distinguishing this species from *Ch. kuwanae* and I doubt that in this case we deal with distinct species." In the light of their diagnostic chromosome differences, it thus becomes clear that we are here concerned with sibling species; these are tolerably common in the Chilocorini (*5, 6, 12*).

The accumulated cytological evidence immediately exempts *C. kuwanae* Silvestri and *C. renipustulatus* Scriba from synonymy, and, accepting the morphological differences between the Carpinteria material and Silvestri's and Van Emden's descriptions as taxonomically valid, it must be granted that, along with *C. kuwanae* and *C. renipustulatus*, *C. similis* Rossi also occurs in Asia, either allopatrically or sympatrically. With *C. kuwanae* disqualified cytologically and *C. renipustulatus* excluded on morphological grounds, I therefore consider it reasonable to apply the name *C. similis* to the population that by 1957 had perpetuated itself in California over a period of some 10 or perhaps even 35 years and has there been masquerading under the name *C. orbus* Casey. Whether a similar state of affairs exists in Georgia or elsewhere in the east, with *C. similis* now being confused with *C. stigma*, remains an intriguing possibility worthy of investigation.

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13. This report is contribution No. 1212 from the Forest Entomology and Pathology Branch, Department of Forestry, Ottawa, Canada. I thank those already named and C. C. Benedict, district agricultural inspector, for guidance at Carpinteria and T. W. Fisher for the Japanese *C. kuwanae* raised at Riverside in 1958. C. P. Clausen provided accommodation and facilities at Albany.

25 March 1965

Particle Sorting and Stone Migration by Freezing and Thawing

An account of the relative migration of particles of various sizes caused by alternate freezing and thawing of earth was given some time ago in these pages by Corte (*1*), along with experiments he suggests may be helpful in interpreting the phenomenon. However, there is another mechanism (*2*) that explains in a compelling, plausible manner the gradual lifting of a relatively large particle (or boulder or fence post) through the surrounding smaller particles.

Consider a spherical body as in Fig. 1, embedded in an aqueous slurry of finer particles which is being frozen from above, the freezing line having descended to the level A. If the body is a grain of a few milligrams or a stone of a few grams or even kilograms, the adhesion of the ice to the top of the sphere will be strong enough to be capable of supporting its weight. If it is a boulder of several tons, it may be necessary for it to be embedded in a block of frozen slurry down to level B before lifting can occur. With the body adhering to the frozen block, consider the subsequent freezing of a layer of thickness dz. Since water expands on freezing, a mixture of water and particles has an average coefficient of expansion on freezing—here denoted by α—which is somewhat less than that of pure water. The layer of thickness dz then expands by an amount αdz on freezing, lifting the entire thick layer of frozen slurry above it by that amount and the sphere with it. Because of the rigidity of the sphere, a cavity would be left beneath it, except for the fact that the still unfrozen slurry beneath flows in to equalize pressure and fill the void. The extent to which this flow may consist of water filtering through the soil rather than mass movement of the slurry may depend on the porosity and effective viscosity of the slurry and on the time available, which depends on the rate of freezing. (This can explain some of the observed dependence of the migration distance per cycle on the rate of freezing.) The sphere is lifted by a total amount of the order of magnitude of α times the diameter, which may be one or a few percent of the diameter. Some particles and some water move into a space of this thickness below the sphere, as indicated schematically by the curved arrows in Fig. 1.

Consider now the reverse process, thawing from above. When thawing has progressed to level B, for example, the sphere is still firmly supported by the frozen slurry beneath it (including that which flowed in just before freezing). As the thawing surface advances a distance dz, the contraction permits the whole mass of soil above it to fall by αdz. However, the solid dome of the sphere protrudes into this descending mass, forcing some of the fluid slurry above it to flow sideways around the obstruction and help fill in the space being provided above the thawing layer. Thus particles move away from the top of the sphere, and the net result of the whole cycle is that the sphere rests higher with more soil beneath it and less above.

Freezing and subsequent thawing from beneath transport the stone downward by this mechanism, as is easily seen by repeating the argument for this case. The direction of motion is determined by the direction of the freezing and subsequent thawing, not by the direction of gravity, because gravity serves merely to supply a pressure to fill in the voids and thus acts as a scalar, not a vector.

In the case of horizontal motion of a vertical plane of freezing and thawing, as near a steep bank, gravity plays its role not only as a scalar but possibly more prominently as a vector causing a slope of the stone's net motion. An upward slope can be explained as follows: When the nascent cavity is being filled by both rheological flow of the slurry and by porous seeping of the water, the tendency should be for a denser mixture, richer in soil particles, to settle to the bottom of the "cavity" under one side of the stone, thus causing a net lift. On the other hand, an explanation can also

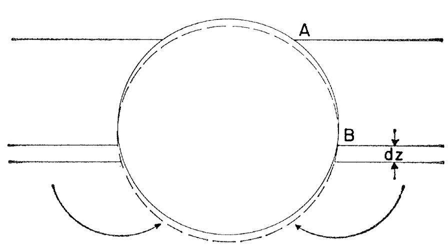

Fig. 1. The spherical stone may be raised by adhesion to the frozen block as the freezing line descends from level *A* to *B* and beyond, because of the expansion of the surrounding mud on freezing.

