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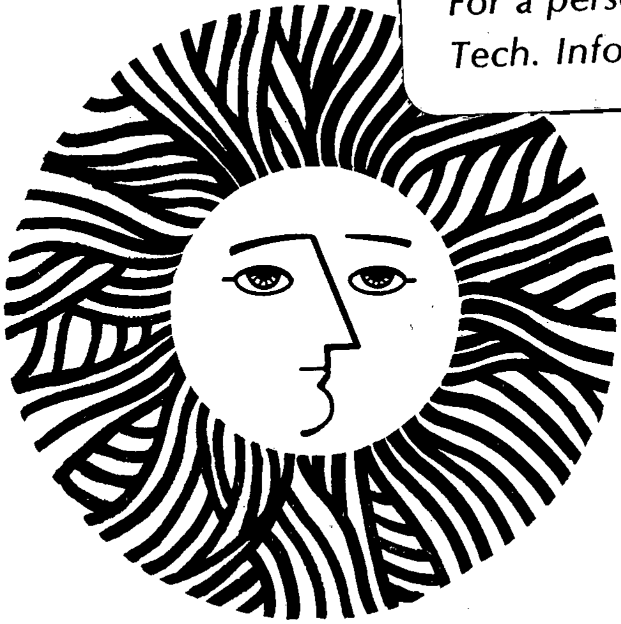

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CURRENT STATUS OF THE IMPACT THEORY FOR THE TERMINAL CRETACEOUS EXTINCTION *

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Abstract

Iridium is depleted in the earth's crust relative to its normal solar system abundance. Several hundred measurements by at least seven laboratories have disclosed an iridium abundance anomaly at the Cretaceous-Tertiary (C-T) boundary in 36 sites worldwide. Discovery of the first iridium anomaly in non-marine sediments, by Charles Orth and his colleagues, shows that the iridium was not extracted from sea water. Sediment starvation and a nearby supernova have also been eliminated as possible sources. Impact of a large extraterrestrial object is now widely accepted as the best explanation of the iridium anomaly. Paleomagnetic reversal stratigraphy of four marine and five non-marine C-T boundary sections is consistent with simultaneous extinction world wide, but does not prove it. Ultra-high-resolution stratigraphic studies at Caravaca, in southern Spain, by Jan Smit, give an unparalled record of the extinction of the planktic foraminifera and the associated geochemical patterns. Au/Ir and Pt/Ir ratios from two C-T boundary clays indicate a type I carbonaceous chondrite composition for the impacting object. Iridium anomalies are known from two other stratigraphic horizons, in each case associated with direct evidence for an extraterrestrial impact: in the Pliocene, with chondritic ablation debris, and in the late Eocene with microtektites. The C-T impact site has not been located. Two interesting candidate sites are the circular sea-floor features west of Portugal and the Deccan Traps of India. There is a 20% probability that impact occurred on sea floor that has subsequently been subducted. Recent computer modelling of impact processes is yielding important information. The killing mechanism has not yet been established, but both temperature changes and darkness due

to atmospheric dust are probable contributors. Darkness would have lasted a few months, rather than our originally suggested few years; this is indicated by (1) calculated rapid dispersal of dust in ballistic trajectories, (2) more rapid settling of heavier, coagulated dust particles, (3) calculated effects of darkness on phytoplankton, and (4) compatibility of the plant record with a few months, but not with a few years of darkness.

Introduction

The siderophile trace element iridium is strongly depleted in the earth's crust relative to its normal solar system abundance. Evidently the earth's original allotment is largely concentrated in the core. Beginning in 1978, anomalous concentrations of iridium were discovered in precise correspondence with the Cretaceous-Tertiary (C-T) boundary in various marine sequences around the world (W. Alvarez and others, 1979a, 1979b, 1979c; L. W. Alvarez and others, 1979, 1980; Smit and Hertogen, 1980). It was possible to show that the anomalous iridium did not result from reduction in sedimentation rate of the other components and was most probably not supplied by a nearby supernova; we attributed it to impact of an extraterrestrial body about 10 km in diameter and suggested that the mass extinction resulted from food-chain collapse when photosynthesis was suppressed by dust carried aloft by the impact (L.W. Alvarez and others, 1979, 1980).

Since then many workers have become involved in the observational, analytical, and theoretical research generated by recognition of the iridium anomaly at the C-T boundary. The present review, although not exhaustive, briefly covers the salient findings and some of the major unresolved questions on this topic as of the end of 1981, with some updating through mid-1982.

