silt-sized particles were suspended in the water. The suspended fine fraction was concentrated by centrifugation. The average amount of fine fraction obtained from a sample was ca. 30 cm^3 (wet).

The recovered fine material was submitted to acetolysis, following standard procedures (Jackson 1999). It was treated with a 9:1 mixture of acetic anhydride and concentrated sulfuric acid. After heating at 70°C for 12 minutes, the fine material had

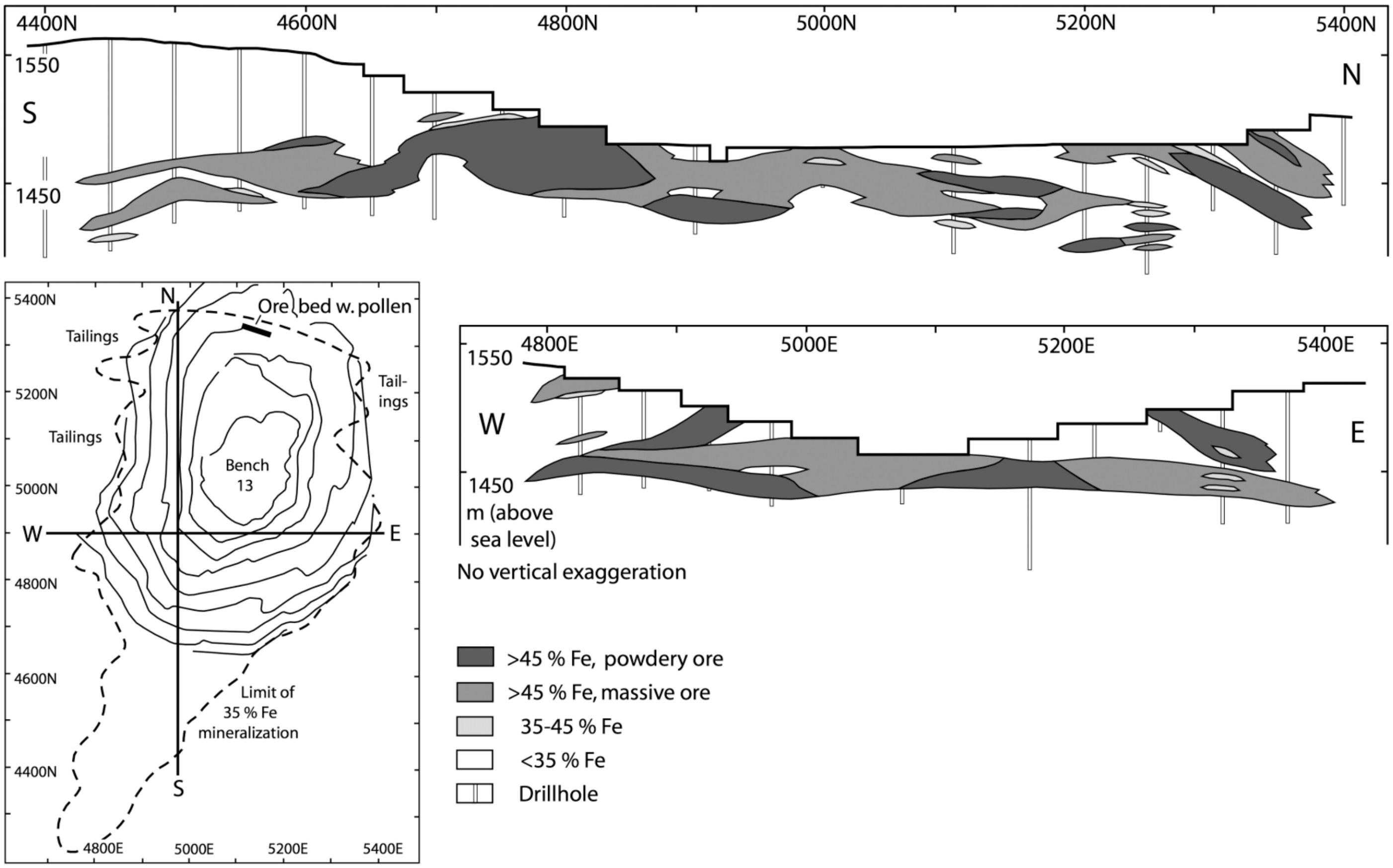

Fig. 2. The partly exploited La Perla iron deposit in March 1976 (after unpublished cross sections and a mine map modified by Van Allen 1978). The pollen-bearing ore bed treated in this study is projected as a short thick line on the inset map. Available maps and sections of the iron mineralization are based on ore grade (% Fe) and physical nature (hardness): as used in the mine, *massive ore* requires dynamite during mining, whereas *powdery ore* can be loaded as it is. Thus, the massive ore of the sections includes powdery ore (in the sense used in our study) of moderate to low friability.

dissolved, leaving only a small organic residue, including pollen, if present, in the sample. The organic material was mounted on glass slides, using Canada balsam and hydroxyethyl cellulose as an immersion medium, and studied with an optical microscope.