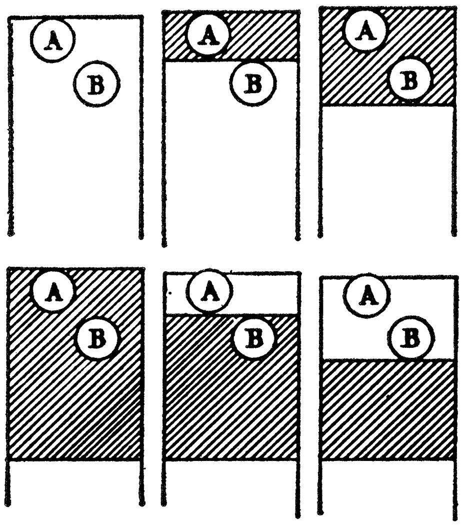

Fig. 2. Migration of two stones through mud, according to Hamberg (*2*). The shading represents the frozen block.

be provided for a downward slope if the stone is near the face of a steep bank, rather than in a slurry contained and supported in an experimental cylinder. Near the surface of a bank, gravity supplies little or no isotropic pressure but rather a flattening compression that is resisted by the semi-rigidity of the soil. Water is held by capillarity. The filling of the nascent cavity is aided by gravity more on the upper side, where it causes local "cave-ins," than on the under side, which may be left partly void. The higher density of the stone also favors a downward slope. For freezing and thawing from the side, then, the nature of the motion may be particularly sensitive to the local conditions.

For freezing from below and thawing from above, as encountered just above permafrost, this mechanism results in no net motion.

It must be emphasized that the mechanism applies to particles of all sizes, to fairly small particles in a mass of still finer particles, to pebbles or stones in a coarse mixture of sand and mud, and so on, for what matters is the size of the object discussed relative to the average size of the particles surrounding it, the speed of migration being roughly proportional to the size of the object.

This explanation cannot account in detail for all of the observations, but it gives a simple physical notion of why freezing and thawing causes particle sorting.

The mechanism favored by Corte, on the other hand, does not seem to be physically plausible. It is one proposed by Taber (*3*), and according to this explanation, in the relative migration a particle is pushed ahead of a constantly replenished layer of water between the particle and the advancing water-ice interface. Corte reports laboratory experiments and suggests that they support this hypothesis. Isolated particles were placed in water on an ice surface advancing upward, and the very small particles were indeed pushed ahead of the freezing surface, but not the larger particles. Though he does not suggest an explanation, this observation is presumably to be understood in terms of differential molecular forces of the sort responsible for surface tension, so that the mechanism propels only those single particles that are light enough to be supported by the forces of surface tension (or even smaller forces, since force differences between water and rock molecules are involved rather than water and air). It thus does not seem plausible that this mechanism could propel particles weighted down by a thick overburden, as would be necessary to cause particle sorting in soil, just as it cannot propel the heavier free particles with no overburden in Corte's experiments. By this point his experiments seem to disprove, rather than to confirm, the alternative mechanism that he favors.

Although this description of the plausible mechanism was written as a comment on Corte's discussion, it would be surprising if so simple a process should not have been understood much earlier. A referee of this paper has kindly pointed out that it originally appeared as a small part of a long paper by A. Hamberg (*2*). Hamberg's presentation differs from this one in being more macroscopic, discussing the relative motion of two stones without discussing either of them in detail (Fig. 2), and in tacitly assuming the appropriate filling and parting motions of the slurry.

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29 January 1965

My report included references to previous papers (*1, 2*) without repeating all the information contained in them. In one of those papers (*1*), fig. 9 shows the mechanism of lifting that Inglis proposes in his fig. 1. Earlier (*2*, p. 1090) I acknowledged that it was Taber who proposed that a layer of water should be present between the particle and the moving ice front.

I did not intend it to be understood from my report that all sorting by freezing is produced by migration, but that sorting by migration has been demonstrated in laboratory experiments with particular kinds of samples. As noted (*2*, p. 499), as well as in the report under discussion, all experiments were carried out under controlled conditions with a particular type of sample of noncohesive sand and gravel grains. What happens with a slurry or other types of soil, and what happens under field conditions, remain to be investigated experimentally.

In a more detailed work (*3*) I discuss processes of sorting other than migration.

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18 March 1965