Distribution of the anomalous Cretaceous-Tertiary iridium

At least seven laboratories have undertaken systematic iridium analyses of Cretaceous-Tertiary and related sediments. There are, published or in press, reports of 36 occurrences of abnormally high iridium at the boundary, as summarized in Table 1 and Figure 1. It is customary to report the iridium abundance as parts per billion, (10^{-9} g Ir/g whole rock) for each specimen analyzed. If several samples are analyzed from a stratigraphic section, the area under the depth-abundance curve can be integrated and multiplied by an appropriate density factor to obtain a value for the mass of excess accumulated Ir per unit area. These results are reported in units of 10^{-9} g Ir/cm^2 for presently available sections in Figure 2. It was hoped that these integrated "nannogrammage" values would show a global trend increasing toward the impact site. So far, this has not been the case (Fig. 1). Post-depositional lateral sediment transport toward or away from sample sites may have obscured an original global trend. Alternatively, the original distribution may have been irregular, as is the case with the Australasian tektites (Chapman, 1971).

Iridium anomaly in non-marine sediments

The view that the anomalous iridium was due to a major impact has been questioned on the grounds that it could be due either to normal iridium deposition while the deposition rate of other marine sedimentary components was severely reduced (Kent, 1981; Rampino, 1981), or to extraction of iridium from sea water during a brief episode of unusual ocean chemistry (S. Gartner, pers. comm., 1980). Although we presented arguments against these possibilities (L.W. Alvarez and others, 1979, 1981) they have been firmly laid to rest, at least in the case of the C-T iridium anomaly, by the discovery of an iridium concentration at the C-T boundary in non-marine sediments. This extremely important result was obtained by Orth and others (1981, 1982), on sections in the Raton

Basin of northeastern New Mexico. The iridium anomaly falls within a coal bed, in precise correspondence with the extinction of four pollen taxa and a major shift in the ratio of angiosperm pollen to fern spores.

We note with some embarrassment that at one point we thought we had discovered a C-T iridium anomaly in a non-marine section from eastern Montana (L.W. Alvarez and others, 1981). The results, however, were not reproducible and were eventually traced to contamination from the wedding ring of a technician who worked briefly in our laboratory (jewelry platinum contains about 10% iridium). We rectified the error in a review by Kerr (1981), and we stress that credit for discovery of the first non-marine C-T iridium anomaly belongs to Orth and his colleagues. A positive result of this mishap is that all laboratories doing iridium work are now aware of this source of possible contamination and alert for others.

Time Correlation

The impact theory could be controverted, or at least forced into a more complicated form, if diachroneity were found in the terminal Cretaceous extinction from one biological group to another, or geographically within groups. Diachroneity could be shown if the extinction occurred in different paleomagnetic polarity zones in different sections. This would be evident if the extinction were found in normal zones in some places and reversed zones elsewhere. Sedimentary rocks of the same polarity can be attributed to the same or to different polarity zones only if a thick enough section is present to yield a diagnostic "fingerprint" sequence of long and short zones of normal and reversed polarity.

The terminal Cretaceous extinction of planktic foraminifera was shown to occur within reversed polarity zone 29R (= Gubbio G-) in the Bottaccione section at Gubbio, Italy (Lowrie and Alvarez, 1977a, 1977b; Roggenthen and Napoleone, 1977; W. Alvarez and others, 1977), where the first C-T iridium anomaly was subsequently found. Since then the following marine sections containing the C-T iridium anomaly have also been shown to occur in the 29R zone: Caravaca (Smit, 1981a), DSDP Site Leg 73 (Tauxe and others, 1980), DSDP Leg 74 (Chave, 1980). Polarity stratigraphies are not yet available for any other marine sections containing the iridium anomaly. Rotary-cored DSDP sections are commonly too disturbed by drilling to give good paleomagnetic results, but Tauxe et al. (1980) and Chave (1980) have been successful in obtaining polarity stratigraphies on recent hydraulic piston cores.

The record is not yet clear for reversal stratigraphy in non-marine C-T sections. The San Juan Basin in northwest New Mexico was reported to have a dinosaur extinction in a zone younger than zone 29R (Butler and others, 1977; Lindsay, and others, 1978). This conclusion must be considered tentative, as there is a strong possibility that the C-T boundary occurs at a major erosional unconformity (Fassett, 1981), and in addition, the stratigraphic control on the critical fossils needs to be improved. The San Juan Basin results have been extensively debated (Alvarez and Vann, 1979; Fassett, 1979; Lucas and Rigby, 1979) and further work is still in progress. In four non-marine sections in Montana, the dinosaur extinction occurs in a reversed polarity zone (Archibald and others, 1982), but since only short sections can be studied, it is not clear whether this is the 29R zone or another reversed zone.

The ambiguity of present paleomagnetic data has led some observers to conclude that we will never know if the extinctions were synchronous world wide and from group to group. If the impact hypothesis is correct, however, the iridium anomaly itself potentially offers a world-wide time marker of high precision. So far it appears to be at the same level as the extinctions in all marine sections. The discovery by Orth et al. (1981, 1982) of an iridium anomaly precisely at the palynological C-T boundary in a non-marine section suggests that it will eventually be possible to test the synchroneity of extinctions world wide and for most or all biologic groups and depositional settings.

