AMOUNT OF EXTRATERRESTRIAL MATERIAL IN THE K/T BOUNDARY SEDIMENTS.


Introduction. The global mass of extraterrestrial material at the K/T boundary was estimated (1) from amount of Ir with provided that Ir came into the K/T sediments with fallout spread evenly over the Earth. However, the studied K/T sections are clear distinct each other in Ir content (2). It suggests that the surface and stratigraphical Ir distributions should be controlled by processes of lateral transport and sedimentation but not deposition of the fallout from the atmosphere. In the paper we consider constraints on the global Ir mass and the element fractionation at the K/T boundary taking into account the effects of these processes.

Surface distribution of Ir. The lateral transport must lead to redistribution of Ir on the Earth surface. In this case the global Ir mass, M, can be expressed as

\[ M = \int_{x} \int_{y} s(x) ds = \frac{1}{2} x_{2} \times s_{2} = \bar{X} \cdot s \]  (1)

where \( s \) is a square with a surface density of Ir, \( x \), \( z \) is the Earth square, and \( \bar{X} \) is a mean value of \( x \). The problem is how to find \( \bar{X} \) because the population of the measured values of \( x \) is not representative for the Earth surface. Obviously for estimation of \( \bar{X} \) we need to establish a type of the \( x \) distribution, \( s = f(x) \), and to show that the measured data are representative in some part of the distribution. As a first step it can be suggested that the measured data are representative only for areas of sedimentation (70% of the Earth surface), while \( x = 0 \) on the continents. Then using literature data (2-5) and the corrected x values of 580, 540 and 44 (ng/cm²) for the Furmanova 584, 595 and 595 sections, respectively (6), we found \( M = 5 \times 10^{12} \) ng/cm². In general this law of the \( x \) distribution should permit that \( x = 0 \) at \( s = 0 \), and \( x \to \infty \) at \( s \to 0 \). The exponential distribution seems to be most available because it allows \( s \) to be high at \( x = 0 \). The \( X^{2} \) test of the observed \( x \) distribution shows that it can be approximated by the exponential law at \( x > 20-30 \) ng/cm². Then using the features of the exponential distribution one can find that

\[ s_{0} = \frac{h \cdot \exp(-bh)}{x_{0}} \]  (2)

\[ \bar{X}_{x} = \exp(bh) \cdot \frac{x_{0} \cdot \exp(-bh)}{x_{0} \cdot \exp(bh - bh)} = y + 1/h \]  (3)

\[ M = \frac{1}{2} x_{2} \cdot h \cdot \exp(-bh) \]  (4)

where \( s_{0} \) is a quota of the Earth surface with \( x > y \), \( \bar{X}_{x} \) is a mean value at \( x > y \), and \( h \) is a parameter. The \( \bar{X}_{x} \) value can be estimated from the measured data on \( x \). It is 120-60 (26) ng/cm² at \( x > 30 \) ng/cm². Substituting this value, the Eqns. (3) and (4) yield \( M = 4.6 \times 10^{12} \) ng/cm². Then using Eqn. (2) a quota of the Earth surface containing \( > 30 \) ng/cm² of Ir can be computed to be 0.72 with the 26 interval of 0.37-0.82.

Stratigraphical distribution of Ir. The measured values of \( x \) are found by integration of \( x \) through the stratigraphical sequence, hence it is important to find a theoretical expression of the integral for estimation of the global Ir mass. As a first approximation it can be suggested that a rate of Ir sedimentation is a linear function from Ir content in a basin of sedimentation, i.e., deposition of Ir is controlled by first order kinetics. Then assuming that time, \( t \), can be expressed as \( h/v \), the stratigraphical Ir distribution is given by

\[ C = C_{0} \cdot \exp(-h/v) \]  (5)

where \( h \) is distance (thickness) from the \( K/T \) boundary, \( v \) = dh/dt is a rate of sedimentation, \( C_{0} \) is Ir content at the \( K/T \) boundary when \( h = 0 \) or \( t = 0 \), and \( k \) is a parameter similar to a residence time. In fact the observed stratigraphical distribution of Ir (5-8) follows roughly Eqn. (5). The deviations from the law can be resulted from secondary processes, i.e., bioturbation and diffusion, or a change of \( v \) and \( k \) during sedimentation. Integration of \( C \) leads to the statement

\[ x = d \int C(t) dt = d \cdot v \cdot t \cdot C_{0} \]  (6)

where \( d \) is a density of the main problem. Finally taking into account Eqs. (1) and (5) the global Ir mass can be expressed as

\[ M = d \cdot v \cdot x \cdot C_{0} \cdot s_{2} = U \cdot k \cdot C_{0} = d \cdot C_{0} \cdot s_{2} / (1 + C_{0} - \ln C_{0}) \]  (7)

