IMPACT CRATER DEPOSIT PRODUCTION ON EARTH: Verne R. Oberbeck, NASA Ames Research Center, Moffett Field, Calif. 94035 and Hans Aggarwal, Eloret Institute, Sunnyvale, Calif. 94087

In this paper we present the first comprehensive analysis of the thickness distribution of expected crater deposits on Earth after three billion years ago. The rate of formation of terrestrial impact craters was constant after three billion years ago. It has been estimated for the craters formed in the past 600 my by Grieve and Dence (1). We averaged their crater production rates listed in their Table III for craters larger than 20 km and obtained a lower bound cratering rate of $2 \times 10^{-15}$ km$^{-2}$ year$^{-1}$. Grieve and Dence (1) adopted a function for the cumulative number of impact craters larger than $D$ (km) produced per km$^2$ per yr that is given by $N = kD^{-2}$. Thus, from this conservative estimate of the production of craters larger than 20 km diameter craters after three billion years ago, we obtain the general expression for craters larger than any given diameter:

$$N/km^2/yr = 7.5 \times 10^{-13} D^{-2.0}$$ (1)

Equation (1) and the surface area of Earth, imply that abundant deposits of craters larger than 20 km diameter should exist in the geologic record. A convenient and conservative measure of how frequently we should expect to encounter such impact deposits in randomly selected stratigraphic sections of the geologic record of Earth is the percentage of the area of the surface of the Earth that would be covered by crater ejecta of thickness greater than or equal to a given thickness over a given span of time.

The thickness, $t$, of ejecta at range, $r$, from an impact crater of radius $R$ formed on Earth is given according to McGetchin et al. (2) and Seebaugh (3) as:

$$t = b (r/R)^{-a}$$ (2)

where $a$ and $b$ are constants. We assume that craters have a spherical segment shape, set crater volume equal to ejecta volume and distribute the ejecta around the craters. We then obtain, from the differential number of craters of size $R$ produced per km$^2$ per year on Earth, an expression for the differential number of ejecta blankets of size $D_e$ per km$^2$ per year having thickness greater or equal to $t$. This is given by:

$$n_e(D_e) = [1.8k\alpha/1+\alpha] f(T) [(\alpha-2) C (3+C^2) / 24 t ]^{1.8/1+\alpha} (1/D_e)^{1+2.8\alpha/1+\alpha}$$ (3)

where $f(T) = 1$ after three billion years ago. Multiplication of this by the area of the ejecta blanket $\pi D_e^2 / 4$, and integration over ejecta blanket diameters = 10D followed by substitution of $\alpha = 3.5$, $k = 7.5 \times 10^{-13}$ and $f(T) = 1$ gives the following area of ejecta blankets per km$^2$ of Earth's surface per yr with thickness greater or equal to $t$ from craters of size $D_1$ to $D_2$ formed after three billion years ago:

$$A(\text{km}^2 \text{ ejecta / yr, km}^2 \text{ Earth}) = 1.8 \times 10^{-12} [ C (3+C^2) / t ]^{0.4} [D_2^{0.6} - D_1^{0.6}]$$ (4)

where $D_2$ and $D_1$ are crater diameters in km and $C$ is the ratio of impact crater depth to crater radius. With $C=.02$, a very conservative value, we simplify equation (4) to:

$$A = 5.85 \times 10^{-13} [ \text{km/t}]^{0.4} [D_2^{0.6} - D_1^{0.6}]$$ (5)

As an independent calculation of percent of the area of the earth covered by ejecta of thickness equal or greater than $t$, we use an expression for the differential number per year per km crater diameter per km$^2$ of Earth's surface for ejecta blankets, $D_e$, with thickness greater or equal to $t$, given by Maher and Stevenson (5) and expressed here in kilometers:

$$n_e(D_e) = 0.24 k f(T) [1 \text{km/t}]^{0.425} [1/\text{km}/D_e]^{2.49}$$ (6)

Multiplication of this by the area of the ejecta blanket and performing the integration and
evaluating the integral gives:

$$A (\text{km}^2 \text{ ejecta} / \text{yr. km}^2 \text{ Earth}) = 4.65 \times 10^{-13} [1 \text{ km} / t]^{0.425} [D_2^{-5.1}, D_1^{-5.1}]$$  (7)

where $D_2$ and $D_1$ are maximum and minimum crater diameters in km. Equations (5) and (7) are very useful for assessing the likelihood of finding ejecta deposits in the strata spanning any given period of geologic history. In order to evaluate them we need a value for the largest expected $D_2$ and $t$.