As discussed in the next section, it is inherently difficult, or impossible, using stratigraphic evidence alone, to establish the time interval in years represented by the iridium layer, or the chronological precision of correlations based on the iridium layer. For this reason, it may be more useful to turn the argument around. In this veiw, if one accepts the evidence from geochemical data that the iridium anomaly resulted from an impact, then it follows that the iridium layer represents an interval on the order of one year. Thus, where sections with excellent stratigraphic records are preserved, the anomaly can be used to make correlations approaching this level of precision as a limit. Although this inference is deductive, it is both strongly supported and potentially very useful.

Ultra-high-resolution stratigraphy

The original iridium-anomaly sites in Italy, Denmark, and New Zealand have thin, decalcified layers at the C-T boundary, where low sedimentation rates and the absence of fossils obscure the stratigraphic record over the most critical few hundred to few thousand years. This crucial defect has been remedied by the excellent work of Smit (1977, 1979, 1981a, 1981b) and his colleagues (Smit and Hertogen, 1980; Smit and Klaver, 1981; Smit and ten Kate, 1981) on the Barranca del Gredero section at Caravaca, in southern Spain. The Caravaca section has a continuous record of the evolution of planktic foraminifera across the C-T extinction event, allowing the foraminiferal lineages to be traced from Cretaceous ancestors through rapidly evolving transitional forms to Tertiary descendants.

The 0.44 m.y. reversed polarity zone in which the C-T boundary occurs is 16.8 m thick (Smith, 1981a, p. 113B), so that on the average, 1 mm represents 26 years. Smit (1981b) therefore evaluates the one mm of sediment that contains the iridium anomaly and marks the foramineriferal extinction, as representing less than 50 years. As discussed by Thierstein (1982), there are difficulties in attempting chronological resolution at this level on the basis of sedimentation rates averaged over long intervals. However, as described in the previous section, one may deductively infer that the iridium layer represents a time as short as one year. The iridium layer also contains abundant sanidine spherules, whose significance is not yet understood (Smit and Klaver, 1981), as well as various geochemical anomalies. The recently recognized C-T boundary section at El Kef, in Tunisia (Perch-Nielsen and others, 1981; Smit, 1981b), may perhaps give even more detailed information than Caravaca, when studies currently underway have been completed.

The view has been expressed that we will never know what happened at the C-T boundary, because a marine regression at about that time destroyed the stratigraphic record, so that the boundary is always represented by a hiatus (e.g., McLean, 1980). This view is incorrect: regressions at about the time of the C-T extinctions did not affect deeper marine sequences. Sections with exquisitely complete stratigraphic records have been discovered, and almost surely more of them wait to be found. For this kind of work, sections with a C-T hiatus are simply irrelevant.

Fingerprinting the impacting object

Iridium is not the only rare siderophile element that is depleted in the earth's crust; this is true also of Ru, Rh, Pd, Re, Os, Pt, and Au. Ratios amongst these elements are diagnostic of various rock types, both terrestrial and extraterrestrial, which might have been the source of the C-T iridium anomaly. Figure 3 gives analytical results which show that the Au/Ir and Pt/Ir ratios of the C-T boundary layer at two sites are different from virtually all potential terrestrial sources, but indistinguishable from C1 chondritic meteorites, although distinguishing C1 from C2 and H chrondrites is probably beyond the capability of this technique (Asaro, in Russell and Rice, 1982, p. 8). A similar result was reported by Ganapathy (1980). This holds the promise that a number of meteorite impacts may have left deposits with very distinctive geochemical signatures.

Other iridium anomalies

Iridium anomalies have been reported at two stratigraphic levels, in addition to the C-T boundary. Kyte and others (1981) found concentrations of Au and Ir comparable to C-T boundary concentrations in 2.3 m.y. Pliocene sediments near Antarctica. The authors concluded that this geochemical anomaly was due to the nearby fall of a meteoroid much smaller than the C-T object, because chondritic ablation debris is found at the same level, but there is no dramatic extinction event associated with it.

In the abstracts for the Snowbird meeting (Asaro and others, 1981) we reported a high level of iridium in DSDP site 149 in the Caribbean, in correspondence with the North American microtektite level. In an unannounced talk at the same meeting, R. Ganapathy confirmed this by reporting an Ir anomaly at this tektite level in Conrad piston core RC9-58, also from the Caribbean. The North American microtektites provide very strong evidence for a major impact event near the end of the Eocene (Glass and Zwart, 1979; Glass and Crosbie, 1981), although this interpretation is contested by O'Keefe (1980). Recognition of the new iridium anomaly thus provides further evidence for an association between impact events and high levels of iridium. Glass and Crosbie (1981) consider the North American event (34.2 ± 0.6 m.y.) to be about 2 m.y. older than the Eocene-Oligocene boundary as defined in the Initial Reports of the Deep-Sea Drilling Project, but the event coincides with the disappearance of four species of radiolarians (Maurasse and Glass, 1976). The timing of the microtektite event relative to the terminal Eocene mammalian extinctions ("la Grande Coupure": Stehlin, 1909;

Brunet, 1977) is not yet clear.

