Yardangs of different sizes were developed in the Payun Matru Volcanic Field, a semiarid area east of the southern Andes mountains. Yardangs from volcanic terrains have not been described previously from Earth, although studies from Mars interpreted linear ridges found by Mariner and Viking images as yardangs. The Payun Matru Volcanic Field is an extensive plateau at 2000 m a.s.l. covered by basaltic lava and ignimbrite flows. Strong westerly winds affect the extensive plateau. Micro- and mesoyardangs are formed on the ignimbrite rock blanket, and macroforms or megayardangs, several kilometres in length, are developed in the basaltic lava flows as long parallel troughs. They all have a distinctive 320° azimuth, which is the prevailing wind direction. No yardang features are noted in the more recent lava flows, younger than 1000 years, indicating that their formation needed a longer time or they developed in earlier periods with stronger winds. The yardang development is explained by the strong unidirectional winds, the poor vegetational cover due to the aridity of the region, the available quartz sand and volcanic ash particles as abrasive agents, and the volcanic lithology texture and flow structure. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: yardangs; wind erosion; volcanic geomorphology; Holocene; Payun Matru; southern Andes

INTRODUCTION

Wind erosion surfaces and forms are known in many arid and semiarid regions in the world (Breed et al., 1989). However, yardangs are not well reported and studied. Yardangs are defined as positive topographic forms a metre to a kilometre long, elongate and streamlined, resulting from erosion of lithified substrates by the wind (McCauley et al., 1977). They were originally named from a local word in Chinese Turkistan (Hedin, 1903). Their typical shape is of an inverted boat, and they are streamlined according to the prevalent wind direction, with length to width ratios of 3:1 or 4:1 (Grolier et al., 1980). Their best development is noted on large plateaus, where strong winds are unidirectional (Laity, 1994).

Yardangs from volcanic terrains have not been previously described on Earth; however, there are studies from Mars, where linear ridges found by Mariner 9 and Viking images of volcanic terrain were eventually interpreted as yardangs (Ward, 1979). They were also recorded in the geological record, in the Permian of Utah (Tewes and Loope, 1992).

The southern Andes and Patagonia of South America are characterized by strong westerly winds, but few research efforts have been made on the aeolian morphology and processes in this region. The only reported yardangs from South America are from the Pacific coastal arid area of Peru (McCauley et al., 1977a).

During a volcanic geomorphological study carried out by the authors in 1998 and 1999, linear features were recognized as yardangs in airphotos and checked in the field. Previous geological works in the area identified them as structural geomorphological features (González Díaz, 1972; Llambias, 1966).
The aim of this paper is to report on yardangs in the Payun Matru Volcanic Field, a semiarid area east of the southern Andes mountains, and to analyse the geomorphic factors for their formation, and their relationship to the upper Pleistocene and Holocene lava flow events in the area.

THE PAYUN MATRU VOLCANIC FIELD

The Payun Matru Volcanic Field (PMVF) is located between latitudes 36 and 37°S and longitudes 70 and 68°W in the Mendoza province of Argentina, about 100–200 km east of the main Andes Cordillerra. It is an extensive plateau, covering an area of 5200 km² at an altitude of 2000 m, and contains about 300 volcanic vents, most of them to the west of the main andesitic Payun Matru shield volcano (Figure 1). The Payun Matru plateau is enclosed to the west by the Andes chains that rise up to more than 3000 m; on the eastern side it is bordered by low hills and the pampas lowlands. Older lava flows are of the pahoehoe type, while recent ones are typical aa blocky flows, with elongated crests and sharp lobal edges. The older cones and lava flows are of Plio-Pleistocene age, but the majority of the cones and lava flows are of a young Upper Pleistocene to Holocene age. No volcanic activity has been witnessed in the last 200 years, but local oral traditions refer to eruptions in the area, and it is unlikely that these traditions last more than hundreds of years.

The basalt rocks are of the alkaline olivine type, with 46–52 per cent SiO₂ and 3.5–6 per cent alkalines (Na₂O + K₂O). Rock texture is porphyritic with granular matrix and olivine and plagioclase phenocrysts. Matrix minerals are olivine, plagioclase and pyroxene microlithics. The trace element composition indicates a common genetic source, and the basalts have a geochemical composition characteristic for backarc and orogenic environments (Bermúdez and Delpino, 1989).

The climate is semiarid, with annual precipitation around 200 mm. Summers are hot and winters cold with average temperatures of 20°C for January and 2°C for July. Strong westerly winds affect the area, and the predominant wind directions are northwest and west (Servicio Meteorológico Nacional, 1991). Soils are loess type and shallow, mostly rocky; vegetation is xerophytic and mostly composed of shrubs and herbaceous
taxa. The possibility that the yardangs were formed by glacial processes is rejected because there are no glacial features in the area. The actual snowline is above 3000 m, and probably was above most of the area during the glacial time, excluding the higher parts of the larger volcanoes.