Mineralogical study

The mineralogy, texture and crystal habit in the samples of powdery ore from La Perla were studied with a binocular microscope. SEM photos of representative material were taken using a Hitachi S-4300 scanning electron microscope (accelerating voltage = 6 kV; beam current 10 μA), at the Swedish Museum of Natural History in Stockholm.

Powdery ore

The beds of powdery ore show variations with regard to texture, grain size, composition, percentage of included silicate material, and resistance to erosion. Stratification is common, especially in the ore bed in the northern side of the open pit (Figs. 4–5). The stratification varies from coarse to fine. As a rule, the finer the grain size, the thinner the strata. Cross-bedding is reported, but the observations are too few to establish a consistent dip direction. The ore lacks discernible stratification in some places, especially in the eastern side of the open pit.

The powdery ore is a friable, locally unconsolidated, aggregate of iron oxide, either hematite or martitized magnetite. It was often difficult to determine the nature of fine-grained iron oxide with certainty in the field. Readily visible crystals consist of tabular hematite (Fig. 6). Inspection under microscope shows that all the samples, except two, are composed of seemingly unaltered hematite; control with X-ray diffraction reveals no trace of magnetite in the samples. The hematite plates are subhedral to euhedral with well-developed crystal faces, and most of them range from c. 0.05 mm to 3 mm in size. An incipient to partial corrosion of the crystals is common. Some ore layers or parts thereof are unconsolidated (Fig. 7A), whereas others are friable open frameworks of platy crystals (Fig. 7B–C). The hematite plates lack preferred orientation, and are seemingly piled upon each other.

The two exceptional samples come from two different beds of powdery ore: the thick ore bed in the northern part of the open pit and another bed in the southwestern part (Malvinas). The samples consist of martitized magnetite of octahedral habit (Fig. 7D), without visible hematite plates.

Apatite is absent, or present only in small amounts, in the powdery ore (Fig. 7A–D). However, a few samples are relatively rich in apatite. The mineral occurs as tiny euhedral needles invisible to the unaided eye (up to 0.1 mm long). Many needles

Fig. 3. Pollen-bearing, stratified powdery ore composed of submillimeter-sized hematite crystals in the northern part of the open pit at La Perla. The vertical flows of ore at the left side of the photo, caused by rain water, illustrate the poorly consolidated nature of the powdery ore.

project from hematite crystals, and form radiating clusters in apatite-rich parts of the ore. Some needles end with a hollow point.

Other minerals in the ore are quartz, kaolinite and small amounts of K-feldspar and smectite, derived from altered rhyodacite. Some of the ore is incipiently to partly cemented by quartz (Fig. 7C), or calcite; fluorite is also found. The lower part of the thick ore bed in the north is locally silicified, with loss of its original texture and pore space. The silicification is gradual and has a patchy distribution. The rhyodacite hosting the ore is marked by silicification and kaolinization of varying intensity, and local concentrations of fluorite (Cárdenas-Vargas & Del Castillo-García 1964; Van Allen 1978).

Angular fragments of partly to strongly altered rhyodacite with knife-sharp contacts are common in the powdery ore. They show a general increase in size and abundance towards the bottom of

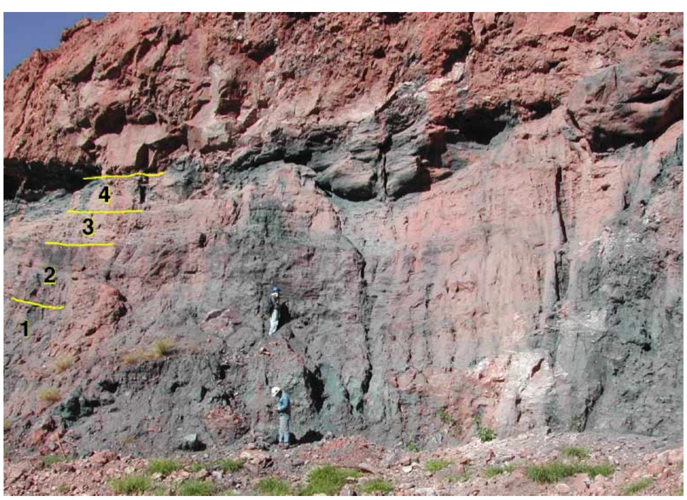

Fig. 4. The type section of powdery ore in the northern part of the open pit where pollen was first found (Layers 1–4 are indicated at the left side).

