Dispersion of Debris in Amber Ice Zone

1. Distribution of debris. The bulk of the amber zone extends no more than about 60 cm above the "effective base". Above this level further material of macroscopic size occurs but in such minor quantities and in defined layers as to suggest a different mechanism of emplacement. Particle size distributions (Fig. 21) support this suggestion. Sample 40/380 shows a pronounced sorting indicative of a wind-blown material. Table 3 gives the cumulative curve parameters useful in the identification of a particular horizon of debris. It is concluded that upward dispersion of the original basal debris is marked by the top of the amber zone. Above this, debris bands, which are visible only under favorable lighting conditions, are interpreted as representing horizons which originated in the névé area as wind-blown sand and silt. Mineralogic investigations (Table 2) tend to support these contentions.

2. Discussion of dispersion mechanism. The shear dispersal mechanism proposed by Weertman (1968) uses a diffusion type law and applies to hard spherical uniform particles. Furthermore, the diffusion distance is a function of the particle size.

In the amber zone, particles from clay size to pebbles occur at the same levels and the average debris content in the amber zone does not very significantly with height (Table 4). For these reason we suspect the Weertman mechanism may play only a minor role in the dispersion of debris near the base. In fact, according to Weertman's equations silt-sized particles could only rise less than 1 cm above the bed in 10^6 years, assuming a shear strain rate and volume concentration applicable to the present case.

TABLE 3

Heavy Mineral Suites in Basal Debris
(0.05 to 0.10 mm fraction)

Mineral Sample	T7 Basal (%)	54/0-10 cm (%)	54/30-40 (%)	48/100-150 (%)	40/300 cm (%)
Pyroxenes					
ortho	5.71	10.03	13.81	4.53	28.56
Augite	48.55[a]	43.60[a]	49.65[a]	3.88	0.68
Diopside	4.08	0.69	0.21	--	9.52
Other clino-pyroxenes	9.38	25.95	23.07	76.70[b]	31.28
Amphiboles					
Hornblende	8.16	2.08	2.68	2.59	0.68
Tourmaline-Actinolite	3.67	0.35	--	0.65	6.80
Others	--	0.69	--	0.32	0.68
Magnetite/Ilmenite	8.57	13.15	5.56	5.50	8.84
Hematite/Limonite	--	0.35	1.24	0.65	2.72
Epidote	--	0.35	--	--	6.80
Tourmaline	0.82	1.04	0.82	--	--
Andalusite	0.41	0.35	--	--	--
Kyanite	0.82	0.35	0.41	0.32	--
Zircon	2.04	--	--	--	--
Wollastonite(?)	1.22	--	--	--	--
Staurolite	0.41	--	--	1.94	
Biotite (brown)	3.67	1.04	1.85	0.97	1.36
Muscovite	--	--	--	--	0.68
Chlorite	1.22	--	--	--	--
Others	1.22	--	0.41	1.94	1.36
(Type)	(pyrite)		(green biotite)	(green biotite)	(green biotite)

[a] Pigeonitic augite

[b] Johannesenite(?) 73.46; other clinopyroxenes 3.24.

Remarks: Grains generally unweathered; often rock fragments, not single minerals.

TABLE 4. CUMULATIVE FREQUENCY CURVE PARAMETERS

FOR BASAL AND NEAR-BASAL ICE

(See Fig. 19)

Sample No.	Curve No.	Height above bed (cm)	Sorting Coefficient	Median Size (mm)	Remarks
T7 Basal	G	-5 to -10	11.2	1.8	static ice interstitial to boulders
54/0-10	E	0 to 10	3.5	0.42	lowest basal deforming amber ice
48/20-45	H	20 to 45	4.7	3.5	amber zone
40/ 380	C	380 ± 10	1.4	2.1	narrow band parallel to flow lines
48/ 100-150	D	100-150	1.5	14	"clear" ice

The existence of a basal temperature gradient of about $0.024^{\circ}\text{C m}^{-1}$ produces a tendency for downward particle drift, if the mechanism proposed by Hoekstra and Miller (1965) is valid. No calculations are made as there are no data available for these ice temperatures and thermal gradients. Furthermore, the presence of salts in the ice is likely to complicate the process by accelerating creep within the ice.

Changes in Basal Shear Strain Rate with Time

Changes in the width of the ice tongue are accompanied by changes in the thickness of the ice. Weertman (1964) has established the cross profile of an ice cap that is semi-infinite in one direction. From his equations it is possible to show that $dH/H \approx \frac{1}{2}\, dR/R$ where R is the half width of the glacier and H is the centerline thickness. This may be taken as a crude approximation for the ice tongue, which satisfied some of the assumptions made in the Weertman model. When the glacier margin was in the position of station G (Fig. 2) there was a 150 percent increase in the half width and therefore about a 75 percent increase in the central thickness; toward the edges it would be even greater. For a flow law of the type

$$\dot{\gamma} = \left(\frac{\tau}{B}\right)^{n}, \text{ where } \tau \text{ is simply the shear stress,}$$

it can be shown that $d\dot{\gamma}/\dot{\gamma} = n\, dH/H$, where n may be at least as high as 4 in the basal zone. In the Weertman dispersion theory, the dispersion distance λ is proportional to $\dot{\gamma}^{\frac{1}{2}}$ and from this it may be shown that

$$d\lambda/\lambda = \frac{n}{2} . dH/H.$$

Hence the dispersion distance is quite strongly influenced by changes in the ice thickness and one would have to take the latter into account in order to obtain a quantitative assessment of the dispersion mechanism.

