

## NOTES

### CONVECTION PATTERNS IN SHALLOW POOLS OF EVAPORATING CLAY SUSPENSIONS

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Evaporation at the surface of a pool of liquid lowers the temperature of the surface layer, thus increasing its density. Consequently, the higher density of the surface layer tends to overturn the fluid, producing convection within the pool of evaporating liquid. Theoretical calculations (Pellew and Southwell, 1940) indicate that thermal convection should occur when the Rayleigh number,

$$g \beta \Delta T L^3 / K \gamma,$$

exceeds 1100. In this equation,  $g$  is the acceleration due to gravity;  $\beta$ , the coefficient of thermal expansion;  $\Delta T$ , the temperature difference between the top and bottom layers;  $L$ , the depth of the liquid;  $K$  and  $\gamma$ , the thermal and viscous diffusivities respectively. Thus, in a pool of water where  $\Delta T \approx 1^\circ\text{C}$ , convection should occur when the depth of the pool is greater than 0.3 cm.

In various investigations with water (Spangenberg and Rowland, 1961; Berg *et al.*, 1966), however, convection was observed only at depths greater than 1 cm, corresponding to a Rayleigh number almost 40 times larger than 1100. In these cases then, the Rayleigh number becomes much less important, and physical factors other than those which affect the Rayleigh number must control convection. For example, it has been suggested that surfactants, which are extremely difficult to remove from water, are stabilizing factors against convection; hence increased depths are required to induce convection. The dependence of surface tension on temperature, solutes and surfactants is of great importance in determining convection patterns (Scriven and Sternling, 1960). Indeed, in the original experiments with spermaceti oil (Bénard, 1901), the variation of surface tension with temperature was, most likely, responsible for convection. Also, the convection patterns caused by evaporation in pools of pure water were observed only through the use of schlieren optics (Spangenberg and Rowland, 1961; Berg *et al.*, 1966).

We studied convection effects in evaporating clay suspensions rather than in pure water for the following reasons. One, we hoped that the changing orientation of clay platelets during overturn of the liquid would facilitate direct observation of the convection patterns. Two, convection effects in clay suspensions should be similar to those occurring naturally in shallow ponds and flooded soils; thus, our understanding of natural convection patterns in turbid waters should be enhanced.

Suspensions of vermiculite, bentonite and kaolinite clays were used in preliminary studies. Convection patterns with the sharpest contrast were produced with vermiculite while no clear patterns were produced with kaolinite. In further experiments, convection patterns were more evident with larger silt-size particles than with smaller clay-size particles.

Also, the patterns were more readily visualized in higher concentrations of the suspension. However, the larger particles and higher concentrations caused greater settling of the suspensions, making the lower layers more dense and hindering convection. A 2 per cent suspension of clay-size ( $< 2 \mu\text{m}$ ) provided a satisfactory compromise between visualization and settling.

Suspensions were placed in Pyrex dishes  $24 \times 36$  cm and allowed to evaporate at temperatures of about 20 or  $35^\circ\text{C}$ , and at a r.h. of about 50 per cent. The latter environment may correspond to a shallow pond after it has been heated by the sun. Convection patterns were similar in both cases. At the higher temperature, however, the patterns were more readily seen because of the sharper contrast between the rising and the overturning liquid.

In Fig. 1 photographs A, B, C, D represent a sequence of convection patterns observed in 0.5-cm deep vermiculite suspensions at  $35^\circ\text{C}$ ; E represents a 1-cm deep vermiculite suspension at  $35^\circ\text{C}$ ; and F represents a 3-cm deep bentonite suspension at  $20^\circ\text{C}$ . The dish containing the 0.5-cm deep suspension was rocked a few times to mix the suspension thoroughly and then allowed to stand. The eddies created by the mixing disappeared within a minute and rolls then appeared which tended to be parallel to the side of the dish along which it was rocked. Thus, rolls could be created parallel to the short or long side of the dish. However, the rolls were unstable and pinching instability developed. Photograph A corresponds to this state; the pinching instability is clearly visible where rolls terminate. As time passed the rolls continued to break and hexagonal cells developed. In photograph B, the arrow indicates a region dominated by cells while the rest of the photograph is largely occupied by rolls. Photograph C shows the complete dish filled with cells, although some remnants of the original rolls can still be surmised. The width of the rolls was roughly twice the depth of the suspension and slightly less than expected (Chen and Whitehead, 1968). As time progressed further the cells merged to form bigger cells until their size was about five times the depth of the suspension (photograph D). The characteristic time of evolution from one pattern to the next was of the order of a minute. However, the final configuration fades away only slowly as settling destroys the convection patterns.