Fig. 5. Stratified powdery ore in the northern part of the open pit (cf. Fig 4).

the thick ore bed. However, in the northeastern wall large angular blocks of rhyodacite occur near the top of the bed.

Type section with pollen. – A vertical, 105 m long cross section through the thick bed of powdery ore in the northern part of the open pit, where pollen was discovered, illustrates the variation within the powdery ore (Fig. 4). The >10 m thick ore bed is overlain concordantly by 12 m of rhyodacite, that in turn is covered discordantly by 30 m of arkose. During sampling, the ore bed was subdivided into four layers, based on differences in texture, abundance of rock fragments, and friability. The lateral extension of the layers were not determined due to discontinuous outcrop and difficult access. Figure 4 shows the wall of the open cut in November 2005, when the original 20 samples were collected, and the lower part of the section had not yet been exposed by mining. From bottom to top the layers are:

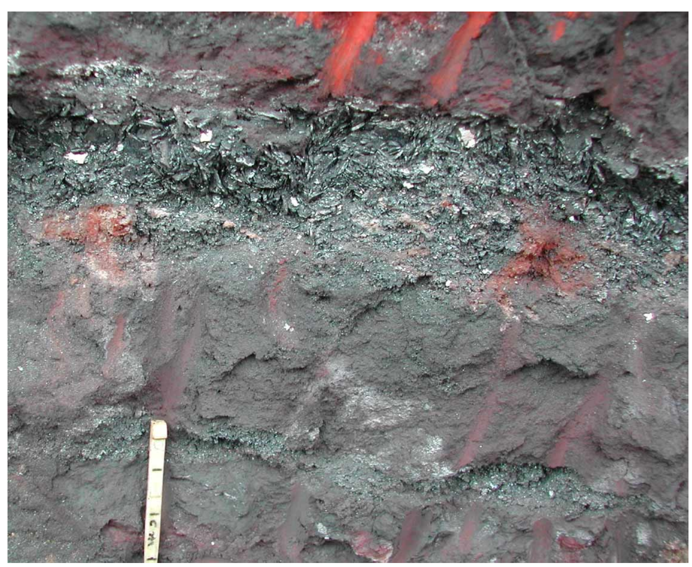

Fig. 6. Variation of grain size in stratified powdery ore in the northern part of the open pit. The coarse-grained ore below the bright red grooves at the top is composed of 0.1–0.8 cm large hematite plates without preferred orientation.

Layer 1 is a chaotic breccia with a matrix of powdery ore. Angular to subangular blocks, as large as 60–80 cm, and smaller fragments of altered rock are abundant, though irregularly distributed in the ore. They make up between 10 and 90% of the volume of the layer. The iron-oxide matrix is fine- to medium-grained with 0.2 to 1.5-mm-long hematite plates. The latter typically have a rounded, corroded appearance. The ore lacks stratification, and the friability is low to moderate. During the sampling the exposed part of Layer 1 was ca. 5 m thick; subsequent mining uncovered 12 m more without reaching its base.

Layer 2 ranges considerably in thickness, from 1.5 to 5 m. It rests concordantly on Layer 1, with an irregular contact surface. The ore is stratified on the 1–2 cm scale and fine-grained, with up to 2 mm large crystals of iron oxide. It is highly friable and can be dug out by hand. Rock fragments occur in highly variable amounts and sizes. Locally they make up 40% of the volume and attain sizes of 20–40 cm.

Pollen was discovered in ore from Layer 2, and the subsequent search for more pollen consumed most of the samples from this layer. The iron oxide is martitized magnetite in some of the sampled ore (Fig. 7D). Other parts of Layer 2 consist of platy hematite (Fig. 7B–C). The nature of the iron oxide was not systematically determined in the field due to difficult access and small grain size, and could not be clarified on the second visit since mining had removed the type section.

Layer 3 lies concordantly on Layer 2 and has a uniform thickness between 1.5 and 2 m. The stratification is more pronounced and finer here, on the 0.5–1 cm scale. The ore is very friable and, in part, unconsolidated. The iron oxide is euhedral hematite, predominantly of submillimeter-size, alternating with thin strata of coarser grain size. Tiny apatite needles (up to 0.1 mm long) are more common in samples from this layer than in the other layers. Angular, ca. 2-cm-large rock fragments occur in a 15 to 20-cm-thick part of the layer.

Layer 4 has a thickness between 1 and 2 m, and is covered concordantly by a rhyodacite flow. A disconformity at the base of the layer is the reason for its separation from similar ore in Layer 3. The friable, stratified ore is characterized by tabular hematite crystals ranging in size from 0.1 to 2 mm. Cross-bedding is observed locally, and ca. 3 to 4-cm-large rock fragments are common.