Sandstone sedimentary formations, about 20 km to the west of the PMVF, are the source of sand blown to the volcanic area; small deposits of sand are found on the volcanic cone escarpments and in the yardang areas.

THE IGnimBRITE YARDANGS

On the western slopes of the composite Payun Matru volcano, a pyroclastic flow forming an ignimbrite
blanket of early Holocene age covers several square kilometres (González Díaz, 1972). On the lower part of
the escarpment a sub-recent basaltic lava flow partially overlies the ignimbrite blanket (Figure 2). The
ignimbrite rock is consolidated, with distinctly elongated crystals, and the formation is known as Tobas del
Portezuelo (Llambias, 1966) or El Portezuelo (González Díaz, 1979). The rock is crystalline, welded with a
dark pink colour and it contains many volcanic clasts from different sources. It has a porphyritic texture with
30–40 per cent phenocrysts, mainly plagioclase and in lesser proportion clinopyroxene and olivine minerals.
The plagioclase phenocrysts are broken, angular and filled by the matrix material. The matrix is mainly
hyaloophyllitic and consists of feldspar tables and interstitial glass, with apatite, zircon and magnetite as
minor minerals.

The ignimbrite blanket is homogeneous with an annular form around the old Payun volcano dome. The best
exposures are to the northeast and southeast of the volcano, being covered in other areas by younger lava
flows (González Díaz, 1972). Two kinds of yardangs are found in this lithology: micro and meso forms,
according to the division proposed by Cooke et al. (1993). The microyardangs are long, parallel, U-shaped
channels, 50 m long, 2.5 m wide and 0.3 m deep, carved into the ignimbrite blanket (Figure 3). The largest is
100 m long and 8 m wide. The channel floor is smooth with ripple-shaped ridges parallel to the main yardang
trough direction. The erosive straight channels are in a 320° direction, similar to the prevailing winds, and are
partially covered by blown quartz sand grains derived from the exposed sandstone formations to the west of
the area. Figure 3 illustrates the cross-section and shape of the ignimbrite trough, showing an accumulation of
quartz sand on the lee side; the lack of vegetation may indicate that strong winds winnowing fine particles
impede the growth of plants and root development.

Other wind-shaped features in the same ignimbrite rock are the demoiselles, mesoyardangs about 1.5 m
high and 3–4 m long, well streamlined with the bow part to the wind direction, very similar to the ones carved
in the Tarawan Chalk of the Farafra Depression in Egypt (Breed et al., 1989, p. 286). They are distributed on a
relatively small area of a few square kilometres near the flank of the Payun Liso volcano (Figure 4a and b).
The main axis depends on wind direction and not on structural rock joints, which in this case do not affect
their shape, as shown in Figure 5. Width/length ratio is approximately 0.25, when total drag is at a minimum
(Ward and Greeley, 1984).
Figure 4. Carved demoiselles yardangs in the ignimbrite blanket. (a) A 2.5 m high yardang; in the background is the Payun Liso volcano. The structural joint is perpendicular to the main yardang axis. (b) Sand-blasted flutes and grooves in the ignimbrite rock, oriented to the prevailing wind direction, 320°, indicated by the compass.
THE LAVA FLOW YARDangs

Long megayardangs, several kilometres in length, are discernible in airphotos and in the Landsat image (Figure 6). These are unusually large features, similar to the large yardangs in Iran, China and Chad (Dresch, 1968; McCauley et al., 1977; Halimov and Fezer, 1989).

Field observations reveal lower areas, about 100 m wide between higher lava ridges. The lower parts are covered by a thin blanket of blown quartz sand. The depressions are interrupted by lava crests, indicating abrasion activity on the lava flow ‘crevasses’, widening them and leaving higher sharp crests, up to 10 m high (Figure 7). Several features reach up to 10 km in length. They are linear and parallel on a distinctive 320° azimuth, which is the prevailing wind direction. They are developed in the basaltic lava flows of E1 Mollar formation of Holocene age (González Díaz, 1972).

In the Mojave Desert, Blackwelder (1934) used the term ‘yardang troughs’ for similar geomorphic features. Small ravines in the area are said to be the triggers that start the formation of troughs, by drifting sand and grinding the bottom and particularly the sides of the yardang. Ridges are left in a ragged condition.

These major features may be developed by wind abrasion starting in microtopographic irregularities of the lava flows, and although no smooth paved surfaces form, as in the ignimbrite rock area, the patches of quartz sand found on the lava depressions are evidence of sand abrasion. The initial channelling in the basalt flows accelerates local winds, increasing the abrasion processes, followed by deflation, erosion and the widening of the troughs. Flow surfaces act as aeolian traps, increasing wind velocities and erosional processes, as in the Cima volcanic field, Mojave Desert, California (Wells et al., 1985).

Pyroclastic ashfall added fine abrasive material, although the main erosive agent was the sedimentary quartz grains.

Other large aeolian features are fine ash tails along cinder cones on the same lava field, following the main wind direction.