So far the C-T boundary is the only mass extinction known to be associated with an iridium anomaly.

Number of iridium analyses available

It is relevant to ask how many continuous sections, removed from prominent extinction levels, have been studied with the same general sample density accorded to the C-T sections, whether any such sections show iridium anomalies, and what fraction of clay samples taken at random show iridium levels comparable to the C-T boundary clay. For economic reasons, no one has subjected a randomly chosen, high-sedimentation-rate section to the intensity of analysis available for sections across the better-studied C-T boundaries. Kyte (1981) and Kyte and Wasson (1982) are systematically measuring iridium in a large-diameter piston core of abyssal red clay from the north-central Pacific. This core covers the entire Tertiary, and after measuring roughly 25% of the core, the only definite iridium anomaly they have found is at the C-T boundary, although there is a hint of a possible peak in the Eocene.

Between 1970 and 1980, several thousand pottery samples from archaeological excavations were analyzed at Lawrence Berkeley Laboratory using neutron activation analysis (Table 2). Of this large sample, only 22 pottery sherds (about 0.3%) showed iridium levels as high as those in the Stevns Klint C-T boundary clay (excluding an additional 36 sherds with high iridium which can be attributed to glaze or to contamination). These results indicate that clays with anomalously high iridium are indeed rare.

Search for the impact site

As shown by Figure 1, integrated nannogrammage values do not show a global trend that would indicate the general location of the impact site. Figure 4 is a reconstruction of the positions of the plates 65 m.y. ago. The locations of continents and oceans are not radically different from those of today, and the reconstructed map also fails to show a global trend. This map, however, dramatically shows the effect of subduction since the end of the Cretaceous. About 20% of what was then the surface of the earth has been destroyed, and if the impact occurred on crust that has suffered this fate, the crater will never be found.

There are a number of candidates for the impact site, none of which we find very compelling at present. Hsu and others (1981) note that the impact-crater list of Masaytis (1980) contains two fairly large features in the USSR of approximately the right age: Kara (diameter = 60 km) and Kamensk (25 km). Their locations are shown in Figure 4, but both are much smaller than the expected 150-200 km crater (L.W. Alvarez et al., 1980).

The Tagus Abyssal Plain, off Portugal, is surrounded by a nearly circular rim 300 km in diameter. Associated with it are the circular Tore seamount ring, 85 km in diameter, and the two intermediate sized, distorted topographic rings that bound the Horseshoe Abyssal Plain (Laughton and others, 1975). Arnold W. Mantyla suggested the Tagus-Tore complex to us in 1980 as a possible impact site, and it was mentioned also by O. Eckhoff at the Snowbird meeting. Favoring an impact origin are the roughly circular outlines, the recovery of strongly brecciated oceanic crustal rocks from Gorringe Bank on the southeast flank of the Tagus feature (Honnorez and Fox, 1973; Gavasci and others, 1973) and the fact that the complex occurs on crust old enough to have been in existence at the end of the Cretaceous (alternately, it might have been the impact site for the North American tektite event in the late Eocene). On the other hand Smit (1981a, p. 1) has noted that turbidites have not been found in any of the C-T boundary sections in or around the Atlantic, which would be very unlikely if the Tagus-Tore complex were the impact site. Also on the negative side is the fact that the "J" magnetic anomaly, which is probably equivalent to anomalies M-0 and M-1, has been traced at least to the edge of the Tore seamount ring (Rabinowitz and others, 1979; Groupe Galice, 1979); if the anomaly actually passes through the ring, it cannot be an impact crater. Furthermore, oceanographers who have studied these ring-shaped features in detail incline toward a tectonic origin (Laughton and others, 1975; Auzende and others, 1981). However, J.M. Auzende (pers. comm., 1982) considers an impact origin possible for Tore Seamount, and will carry out surveys to test this possibility in the summer of 1982.

It has been suggested by Seyfert and Sirkin (1979) that large impacts on thin oceanic crust might start a mantle rise that would initiate a persistent mantle plume (Morgan, 1971, 1973). Whipple (1980) suggested that the C-T boundary impact occurred close to the Mid-Atlantic Ridge, and the resulting volcanic outpouring produced the basaltic plateau of Iceland. This is contradicted by the fact that there was no ocean between Greenland and northwest Europe at the time

(Talwani and Eldholm, 1977). Separation began at about 65 m.y. B.P., and it is conceivable that it was initiated by an impact in this area. Cisowski (1982) has suggested that the volcanic centers of the British Tertiary Igneous Province mark the site of the C-T impact, and attributes widespread reversed magnetic polarities to shock remagnetization. In this view, K/Ar ages younger than the 65 m.y. B.P. cut off would be due to argon loss. Somewhat older associated volcanic rocks, however, occur at Rockall and in Greenland (Bell, 1976), suggesting that the initial stages of rifting began well before the end of the Cretaceous.

