Journal of Volcanology and Geothermal Research 86 (1998) 93–96

Journal of volcanology and geothermal research

Experimental simulation of basalt columns

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Received 23 February 1998; accepted 6 May 1998

Abstract

Basalt columns can be simulated by the desiccation of mixtures of starch and water. This note presents photos of starch columns from laboratory experiments and summarizes results of an extended study ([Müller, G., 1998. Starch columns: analog model for basalt columns. J. Geophys. Res. 103, 15239–15253.]). Basalt cooling and starch desiccation are diffusion processes, causing contraction and cracks. Column-related crack patterns in basalt and starch are largely similar. Differences in their spatial and time scales are due to the difference in the diffusion constants which is about two orders of magnitude. Starch experiments give a few new insights into basalt-column formation. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: basalt columns; cracks; desiccation; starch

1. Introduction

Desiccation of starch–water mixtures produces contraction, contraction stresses and tensile cracks of various forms. A spectacular example is a crack pattern, connected with the formation of polygonal columns similar to basalt columns. In principle, this has been long known (French, 1922), but practically it was forgotten, and scientific aspects of the far reaching analogy of starch desiccation and basalt cooling apparently have never been described. I came across the interesting properties of starch accidentally, when doing kitchen experiments with household materials. In Müller (1998), subsequently referred to as M, a relatively detailed description of starch experiments and their interpretation is given. The purpose of this note is to draw the attention of volcanologists to the results and to present a few new photos of starch columns.

2. Starch desiccation, cracks and columns

Starch is a basic ingredient of many plants, e.g., of corn, rice and potatoes. It consists of grains of polysaccharides, which are formed of chain molecules of glucose. Starch powder can absorb water according to a mass ratio of about 1:1, with the consequence of strongly swelling the grains. Subsequent desiccation of a specimen leads to water diffusion to the surface, to evaporation and to grain contraction. Contraction stresses develop throughout the volume of the specimen and finally exceed the material strength. Intergranular tensile cracks of various forms occur. One of the resulting crack patterns first covers the specimen's surface in an irregular fashion. Then, it propagates vertically into the interior behind a crack front and develops polygonal regularity, columnar jointing and columns.

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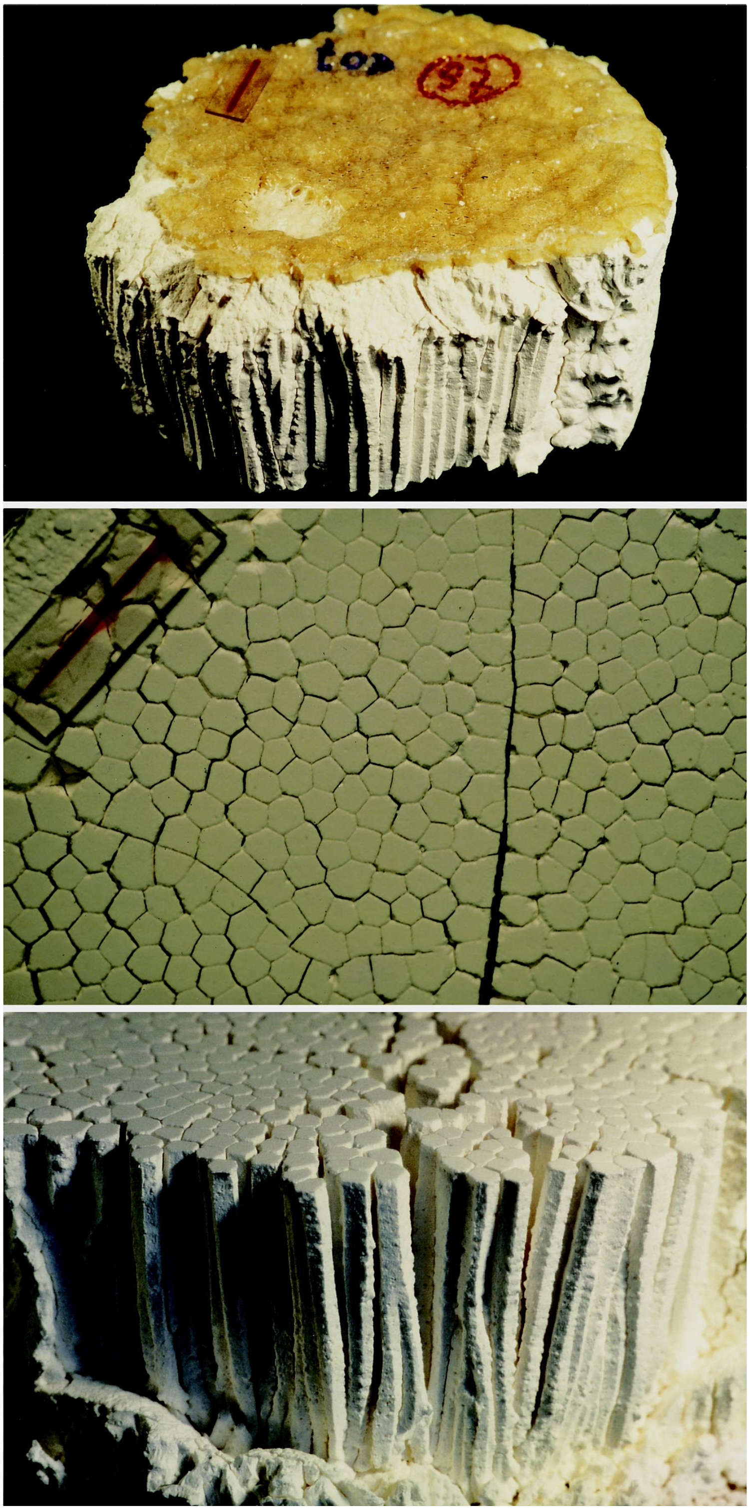
PII: S0377-0273(98)00045-6