where \( s_{0} = 0.72 \) is a total square of basins of sedimentation, \( U = s_{2} \cdot dh/dt \) is a global rate of sedimentation, and others are global mean values of parameters used in Eqs. (5) and (6). It is important that the global Ir mass can be expressed to be dependent on the parameters of Ir stratigraphy only (\( C_{0} \) and \( h \)) and the thickness (\( h \)) of Ir anomaly should not be usually less than 5 and higher than 30 cm when \( C = 0.1 \) ppb. It leads to \( M = 7 \times 10^{19} \) to \( 10^{21} \) ng of Ir, if \( C_{0} = 15.5 \pm 6.2 \) (26) ppb as a mean value of the maximum Ir contents in the K/T sediments, this \( M \) value is
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compatible with the statistical estimations. Then using the statistical estimation of \( M (4.6 \times 10^{15} \text{ng}) \) and Eqn. (7) one can calculate the \( k \) value to be 1500 y with the 2\( \sigma \) interval of 340-5200 y at the rate of sedimentation, \( U \), equal to the erosion rate of \( 2 \times 10^{16} \text{g} \cdot \text{a}^{-1} \). It suggests that the half amount of Ir should be deposited by usual geological processes for 1000 y (240-3600 y).

Element fractionation. When written for other elements Eqn. (5) shows that element fractionation would take place during sedimentation, if the elements had different values of \( k \). In fact using Eqns. (5) and (7) and assuming that the \( K/T \) bolide has chondritic composition at \( 5 \times 10^{20} \) ng of Ir, a rate of sedimentation is \( 5 \times 10^{-5} \) cm/y, and the \( k \) values are equal to the residence times of the elements in the ocean, one can calculate the element profiles at the \( K/T \) boundary. It is of interest that if \( \gamma \) and \( h \) (thickness of element anomaly at \( C/C_0 = 0.5 \)) tend to be higher in the order \( Fe, Co, Sc, Ti, Cu, Zn, Ni, Cr, V, As, Sb, Au, Re \). Moreover the \( Co \) values of \( Fe, Co, Sc \) and \( Ti (k < 100 \text{ y}) \) are higher than the chondrite contents of the elements, and their \( h \) values are less than 1 cm. In contrast the \( Co \) values of \( As, Sb, Au \) and \( Ke (k > 10^3 \text{ y}) \) are very large and their \( h \) values more than 70 cm. Hence anomalous contents of such elements could not be identified at the \( K/T \) boundary. However so heavy element fractionation is not observed in the \( K/T \) sediments. It suggests that the element \( k \) values were not very different during the \( K/T \) sedimentation. To estimate the real \( K/T \) values of \( k \) one can receive from Eqns. (5) and (7) written for any pairs of elements (for example, for Ir and Ni) that

\[
C_{Ni} = (C_{Ir})^{(l-b)} \cdot (W_{Ni}/W_{Ir}) \cdot (C_{Ir})^b
\]

where \( b = k_{Ir}/k_{Ni} \), \( W_{Ir} \), \( C_{Ir} \), and \( C_{Ni} \) are the Ir and Ni contents reduced for terrestrial background in the \( K/T \) bolide and the \( K/T \) sediments, respectively. Then using the \( K/T \) element concentrations \((1,4,5,10-15)\) normalized to the Al content, it can be shown by regression analysis that the \( k \) values of \( Fe, Pd, Pt, Re, Fe, Ni, Co, Cr, V, Ti, Cu, As \) and Sb are mostly in the range of 1000-3000 y, if \( k_p = 1500 \text{y} \). In contrast the residence time of the elements in the ocean vary 7 orders of magnitude \( (9) \). The difference suggests that the \( K/T \) bolide material was deposited without significant fractionation, and the composition of the \( K/T \) sediments is controlled mainly by simple mixing of the extraterrestrial and crust components. The regression analysis based on equations like (8) allows us to estimate the element concentrations in the \( K/T \) object. when computed at 500 ppb of Ir they are: Fe 22, Ti .82, Ni 0.5 \( (\text{wt%}) \); Cr 2800, Co 750, V 637, Cu 400, As 200, Sb 45, Pt 1.7, Pd 1.2 \( (\text{ppm}) \); Au 412, Os 425, Re 260 \( (\text{ppb}) \). These concentrations are close to those in chondrites except for \( Si, Sb, As \) and \( V \) which could come into the \( K/T \) sediments from terrestrial sources during formation of the \( K/T \) anomaly. However the similar element pattern at other concentrations can be in Fe-Po bodies or a cometary material.

Conclusion. The global amount of Ir estimated by the different methods resides in the range of \( 10^{28} - 10^{26} \) ng, the mean to be about \( 5 \times 10^{25} \) ng. We do not need the fallout scenario to calculate the Ir mass. The observed element concentrations, their surface and stratigraphical distributions at the \( K/T \) boundary can be explained by usual processes of sedimentation and lateral transport. During the processes the element fractionation was not significant. The chemistry of the \( K/T \) sediments is controlled mostly by mixing of the extraterrestrial and crust components. The cosmic material can be considered to be chondritic component, but cometary or Fe-Po components are also possible. The mass of the chondritic \( K/T \) bolide is in the range of \( 2 \times 10^{17} - 2 \times 10^{18} \) g, the mean to be \( 10^{18} \) g.