Palynomorphs found in the powdery ore

Out of the 20 samples collected in the type section, only 5 were productive (one of them was richer in clay fraction and contained much more pollen). These samples nevertheless host a well-preserved flora dominated by angiosperm pollen but gymnosperm pollen is also present. Furthermore, two genus of fungal spores have been identified in the palynological assemblages. Recent study of the palynomorphs recovered from the samples collected in June 2008 revealed the same taxa, with the addition of the genus *Typha*.

The exines of the pollen grains have a light yellow color and thus show no signs of thermal alteration. Some pollen grains have a reddish stain caused by impregnation of hematite or goethite.

The palynological assemblages comprise palynomorphs which range in age from the Paleogene to the present. However, presence of two index fungal spores indicates that the minimum age of the fossil flora is Upper Oligocene or Miocene.

Fungal spores

Fungal spores from two genera, *Frasnacritetrus* and *Dyctiosporites*, were found in the samples from Layer 2. They are good index genera, with age ranges from the Eocene to the Miocene. The scarcity of material does not permit species differentiation and further chronostratigraphic refinement.

Frasnacritetrus (Taugourdeau 1968; Saxena & Sarkar 1986), morphologically similar to *F. indicus* from the Cenozoic of India, was described by Saxena & Khare (1992). However, its hyphea and the central body are much smaller (Fig. 8A). This genus was abundant during the Paleogene–Neogene, with different species reported from Oligocene, Miocene and Pliocene formations.

Dictyosporites morularis (Salard-Cheboldaeff & Locquin 1980; Kalgutkar & Jansonius 2000) (Fig. 8B). This fungal spore was reported initially from an Oligocene formation in Cameroon, Africa. In later reports the genus *Dictyosporites* comprises other species of Eocene, Oligocene and Miocene age (Kalgutkar & Jansonius 2000).

Pollen

The most common pollen grains in the analyzed samples belong to wind-pollinated plants of the Betulaceae family. They include *Alnipollenites* (Fig. 8C), *Triatriopollenites* (Fig. 8D), and *Triporopollenites* (Fig. 8E). Different species of these genera appeared during the Late Cretaceous, and became abundant during the Paleogene in Laurasia. At present, Betulaceae is well-represented in temperate plant communities.

Chenopodipollis, produced by wind-pollinated plants such as Chenopodiaceae and Amaranthaceae, is well-represented in the samples (Fig. 8F). The oldest reported *Chenopodipollis* is from the Paleocene of North America and it became more common with the change of climate from the Oligocene on. In Mexico, the oldest finds are of Eocene age (Martínez & Ramirez 2006).

The Compositae family is represented by three morphological types belonging to *Tubulifloridites* (Fig. 8G–I). This taxa first appeared in Laurasia during the Eocene (Cross & Martínez 1980), and became more common during the Oligocene-Miocene (Martínez & Ramirez 2006). The diversity of Compositae pollen in the samples indicates that the maximum age of the La Perla deposit is Oligocene, when these plants probably were abundant in the region.

The form genus *Momipites* is represented by a few pollen grains in the samples (Fig. 8J). It belongs to the group *Coryloides sensu* Nichols (1973), with species that are indistinguishable from the present genera *Engelhardia* and *Alfaroa*. Trees of these genera are characteristic of cloud forests in Mexico and Central America. *Momipites* species were widespread in North America and Europe from the Paleocene to the Miocene.

Myrtaceidites pollen occurs in all of the pollen-bearing samples (Fig. 8K). The affinities of this form genus have been the subject of much discussion. Krutzsch (1969) concluded that this form belongs to the Myrtaceae family. The oldest occurrences reported are from the Late Cretaceous of Africa (Muller 1968). In the U.S.A. *Myrtaceidites* is reported from the Eocene (Elsik & Dilcher 1974), and in Mexico from the Eocene–Oligocene boundary (Martínez & Ramírez 1999).

Quercoidites pollen is found in all the pollen-bearing samples (Fig. 8L, M and Q), suggesting that this genus was widespread in the region. *Quercoidites* was very abundant during the