Smith and Smoluchowski (1981) have suggested that the Hawaiian plume could have been triggered by the Cretaceous-Tertiary event or by an earlier impact. An earlier impact cannot be ruled out, but the Hawaiian plume evidently began its activity before the end of the Cretaceous. Deep Sea Drilling Site 192, on Meiji Seamount, the oldest feature in the Hawaii-Emperor chain, found Maastrichtian sediments resting on seamount volcanics (Creager, Scholl and others, 1973), and still older hot-spot volcanoes may have been subducted in the Aleutian-Kurile Trench.

The Deccan Traps of India are an interesting candidate for a volcanic province that might have been triggered by a C-T impact. The best available dates on the Deccan volcanics (59.0-64.1 m.y.B.P.: Wellman and McElhinny, 1970) have tight error bars and are very close to the age of the extinction. McLean (1981) has argued that Deccan Traps volcanism was the source of the C-T boundary iridium. This is clearly wrong, for two reasons. First, the Au/Ir and Pt/Ir ratios in the C-T anomaly are of extraterrestrial, not volcanic character. Second, the Deccan lava flows were erupted during at least two, and probably four magnetic polarity zones (Wensink, 1973), at a time when individual polarity zones lasted about 0.5-1.0 m.y. (Lowrie and Alvarez, 1981). Thus, the Deccan Traps represent probably more than 1 m.y., far more than the time available for deposition of the iridium. Thus, although the Deccan Traps are almost certainly not the source of the anomalous iridium, the impact could have triggered the Deccan volcanism.

Dynamics of crater formation

An important new development has been the recent work on computer-modeling of major terrestrial impacts, both on land and in the ocean, that was reported by several authors at the Snowbird meeting. Since virtually all work on this topic is published either in the Snowbird abstracts or in the present volume, we will not review it here.

The killing mechanism

Three ways have been suggested in which a major impact could lead to a mass extinction: (1) Dust sent aloft by the impact could block off sunlight, suppressing photosynthesis and destroying food chains (L.W. Alvarez and others, 1979, 1980). (2) The extinctions could be due to thermal stresses, either a warming as water vapor resulting from an oceanic impact produced an enhanced greenhouse effect (Emiliani, 1980; Emiliani and others, 1981) or a cooling as large amounts of atmospheric dust raised the earth's albedo (Toon and others, 1981a). Cooling and warming could occur in sequence, after an oceanic impact, if dust particles coagulated and settled out before water vapor was reduced to a normal level. (3) Poisoning by noxious chemicals has been suggested by Hsu (1980) and Hsu and others (1981).

Theoretical studies in progress should clarify the temperature effect to be expected after impacts of various sizes on land and in the sea, and oxygen isotope studies of the best stratigraphic sections may eventually provide an actual temperature record.

In the dust scenario we suggested that darkness would last a few years (L.W. Alvarez and others, 1979, 1980). This was based on a report of the Royal Society of London (1888) which came to that conclusion after a study of the duration of colored sunsets after the Krakatoa explosion of 1883, and which was the only relevant information we had available at the time. Hickey (1981) strongly objected to the dust scenario. A few years of darkness should have produced drastic extinctions among plants of the tropics, which do not have the capability of remaining dormant for that length of time, and Hickey did not find these extinctions. Against this background, one of the more interesting outcomes of the Snowbird conference concerned the spreading and duration of atmospheric dust. Jones and others (1981) and Jones and Kodis (1982) concluded, on the basis of calculations with sophisticated hydrodynamic computer codes at Los Alamos, that a major impact on the earth would in fact emplace dust in the atmosphere world wide within a few hours. Toon and others, (1981a, b) showed that because of coagulation and consequently more rapid settling of dust particles, three to six months is a better estimate of the duration of darkness than a few years. They also found that such a dust cloud could produce almost total darkness for 50 days. Milne and McKay (1981) calculated that a few months of darkness would produce approximately the degree of extinction among oceanic phytoplankton that is observed in the oceanic record, whereas more than a year of darkness would have caused total extinction, which did not occur. Finally, Leo Hickey (pers. comm., 1981) concluded that a few months of darkness could not be rejected on the basis of survival of the tropical plants. This concordance of results supports the suggestion that darkness was probably at least a contributing factor in the Cretaceous-Tertiary mass extinctions.