With the suspension at room temp, the visible pattern generally resembled photograph B. The larger particles of vermiculite deposited at the bottom of the dish during settling often formed a pattern very similar to that of photograph C. At room temperature, the cells did not merge and the configuration of photograph D did not appear. The failure of the cells to merge at room temp and their ready merging in heated suspensions agrees with the observation that higher

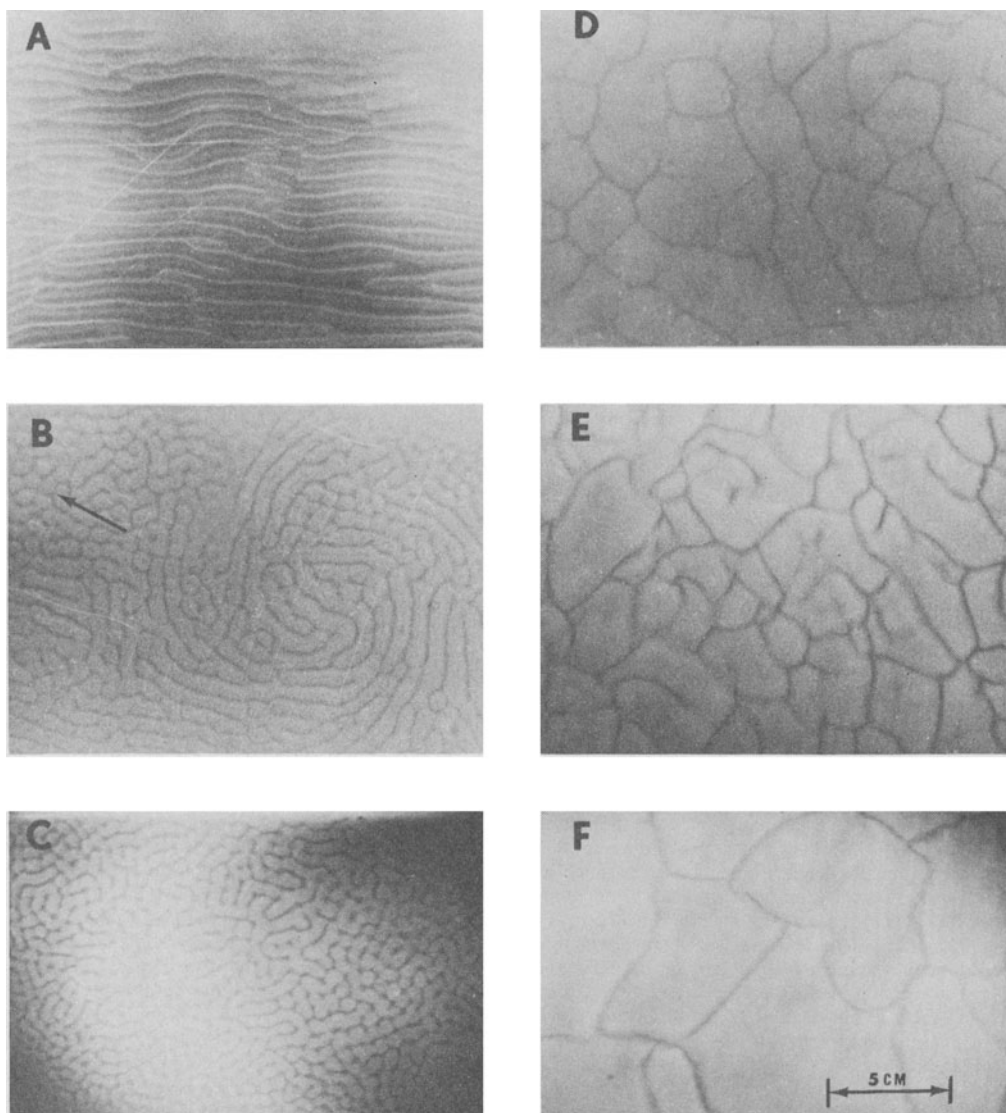


Fig 1. Convection patterns in evaporating pools of 2 per cent clay suspensions: A, B, C, D—sequential changes in a 0.5-cm deep vermiculite suspension, E—1 cm vermiculite suspension and F—3 cm bentonite suspension. Photographs were taken normal to pool surfaces.

temperatures enhance merging (Dauzère, 1912) although the reason is not understood (Schwiderski and Schwab, 1971).