Weertman's equations were developed from the condition of simple shear. In pure shear there is an upward component of velocity perpendicular to the bed. Thus changes in thickness will produce changes in the vertical strain rate.

Dispersion of Amber Ice by Vertical Strain

A simpler model than Weertman's and one which allows less vertical variation in the debris content of the ice as well as a clearly defined upper boundary is shown in Fig. 39, where at z above the bed the vertical strain rate is $\dot{\epsilon}_z$ and the corresponding upware velocity is w_z.

$$\text{Hence } w_z = \frac{dz}{dt} = \dot{\epsilon}_z \cdot z. \qquad (6)$$

If $\dot{\epsilon}_z = \bar{\dot{\epsilon}}_z$, an average small value over the distance interval concerned, then on integrating (6) we obtain

$$\ln z \Big|_{z_o}^{z_1} = \bar{\dot{\epsilon}}_z \, \Delta t,$$

where z_o is the initial thickness of the debris-filled ice layer and z_1 is the final thickness achieved in time Δ t.

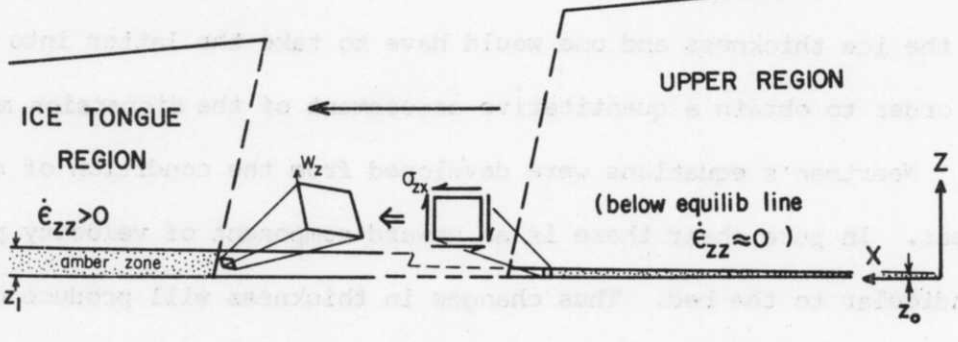

Fig. 39. Dispersion model for basal debris.

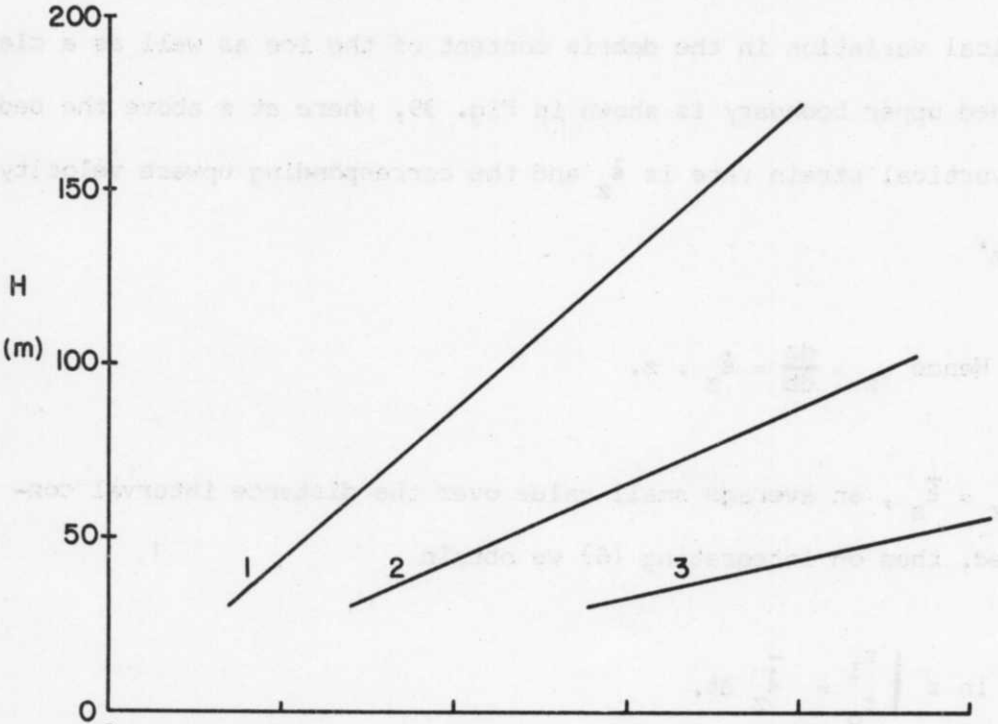

Fig. 40. Dispersion time versus ice thickness, for simple stretch model.