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Figure Captions

Figure 1. Worldwide occurrences of the iridium anomaly at the Cretaceous-Tertiary boundary. Values give best estimate of the integrated amount of anomalous iridium in units of 10^{-9} g/cm^2. Sources of data are given in Table 1. Open circles are sites for which analyses are in progress.

Figure 2. Typical iridium profiles across the Cretaceous-Tertiary boundary. A. Italian sections (Alvarez and others, 1980). B. DSDP Hole 465 A (new data obtained at Lawrence Berkeley Laboratory).

Figure 3. Pt/Ir and Au/Ir ratios in two Cretaceous-Tertiary boundary clays compared with the ratios in type I carbonaceous chrondrites and with terrestrial rocks. C-T clay values measured at Berkeley; other data from the literature.

Figure 4. Position of the continents at 65 m.y.B.P., based on a reconstruction especially prepared by A.G. Smith. Integrated iridium values (small filled circles) are from Figure 1 and Table 1. Shaded ~~Ruled~~ area is oceanic crust subsequently subducted. Craters (large hachured circles, with diameters in parentheses) and volcanic areas (smoking triangles) which are candidates for the impact site are discussed in the text.

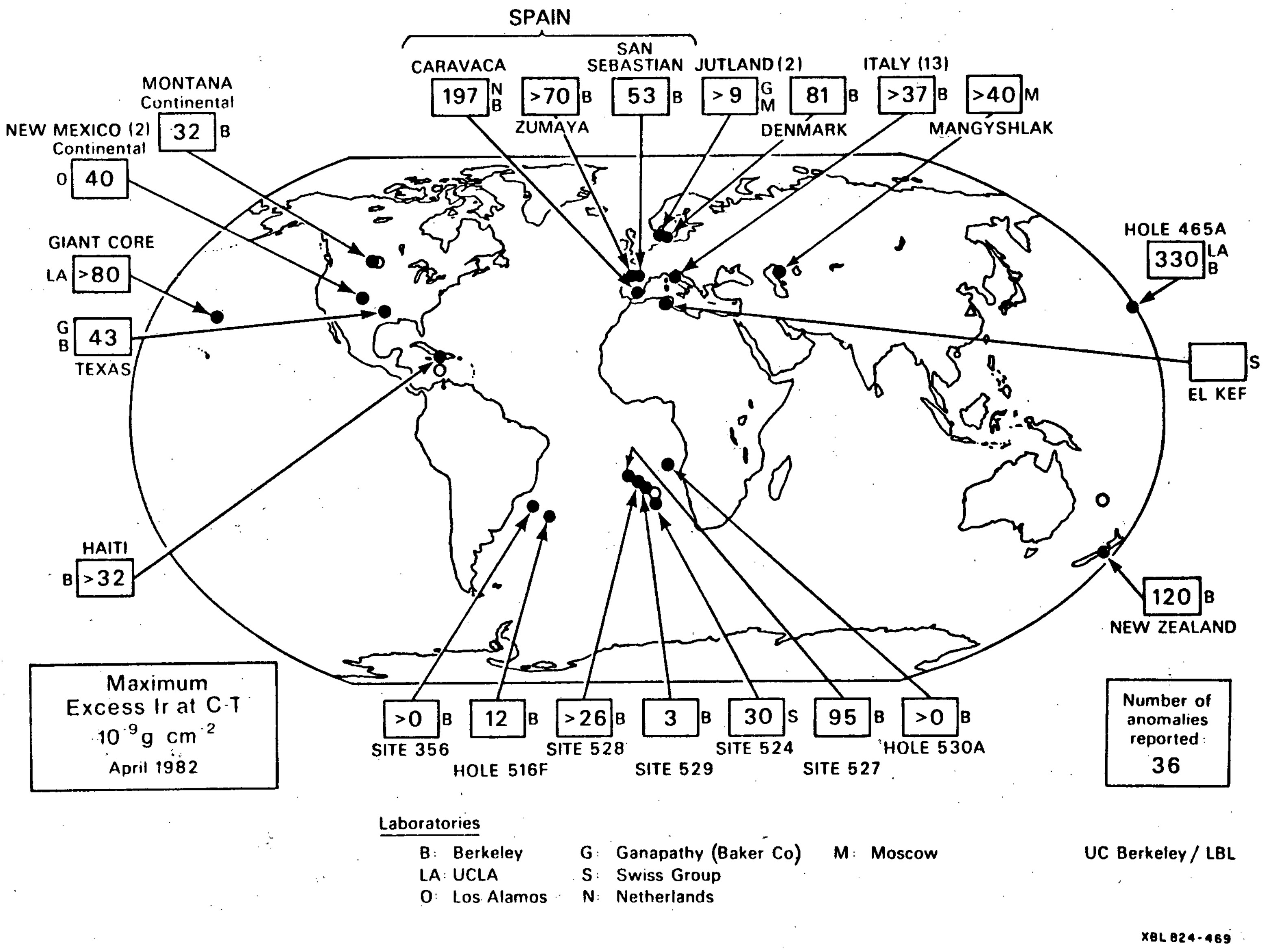
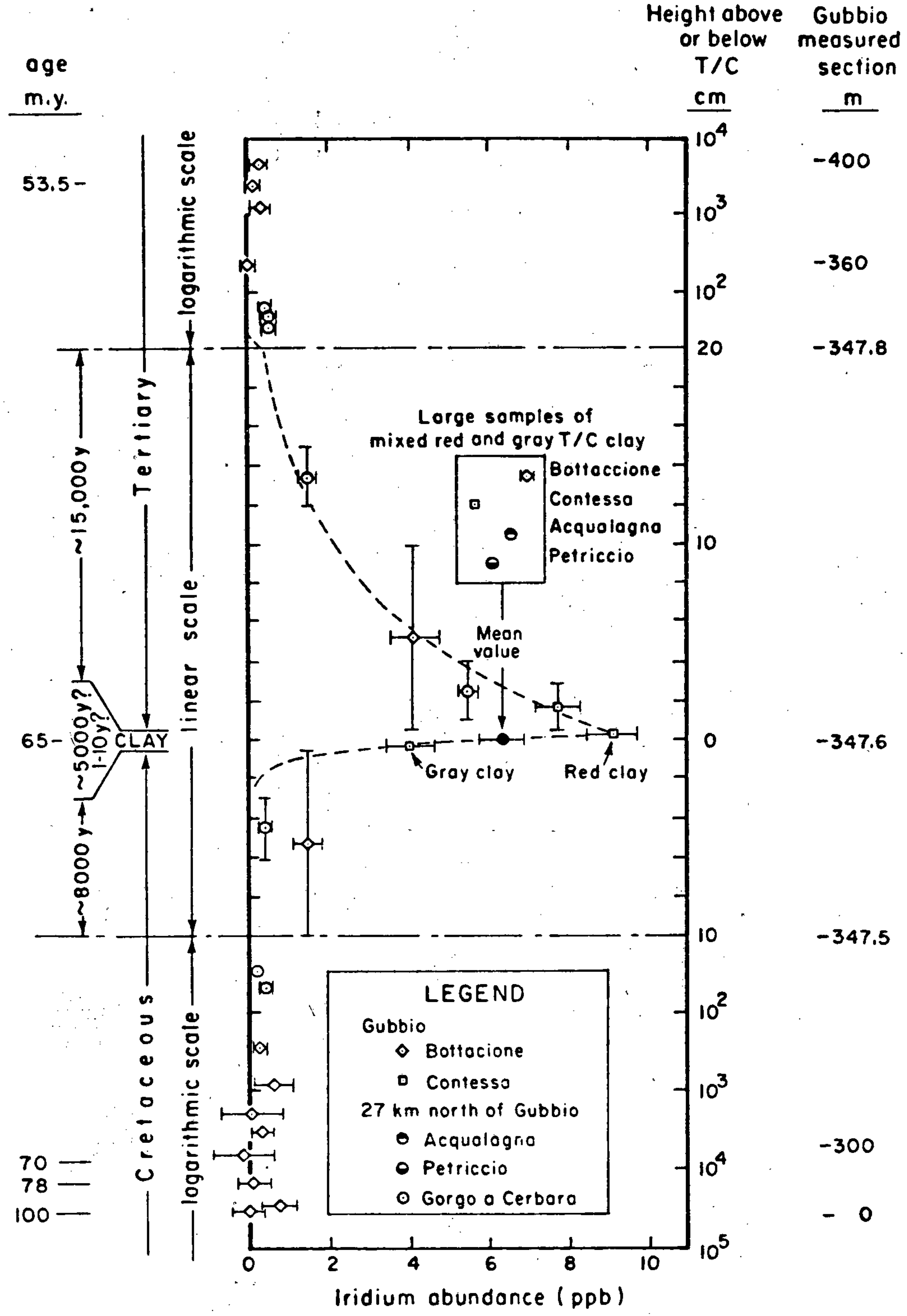

SPAIN
CARAVACA
197 N B
>70 B
ZUMAYA
SAN SEBASTIAN
53 B
JUTLAND (2)
>9 G M
81 B
DENMARK
ITALY (13)
>37 B
>40 M
MANGYSHLAK
MONTANA Continental
32 B
NEW MEXICO (2) Continental
O 40
GIANT CORE
LA >80
G B 43
TEXAS
HAITI
B >32
HOLE 465A
330 LA B
S
EL KEF
120 B
NEW ZEALAND
>0 B
SITE 356
12 B
HOLE 516F
>26 B
SITE 528
3 B
SITE 529
30 S
SITE 524
95 B
SITE 527
>0 B
HOLE 530A
Maximum Excess Ir at C-T
10^{-9} g cm^{-2}
April 1982
Number of anomalies reported: 36
Laboratories
B: Berkeley
LA: UCLA
O: Los Alamos
G: Ganapathy (Baker Co)
S: Swiss Group
N: Netherlands
M: Moscow
UC Berkeley / LBL
XBL 824-469