While photographs A–D correspond to a depth of 0.5 cm, convection was also observed with depths as little as 0.3 cm. Since these patterns have not been observed in evaporating pools of water before, the presence of clay must be crucial in neutralizing the stabilizing effect of surfactants.

As the depth increased beyond 0.5 cm, the pattern changed progressively to that shown in photograph E; rolls changed rapidly to irregular patterns for both the warm and cool suspensions. This configuration of 'streamers' typical of convection in deep layers has been observed previously by Spangenberg and Rowland (1961) and Berg *et al.* (1966).

Their description of streamers applies to ours with but one exception. Spangenberg and Rowland (1961) in particular noted the rapid change in configuration as the streamers constantly moved. In our case, the shape of the streamers changed very slowly. We presume clay is responsible for this difference. Using the standard viscometric technique of dropping a solid sphere in the suspension, we determined that the viscosity at high shear was essentially that of water. However, when gently pouring some of the suspension into pure water, we noticed that the suspension formed a *cloud* which kept its cohesion even though the pure water was not still. This property of cohesion would impede the movement of the streamers in the clay suspension, even though the vis-

cosity of the suspensions at relatively high shear was equal to that of water.

So far we have discussed the convection patterns in a vermiculite suspension. A sodium bentonite suspension gave some interesting patterns as well. No convection was observed in a 2 per cent bentonite suspension until the depth was increased to 1 cm. The lack of convection in shallow suspensions may be related to the tendency of bentonite to form a gel. However, when the depth exceeded 1 cm, streamers similar to those with vermiculite (photograph E) appeared; also, these streamers did not meander around. With time the cells between the streamers tended to merge until an optimum cell size depending upon the depth of the liquid was reached.

In bentonite, as evaporation occurred, the clay particles near the surface formed a thin layer of gel which increased in depth as evaporation proceeded. For instance, in a 3-cm deep suspension, the regions between the streamers eventually appeared as *islands* of gel as illustrated in photograph F. The gel contained about 4 per cent clay and was heavier than the liquid underneath but was apparently maintained afloat by surface tension. The streamers appeared as cracks which remained filled with an approx 2 per cent suspension during drying i.e. no gel was formed to seal the cracks and bridge two islands. This effect must be due to the constant renewal of the liquid rising under the island and plunging down the crack. Finally no liquid suspension remained and the islands were separated by empty cracks where streamers used to be.

The results of this investigation show that in the presence of certain clays, visible convection patterns are formed in evaporating pools of water less than 1-cm deep. This observation suggests that clay platelets may interact with surfactants that would otherwise prevent convection. In addition, the cohesion in clay suspensions increases the stability of the convection patterns produced by evaporation. The ultimate cracking patterns observed in the field when shallow pools dry by evaporation may be influenced, among other factors,

by erosion and deposition of particles at the bottom of pools, following some of the convection patterns described above.

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#### REFERENCES

- Bénard, H. (1901) Les tourbillons cellulaires dans une nappe liquide transportant de la chaleur par convection en régime permanent: *Ann. Chim. Phys.* **23**, 62–144.
- Berg, J. C., Boudart, M. and Acrivos, A. (1966) Natural convection in pools of evaporating liquids: *J. Fluid Mech.* **24**, 721–735.
- Chen, M. M. and Whitehead, J. A. (1968) Evolution of two-dimensional periodic Rayleigh convection cells of arbitrary wave-numbers: *J. Fluid Mech.* **31**, 1–15.
- Dauzère, M. C. (1912) Sur les changements qu'éprouvent les tourbillons cellulaires lorsque la température s'élève: *CRAS* **155**, 394–398.
- Pellew, A. and Southwell, R. V. (1940) On maintained convective motion in a fluid heated from below: *Proc. R. Soc.* **176A**, 312–343.
- Schwiderski, E. W. and Schwab, H. J. A. (1971) Convection experiments with electrolytically heated fluid layers: *J. Fluid Mech.* **48**, 703–719.
- Scriven, L. E. and Sterling, C. V. (1960) The Marangoni effects: *Nature* **187**, 186–188.
- Spangenberg, W. G. and Rowland, W. R. (1961) Convective circulation in water induced by evaporative cooling: *Phys. Fluids* **4**, 743–750.