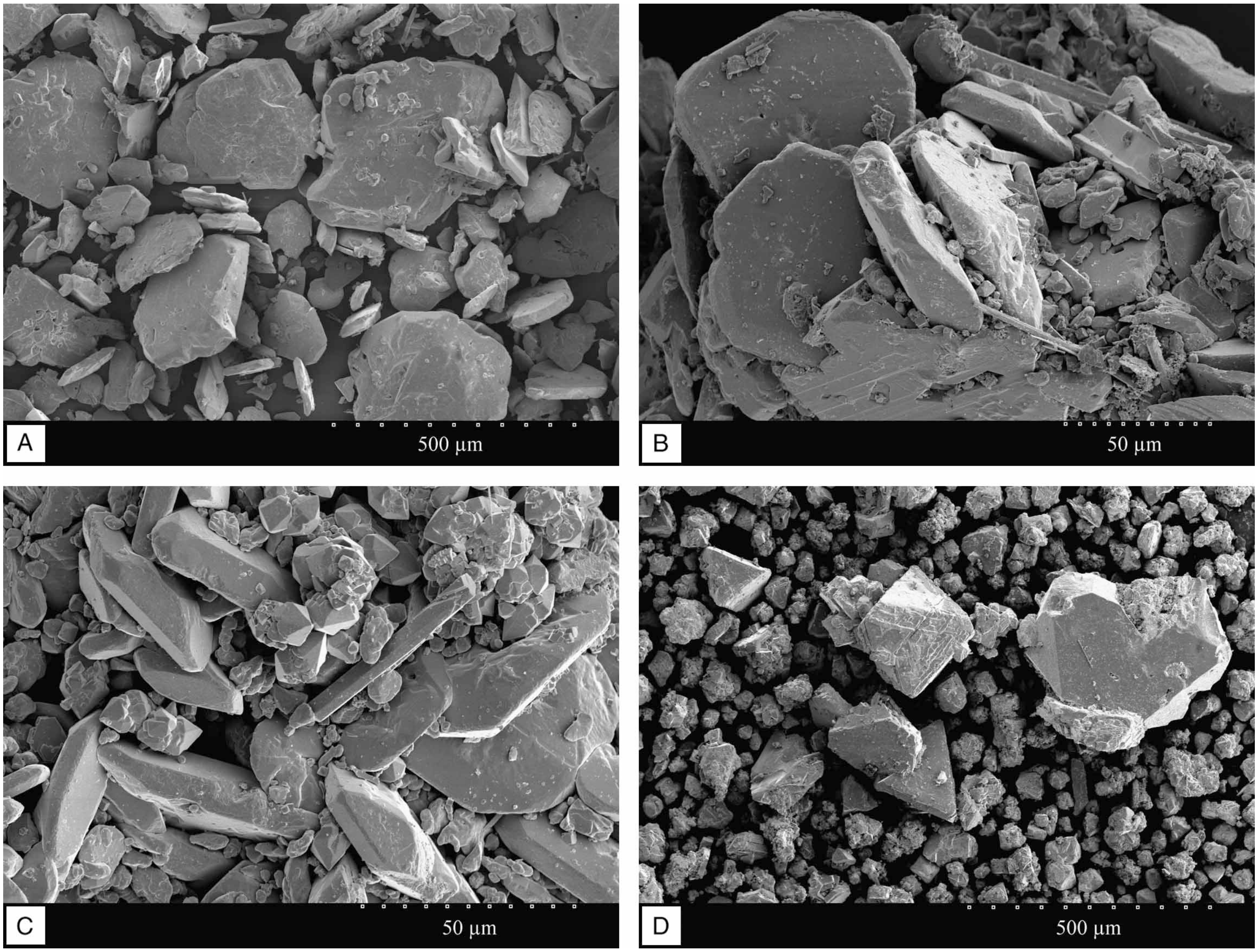

Fig. 7. SEM images of powdery ore from La Perla. **A**. Subhedral to euhedral hematite plates in unconsolidated ore (sample M-1). **B**. Locally corroded hematite plates and small amounts of apatite in friable ore (LAP03-08). **C**. Euhedral hematite plates, stubby quartz crystals and an apatite prism in partly cemented ore (LAP02-08). **D**. Martitized magnetite of octahedral habit in unconsolidated ore (Pb9737).

Oligocene in U.S.A. (Elsik 1978). This genus is also common in Mexico from the Neogene on. At present, oaks (*Quercus* spp.) grow in mountain forests in Mexico.

The form genus *Rugulitriporites* is found in only one sample (Fig. 8N). It is associated with *Bursera*, which is common in Paleogene basin deposits in Mexico (Martínez & Ramírez 2006). *Rugulitriporites* grew in tropical deciduous forests.

Salixipollenites (Fig. 8O–P), with features similar to pollen of *Salix*, is reported from Cenozoic basins from the Paleocene on in North America (Srivastava 1972). However, Muller (1981), quoting Graham and Jarzen (1969), considered that *Salix* first appeared during the Oligocene.

Pollen of the genus *Typha* were found in the samples from June 2008, studied recently. Present-day species of this genus are aquatic, living in wetland habitats.