The starch–water mixtures are dried in glass vessels with diameters and depths of a few centimeters. Lamp drying is performed from above; the distance from the bulb to the starch surface is a control parameter. The crack front can be observed through the vertical wall of the vessel, and its position can be marked at various times for later speed determination. When the crack front arrives at the bottom, almost all water has been lost by diffusion and evaporation. The dried specimen is then removed from the vessel for further inspection and documentation. Typical experiment durations are 1–5 days, and typical column diameters are 1–4 mm.

The experiments, described in M, were performed with corn starch. In Fig. 1 columns in rice starch are shown. Since rice-starch grains are much smaller than corn-starch grains, rice-starch columns have smoother faces and straighter edges than corn-starch columns and are, therefore, even more similar to basalt columns than corn-starch columns.

Interesting features of the photos in Fig. 1 are as follows:

(1) The form of the column cross-sections is predominantly hexagonal and pentagonal and, therefore, very similar to the cross-sections of basalt columns. Side statistics confirm this quantitatively (M, Fig. 2).

(2) Polygonal regularity is not present at the surface, but develops during penetration of the crack pattern. Crack patterns in cooling basalt apparently develop in a similar fashion (Peck and Minakami, 1968; Weaire and O'Carroll, 1983).

(3) Column diameters generally increase with depth, columns merge and their number per unit cross-section area decreases with increasing depth. Whether this trend is similarly strong in cooling basalt, is open.

(4) Large cracks which form prior to columns (Fig. 1, middle) are similar to the megajoints in lava flows (Spry, 1962).

(5) Horizontal striations can be seen on some of the column faces. Probably, they are due to incremental fracture continuation which has also been identified on basalt columns (Ryan and Sammis, 1978; DeGraff and Aydin, 1987).

Visual inspection of dried starch specimens can be supplemented by X-ray tomography. Tomograms for increasing depths yield particularly clear information about the development of the crack pattern and the column diameters (M, Figs. 3 and 4).

3. Further results

Basalt cooling and starch desiccation are diffusion processes which obey diffusion equations. Hence, temperature T in basalt and water concentration C in starch are analog quantities. The essential material parameter is the thermal diffusivity $\kappa_{th} \approx 10^{-6}$ m^2/s of basalt and the hydraulic diffusivity κ_h of starch, respectively. For κ_h a value of $(0.7–2.7) \times 10^{-8}$ m^2/s was determined from one of the desiccation experiments.