The largest value of $t$ (1.87 km and 1.38 km) for evaluation of Equation 5 and 7 are the rim ejecta thicknesses for $D_2$, the largest expected crater. We obtain the largest expected crater from equation (1) and the Poisson probability distribution. Using equation (1), it may be shown that about three craters equal or larger than 500 km should have been formed on Earth in two billion years of geologic history. The probability of $n$ impacts

$$P(n) = N P^n / n! e^{-NP}$$  (9)

where $NP=3$ is obtained using this expression. We find that the probability is 0.95 that one or more craters larger than 500 km in diameter should have formed on Earth in two billion years. Therefore, we can be relatively sure that craters at least as large as 500 km formed in the last two billion years. Therefore, $D_2$ in equation 5 and 7 can be taken as 500 km. $D_1$ is taken as 5 km.

Head et al. (5) evaluated the depth to radius ratio of large lunar impact craters and found $C=0.02-0.42$ for the possible range of depth to radius ratio. If we adopt a very conservative value for $C$ of 0.02 we find that rim ejecta thickness is 1.87 km for a 500 km diameter crater. We then use 1.87 km as a conservative estimate of the maximum value of $t$ in equation (5) to calculate the area-thickness distribution for the crater deposits of all thickness greater than $t$ deposited in the geologic record over the last two billion years. If we substitute 500 km for $D_2$, 5 km for the smallest crater $D_1$, and 1.87 km for the thickest ejecta deposits, and solve equation 5 for the area with thickness greater than $t$, we find that about three tenths of the Earth's surface could have been covered by ejecta deposits equal or greater than 10 meters in thickness in 2 billion years. About one tenth of the Earth's surface would have been covered with crater ejecta 200 meters in thickness or more in 2 billion years. This result is very conservative because it assumes craters were very shallow and that the depth radius ratio was near the lower limit of the possible range given by Head et al. (5) and it does not include secondary crater ejecta. Result using equation (7), which we obtained using a different approach, are similar in that they suggest also that significant areas of the Earth's surface should have been covered by crater deposits in the last two billion years.

These results suggested a study of the nature of impact deposits and a search of the rock strata of Earth for impact crater deposits which showed that tillites resemble crater deposits (6). The form of the thickness distributions of tillites described in that paper and the range of thickness of tillites are predicted by our impact model. This combined with the textures of tillites and impact deposits (6) suggests that many of the ancient tillite deposits could be of impact origin.

IMPACTS, FLOOD BASALTS, AND CONTINENTAL BREAKUP; V.R. Oberbeck & J.R. Marshall, MS 239-12, NASA Ames Research Center, Moffett Field CA 94035

Although asteroids and comets impacted throughout Earth's history, very little attention has been given to the possibility that significant quantities of impact ejecta deposits should survive in the rock record, nor to the implications of such deposits if they were to be found. Oberbeck and Aggarwal (1) provide the first analysis of the production of such crater deposits during the last three billion years. The analysis indicates that extensive deposits of impact ejecta should have been produced.

To assess the characteristics of ejecta material, we have reviewed the textures of deposits at the Ries crater in Germany (2,3) which are known to have formed on land, and the textures of the K/T deposit formed in water at Brazos River, Texas (4). Additional deposits in water from both Precambrian time (5) and Eocene time (6) were also assessed. We find that ejecta deposits of large craters formed on land surfaces are typically massive in structure and contain a wide variety of clasts and megaclasts of crater ejecta and preexisting material. Textures result from a ground hugging emplacement of primary crater material and secondary ejecta as described by Oberbeck (7). Ejecta deposits formed in water exhibit very complex and repeated successions of graded bedding, laminated sediments, and dropstones. We have analytically modeled the emplacement of ejecta in water and find that the complex sequence of events relating to oceanic wave dissipation should generate textures such as cyclic graded bedding, laminations, and dropstones, intermixed with massive and chaotic layers.