Gymnosperms are represented in the samples by two groups of conifers. The first group consists of *Pinus* (Fig. 9A–B) which suggests that conifer forests grew nearby at higher elevation. This genus has existed since the Cretaceous and is known in Mexico from the Miocene on (Martínez & Ramírez 1998). At present, *Pinus* dominates temperate forest at altitudes above 3000 m. The second conifer group is represented by *Cupressacites* which occurs in two different forms with probable affinities to Cupresaceae and Taxodiaceae (Fig. 9C–D). These families have a reported age range from the Cretaceous to the present. In Mexico, they have been common in basins since the Paleogene.

Other taxa found in the samples are *Graminidites* (Fig. 9E), *Liliacidites* (Fig. 9F–G), *Rhoipites* (Fig. 9H–I), and *Striatricolporites* (Fig. 9J).

Discussion

Several lines of evidence strongly suggest an ash-fall origin of the powdery iron ore at La Perla. The most important are:

1. the presence of well-preserved fossil palynomorphs in the ore;
2. the morphology, structure and texture of the orebodies;
3. the physical nature of the iron-oxide aggregate constituting the ore; and
4. the composition of the ore: euhedral crystals of hematite or martitized magnetite; these two phases do not occur together in the same layer or part thereof.

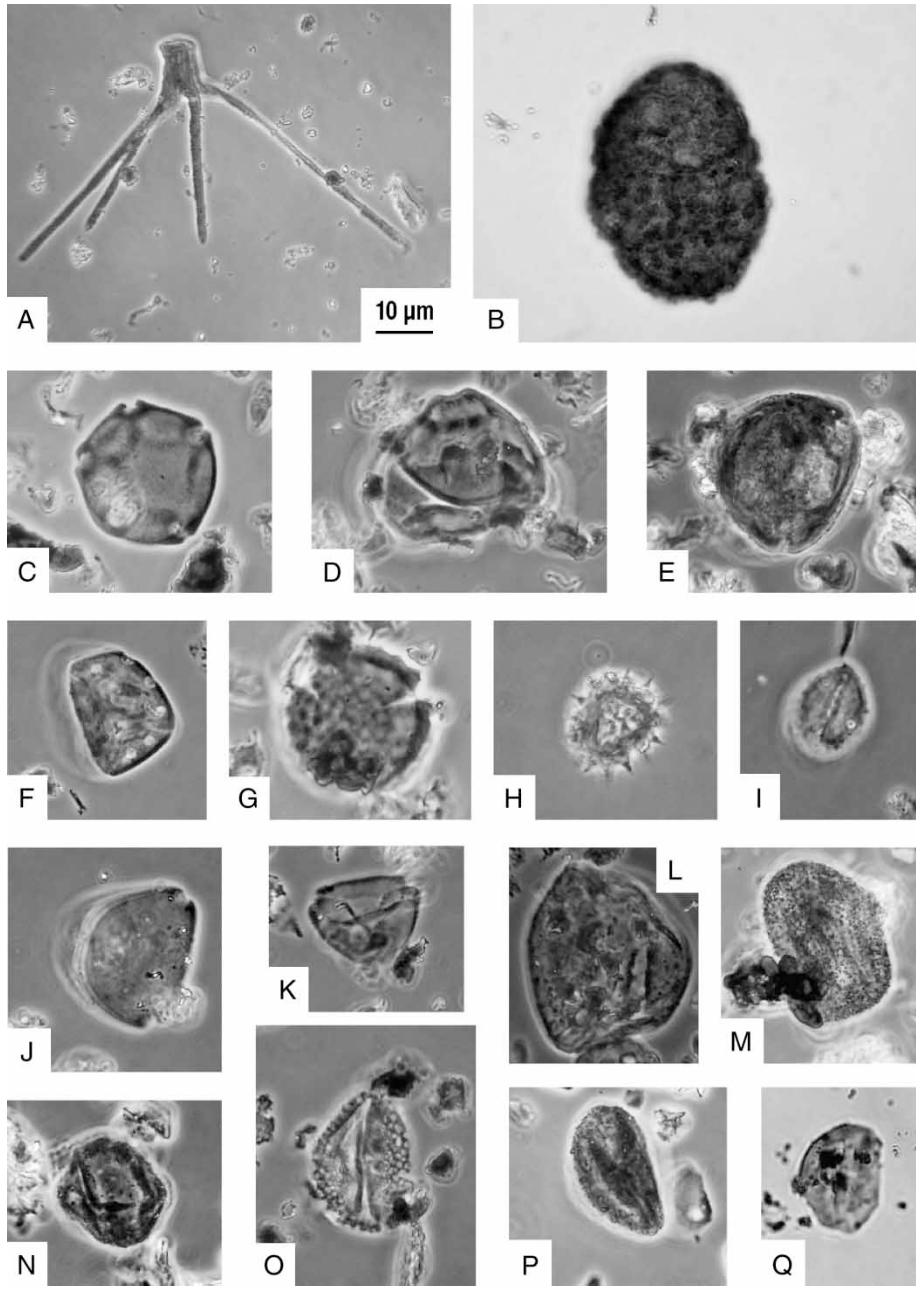

Fig. 8. Photomicrographs of fungal spores (**A**–**B**) and pollen (**C**–**Q**) from powdery ore at La Perla (the scale in **A** applies to all photos). **A**. *Frasnacritetrus*. **B**. *Dictyosporites morularis*. **C**. *Alnipollenites*. **D**. *Triatriopollenites*. **E**. *Triporopollenites*. **F**. *Chenopodipollis*. **G**–**I**. *Tubulifloridites*. **J**. *Momipites*. **K**. *Myrtaceidites*. **L**–**M**. *Quercoidites*. **N**. *Rugulitriporites*. **O**–**P**. *Salixipollenites*. **Q**. *Quercoidites*.