The speed by which isotherms propagate into a cooling lava/basalt half-space is time-dependent and proportional to $\kappa_{th}^{1/2}$. Hence, the speed of the crack front, at $T \approx 900°C$, has the same dependence. Moreover, a similar dependence is expected for the crack-front speed in starch, i.e., proportionality to $\kappa_h^{1/2}$. From the 2 orders of magnitude difference between the diffusivities, a difference in the crack-front speeds according to a factor of about 10 is expected. From a larger number of measurements in starch, the local speed for an average desiccation time of 3 days had an average value of 10 mm/d. A corresponding value for basalt can be estimated from measurements of the solidification of a Hawaiian lave lake (Peck, 1978). Speed measurements are given on p. 9 of this paper for one particular isotherm, $T = 1065°C$, corresponding to approximately equal

Fig. 1. Top: Rice-starch specimen after lamp drying at the top side. The red bar is 1 cm long. The thin yellow layer (which has segregated early in the desiccation process) and the starch immediately below are cracked irregularly. Columns with polygonal cross-sections develop with increasing depth. Middle: Polygonal crack pattern at the bottom of a specimen. Typical polygon diameters are 2–3 mm. The large straight crack occurred earlier than the columns and decoupled column growth on both sides. Bottom: Side view of rice-starch columns. Drying started from below, i.e., the depth axis points upwards. The columns are irregular and thin at the beginning, merging of columns occurs, and the column diameter increases.

amounts of melt and crystals in the lava. These speeds can be taken as estimates of the speed of the crack front. Interpolation gives a local speed of about 100 mm/d after 3 days of cooling. This value is 10 times higher than the crack-front speed in starch for the same time, as expected above. Hence, starch desiccation proceeds much slower than basalt cooling.

Variation of the distance between lamp and starch changes the water evaporation rate j and, hence, the vertical concentration gradient $\partial C/\partial z = j/\kappa_h$ immediately below the crack front. Since the column diameter D is also changed, there is a relation between D and $\partial C/\partial z$: high (low) concentration gradients at the crack front are connected with thin (thick) starch columns. Because of the general analogy between water concentration in starch and temperature in basalt, a similar relation exists for basalt: high (low) temperature gradients $\partial T/\partial z$ at the crack front are connected with thin (thick) basalt columns. Formulated differently, the diameter of basalt columns is controlled by the gradient $\partial T/\partial z$ at the crack front (and not, as is sometimes assumed, by the cooling rate $\partial T/\partial t$).

To compare the gradients in starch and basalt, they are taken from normalized concentrations and temperatures, which approach unity at great depth. Much higher gradients in starch than in basalt are expected, since the crack front propagates much slower in starch. The gradients in starch can be measured via the evaporation rate or the rate of mass decrease of a specimen, and the gradients in basalt can be estimated from the usual half-space cooling model. The starch gradients are about 3 orders of magnitude larger than the basalt gradients. This big difference explains qualitatively why starch columns are much thinner than basalt columns.

The transition from an irregular crack pattern at the surface of a drying starch specimen or a solidifying lava flow or lake to a polygonal crack pattern at depth follows a minimum-fracture-energy principle. Therefore, irregular, rugged cracks develop into linear cracks, and irregular crack cells develop into polygons. Among polygonal crack cells (assumed to be equilateral, of equal size and area-filling) equilateral hexagons have the shortest circumference and, hence, require the least amount of fracture energy for continuation. This description offers an explanation of a major feature of starch and basalt columns, the dominance of hexagonal cross-sections. However, the polygon side statistics (in corn starch: about 50% hexagons, 35% pentagons, 15% heptagons, occasionally quadrangles and octagons) is not explained.

4. Conclusions

Basalt cooling and starch desiccation are similar processes, because they are diffusive. In both cases the resulting contraction is strong enough that contraction stresses exceed the material strength. As a consequence, the crack systems in both media are basically very similar, inspite of extreme differences in microstructure and elastic properties. The difference in the spatial scales (column diameter) and time scales (speed of crack front or column growth) can be explained by the difference in the diffusivities which is about 2 orders of magnitude. Starch experiments give new insights into basalt-column formation, e.g., by clarifying the role of the temperature gradient at the crack front for the column diameter, or by showing that the polygonal regularity of columnar jointing need not be present at the surface, but develops during column growth. Starch appears to be an interesting material also for other studies, e.g., of tensile-crack propagation, crack morphology and crack systems.

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