We have found that tills and tillites (diamictites), which are found throughout the geologic record from the Precambrian to recent times, closely resemble impact deposits formed on land and in the ocean. Gravenor et al (8) described seven different lithologies for tills and tillites which are typically interpreted to be of glacial origin. The first of these is a massive deposit of clasts supported by a fine-grained matrix that sometimes rests on eroded and striated preexisting surfaces and is believed to be the deposits of grounded glaciers. The second type resembles the first except that it contains traces of lineations at the tops of deposits and has been interpreted as forming by melting at the base of active floating ice and was deposited through a slurry at the base of the ice. The third type of tillite is massive with clasts at the bottom which grade upward to rhythmites, mudstones or siltstones and slump structures. These are believed to be redistributed subaquatic glacial deposits. The fourth tillite deposit is laminated, sorted sediments of sand, silt, and clay with dropstones present; the base of the units have graded bedding. These were interpreted as subaquatic slurry flow and suspension flow. The remaining fifth, sixth, and seventh classes of tillites are chaotic melanges of boulders, conglomerate, sand, silt and clay, and mud and silt with clasts as large as boulders. These are interpreted as slump and turbidity deposits of outer shelf material.

We note that all of the textures observed in the seven classes of tillites, including dropstones, are observed in impact ejecta deposits formed on land surfaces or in the ocean. Moreover, the emplacement mechanisms of glacier deposits and ejecta-curtain deposits both erode preexisting terrains, both produce a ground hugging movement of debris, and both produce complex mixite deposits containing foreign and local clasts of rock. Furthermore, the enormous thickness of tillites which can reach kilometers, as well as the individual megaclasts of rock as large as hundreds of meters, are more easily explained by impact than by glaciation. We find that the observed percentage coverage of the Earth's surface by tillites during the last two billion years, the form of the thickness distribution, and the range in thickness of the deposits, show remarkable agreement with the Oberbeck and Aggarwal (1) model predictions for the thickness characteristics of impact ejecta.

There are other reasons to seek a non-glacial origin for the tillite deposits. In particular, it has been difficult to explain the Precambrian tillites by glaciation because of the hot Precambrian climate. Periods of tillite production and inferred glaciation often coincide with periods of major biologic extinctions, but there is no good reason to associate biologic crises with glaciation.
Meyerhoff and Teichert (9) argue that tillites of glacial origin on Gondwanaland could not have formed in the interior of the continent because they believe that a nearby source of open ocean water was necessary to form continental glaciers on this scale. They argue that "until the advocates of continental drift find another non-glacial explanation for the origin of tillite, the reality of continental drift must be questioned". At least one tillite deposit has been redefined as impact ejecta after the discovery of an impact crater at its center (10).

Our suggestion that tillites might be of impact origin is supported by an important new correlation. We have found that there is a remarkable geographic and temporal association of tillites with flood basalts. Tillites and flood basalts occur in the same places on continents, and tillites typically preceded the effusion of the basalts. For example, the Karoo flood basalts in South Africa of Jurassic age are associated geographically with the tillites of Permian age in the same location. Similarly, the 120-130 my old Panana flood basalts in South America are associated with Permian tillites of the same location. There are additional such associations in Siberia, the Lake Superior region and in other places.

It has been suggested that terrestrial flood basalts were erupted as a result of impact cratering (11,12) when large impacts fractured the crust, removed the overburden pressures on magma chambers, and allowed flood basalts to escape. It has also been suggested that impact craters larger than 20 km could have fractured the crust down to the Moho (13). However, White and McKenzie (14) proposed that crustal thinning combined with rifting above mantle plumes initiated flood basalt volcanism, while Richards et al. (15) believe that mantle plume heads alone were sufficient to initiate flood basalt volcanism. It has also been proposed that the onset of continental breakup can sometimes be caused directly by initiation of a new mantle plume (14) but Hill (16) argues that uplift above mantle plumes alone does not generate sufficient stress to breakup a continent.

Our finding of the similarity of tillites to impact ejecta deposits, the agreement of tillite deposit thickness and thickness distribution with predicted ejecta thicknesses, as well as our correlation of the (spatial and temporal) location of tillites with flood basalts, lead us to support the view that it was impact cratering that initiated flood basalt volcanism and the formation of hot spots (12). Because continental breakup is sometimes associated with flood basalt volcanism (14) and because of our new evidence that flood basalts were generated by impacts, we believe that impact fracturing of the crust could have played an important role in facilitating continental breakup. (17). The sequence in tillite formation, flood basalt eruption, crustal rifting and breakup of Gondwanaland are consistent with the hypothesis of the initiation of continental breakup from major impact events.