DISCUSSION

No similar features are noted in lava flows that are younger than 1000 years, indicating that the yardangs
developed in earlier periods with stronger winds or needed a longer time for their formation, but the lack of vegetation cover may indicate that aeolian morphological processes are still active. Yardangs can form quickly (Cooke et al., 1993), and the Payun Matru yardangs probably first developed in the last glacial period. The yardangs are formed by unidirectional winds and are probably indicative of the resultant effective wind (Ward, 1979). The present effective winds are on a 320° azimuth (Servicio Meteorológico Nacional, 1991), indicating no major shifting in the wind direction since the time of the yardang formation. In northern Chile (27–33°S), Veit (1996) inferred that westerly winds were stronger in several Holocene periods, based on geomorphological and pedological studies. However, no major climatic change in the Holocene in the Patagonian Andes was found in palynological studies (Markgraf, 1983), which strengthens the assumption.

Figure 6. Parallel yardangs, several kilometres long, west of the Payun Matru volcano, developed in a Holocene basaltic lava flow.
that a similar vegetational cover prevailed during Holocene times. The major physiographic changes in the Payun plateau in Holocene times were the volcanic eruptions of cinder cones and lava flows. Yardang troughs are observed in two areas: east and west of the main Payun Matru volcano. The western field is younger, probably Holocene in age, while the eastern field is of Upper Pleistocene age. Yardang development is more evident on the eastern side, and there are no major physiographic differences between the two lava flows except their age, which may explain the more developed erosion features in the old eastern field, although it is possible to assume that both systems formed through a continuous process during the same periods of time.

In the Payun Matru area, abrasive quartz sand seems to have been an effective agent in eroding the basaltic rock, and strong winds deflated the eroded particles. The ignimbrite and basalt are hard rocks and they must have undergone an abrasive phase in order to be deflated. Grooves and flutes in the hard ignimbrite rock (Figure 4b), and the undercutting at the bows and flanks of the sphinx-like features, are evidence of the abrasion processes. Quartz sand particles, found today in the yardang features, were the abrasive agents and sculptors of the volcanic hard rocks. On basaltic rocks in the Amboy lava field in California, pits and grooves formed by aolian erosion were found in pahoehoe basalt. The surface roughness of the lava increased the wind threshold velocity (Greeley and Iversen, 1986), and a similar process probably affected the development of the Payun Matru megayardangs.

From laboratory and field studies elsewhere, it has been found that streamlining occurs by deflation and headward erosion (Ward, 1979). Similar wide troughs hundreds of metres wide have been found in Chad (Mainguet, 1972), as well as on Mars on ignimbrite or highly porous lava (Ward, 1979).

Other hypotheses for the formation of the Payun Matru yardangs would be as fluvial or glacial features along structural lines (González Díaz, 1972). No present or palaeofluvial, palaeoglacial sediments or morphologies are recognized in the area, and there is no evidence of water erosion activity in their formation.

The development of yardangs in hard, consolidated basaltic rocks is not common in volcanic terrains on Earth and further studies are required to find the physical processes involved in their formation. Most studied yardangs are developed on fine-grained sediments (Greeley and Iversen, 1985). However, yardangs were
discovered in hard rocks like dense crystalline limestone and granite in Egypt’s Western Desert (Grolier et al., 1980).

SUMMARY

1. In the Payun Matru Volcanic Field, distinctive features of yardangs carved in hard ignimbrite rock, and large yardang troughs in basaltic lava flows are found, streamlined with the prevalent northwesterly winds.

2. The yardangs were formed at episodes of strong winds, which were on the same 320° azimuth as the present wind system, probably indicating an extended period of aridity and strong winds in late Pleistocene to early Holocene times. They were not found in the young, sub-recent lava flows, and there is no evidence of present development of yardangs.

3. The rock texture of the ignimbrite flow allowed the formation of distinctive small features, where on the hummocky lava field large discontinuous yardang troughs were formed.

4. Yardang development in the PMVC is due to the following factors:
   a. Wind strength, frequency and direction: strong unidirectional winds develop in the extensive plateau.
   b. Aridity: there is a meagre vegetation cover, and on new volcanic flows thousands of years may elapse until vegetation is developed. The region has prolonged dry periods.
   c. Abrasive sediments: available quartz sand and volcanic ash particles are the abrasive agents of the volcanic rocks.
   d. Lithology: the ignimbrite and basalt are hard rocks, but the irregularities of the lava flow enhanced wind activity, and the coarse ignimbrite mineralogical texture favoured the abrasive processes.

ACKNOWLEDGEMENTS

The research was funded by grants provided by the Universidad de Buenos Aires Grant UBA-Ex138 and University of Haifa. The authors would like to thank Professor Haim Tsoar and Professor Nicholas Lancaster for critical reading of the manuscript and valuable comments. Professor Andrew Warren and an anonymous reviewer contributed to the clarity of the paper.

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