The Miocene minimum age of the palynomorphs is in good agreement with the Early Oligocene radiometric age of the volcanic rock hosting the ore, and rules out contamination with present-day material during mining. The light yellow color of the exines of the palynomorphs in the La Perla samples demonstrate that they are unaffected by thermal alteration. On heating, exines of pollen and spores become light brown in the 100–150°C range, showing a progressive darkening in color with temperature due to carbonization, until they become almost black close to 200°C, and are then destroyed at higher temperatures (Gray & Boucot 1975; Hemsley et al. 1996). Thus, the temperature of the iron-oxide matrix of the pollen has not exceeded 150°C since its deposition.

The beds of powdery ore occur intercalated in a sequence of lavas and clastic rocks. Exposed contacts with the host rock are razor-sharp and concordant, and rock fragments in the ore lack iron mineralization. Morphologically, the subhorizontal ore beds resemble deposits laid down by sedimentary processes. The stratification of the ore, with prominent size-sorting and even cross-bedding, indicates particulate transport and deposition. However, the euhedral habit characterizing a large proportion of the iron-oxide crystals constituting the ore, and its composition (either hematite or martitized magnetite, not both), are inconsistent with an epiclastic character. The crystals have not been rounded by abrasion. Some hematite ore samples contain crystals with partly rounded faces, but other features reveal that these crystals are marked by corrosion. In addition, there is no evidence that the iron-oxide beds are resedimented deposits.

The friable or unconsolidated nature of the powdery ore and its high porosity rule out formation by replacement of preexisting silicate rock. Such a process would fill open spaces between the constituent phases and destroy textures. The silicified ore at the

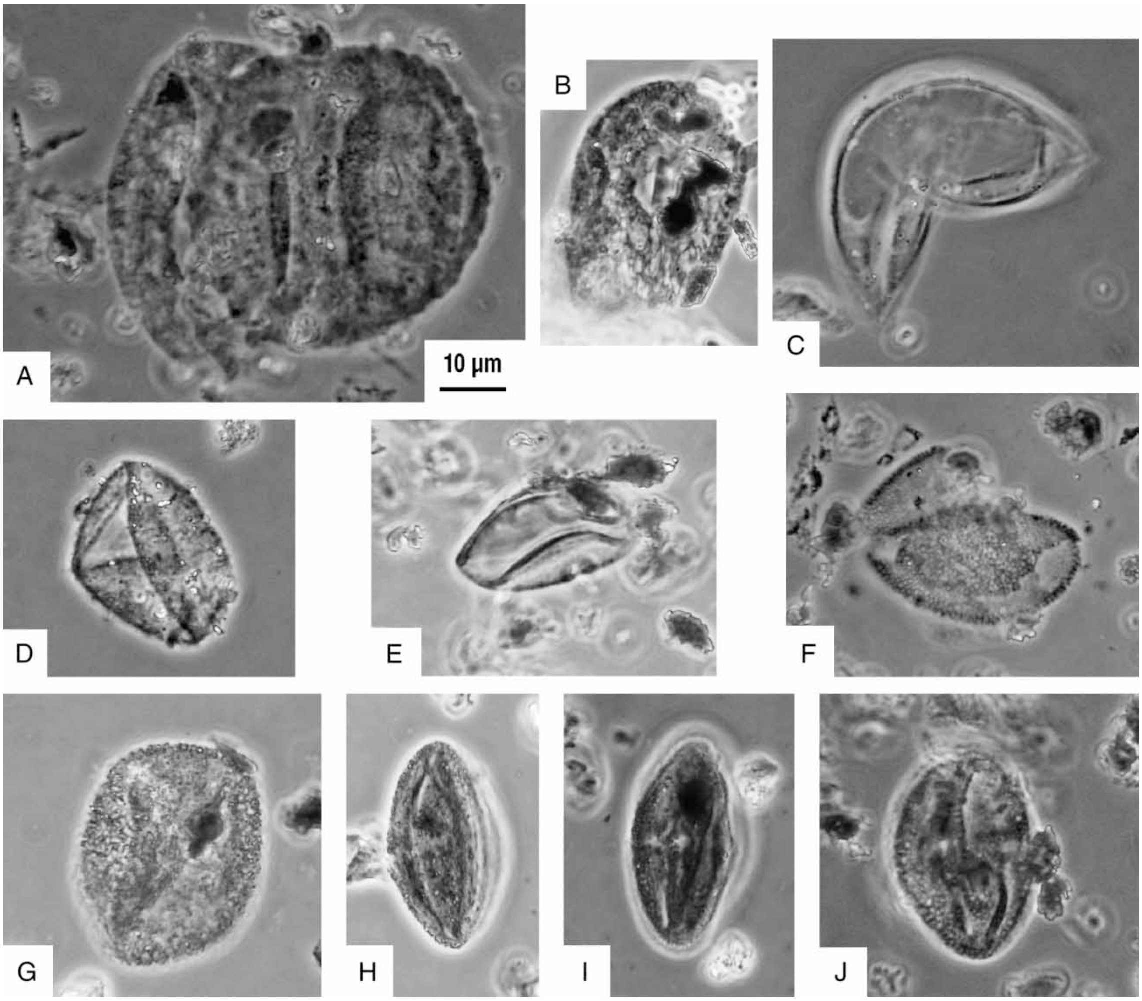

Fig. 9. Photomicrographs of pollen from powdery ore at La Perla (the scale in **A** applies to all photos). **A**–**B**. *Pinus*. **C**–**D**. Cupresaceae and Taxodiaceae. **E**. *Graminidites*. **F**–**G**. *Liliacidites*. **H**–**I**. *Rhoipites*. **J**. *Striatricolporites*.

base of the section is a good illustration: it is dense and nonporous, and its original texture has been erased or remains as relict patches. It is also difficult to imagine a hydrothermal process that would deposit extensive subhorizontal beds of stratified, size-sorted hematite or magnetite, made up of crystal aggregates that remain unconsolidated. The presence of pollen in the ore means that the ore must have formed at the surface, assuming that the palynomorphs were not introduced at a later stage of the geologic history. The low-temperature environment ($<150°C$) inferred from the well-preserved palynomorphs is consistent with the kaolinite-quartz-dominated alteration of the rhyodacite occurring as fragments in the ore and hosting the orebodies.

The fact that a bed of powdery ore or part of it is composed either of hematite plates, or martitized magnetite octahedra, shows that both minerals are primary phases. The simplest and most likely explanation is that the ore beds were deposited by ash fall (or perhaps by surge in the case of Layer 4; cf. Cas & Wright 1987). In fact, the deposits would be regarded as tuffs (or ash) by any geologist familiar with volcanic rocks, were it not for their unusual composition. Formation of hematite requires a relatively high oxygen fugacity, consistent with crystallization at shallow depth or subaerially; magnetite forms at a lower fugacity. This suggests a volcanic setting with fluctuations in oxygen fugacity during episodic eruptions of partly crystallized and highly gas-charged iron-oxide magma. The observations of scoriaceous ore that looked like a vesicular basalt (Cárdenas-Vargas & Del Castillo-García 1964), and flow banding (Van Allen 1978), support a volcanic setting. The exploited lenticular orebodies with these features were probably lava flows.

Thus, the available evidence suggests that the powdery ore is a pyroclastic deposit: a poorly consolidated crystal tuff. The well-developed hematite crystals which compose the friable open framework of most powdery ore (Fig. 7B–C) did not grow in situ; the crystals in unconsolidated parts show no sign of having grown attached to a surface. They were deposited. Wet iron-oxide ash might have captured pollen and spores if the ash fall was accompanied by rain. A more likely alternative is that the iron oxide and wind-blown pollen were deposited in an environment with temporary pools or small lakes. This interpretation is supported by the occurrence of clay-rich strata in the powdery ore (Pérez-Segura 1982), the observation that the sample with most pollen also contains more clay than the other samples, and the presence of *Typha* pollen. The association of pollen and clay argues against the possibility that the pollen was transported into the ore at a later stage by circulating water.

Unconsolidated powdery iron-oxide ore has been described from other iron ore deposits in volcanic settings, in Mexico (Cerro de Mercado; Lyons 1988) and Chile (El Laco; Nyström &

Henríquez 1994; Naslund et al. 2002). These deposits are stratified and size-sorted, or internally structureless. They are characterized by euhedral crystals of magnetite or hematite. The cited authors argued that the iron oxide was deposited as volcanic ash. This suggestion is strongly supported by the existence of very similar pyroclastic ore at La Perla.

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