Figure 1



XBL 7911-13250

Figure 2a

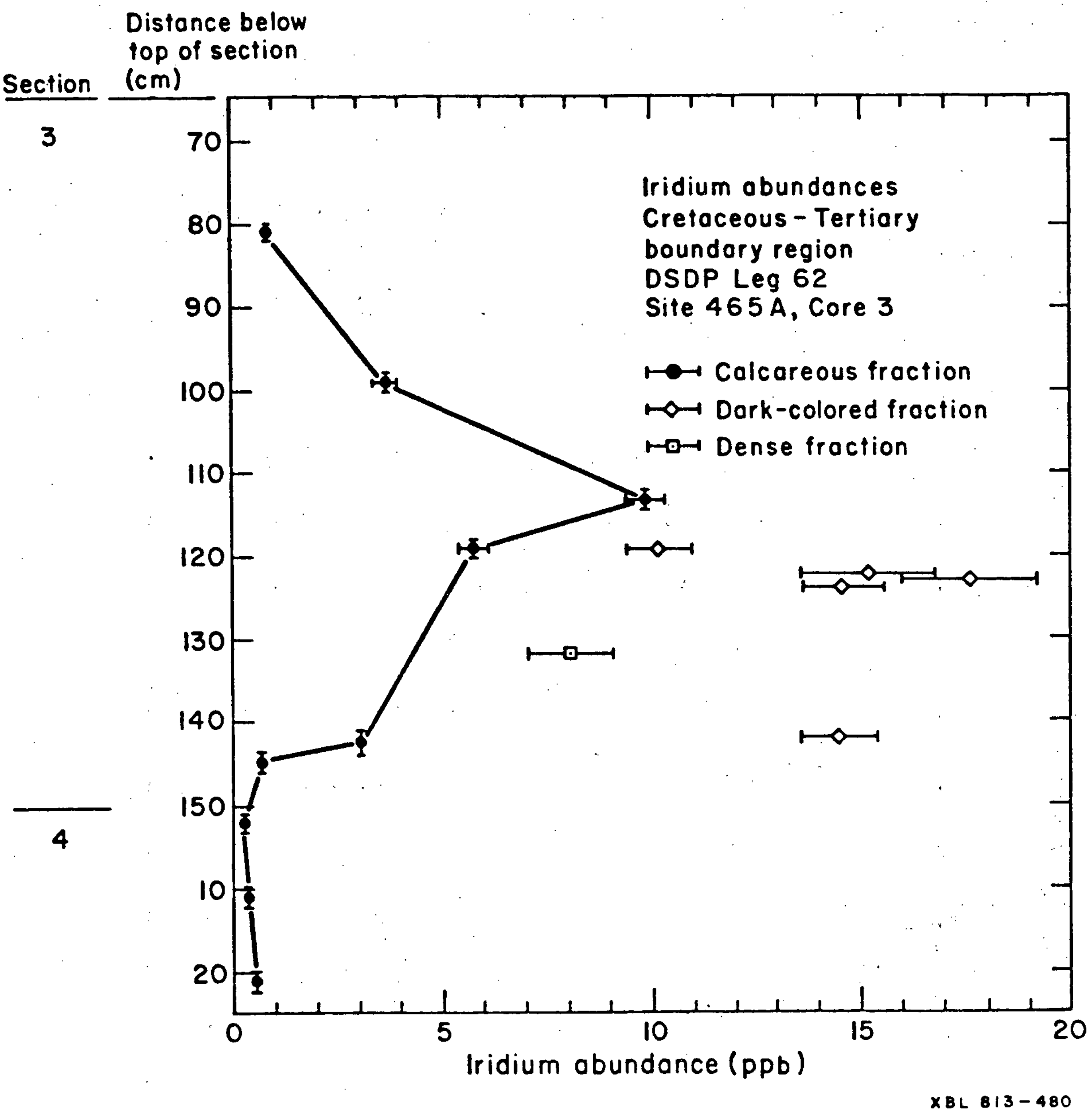

Section
Distance below top of section (cm)
3
4
70
80
90
100
110
120
130
140
150
10
20
0
5
10
15
20
Iridium abundance (ppb)
Iridium abundances
Cretaceous - Tertiary boundary region
DSDP Leg 62
Site 465A, Core 3
Calcareous fraction
Dark-colored fraction
Dense fraction
XBL 813-480

Figure 2b

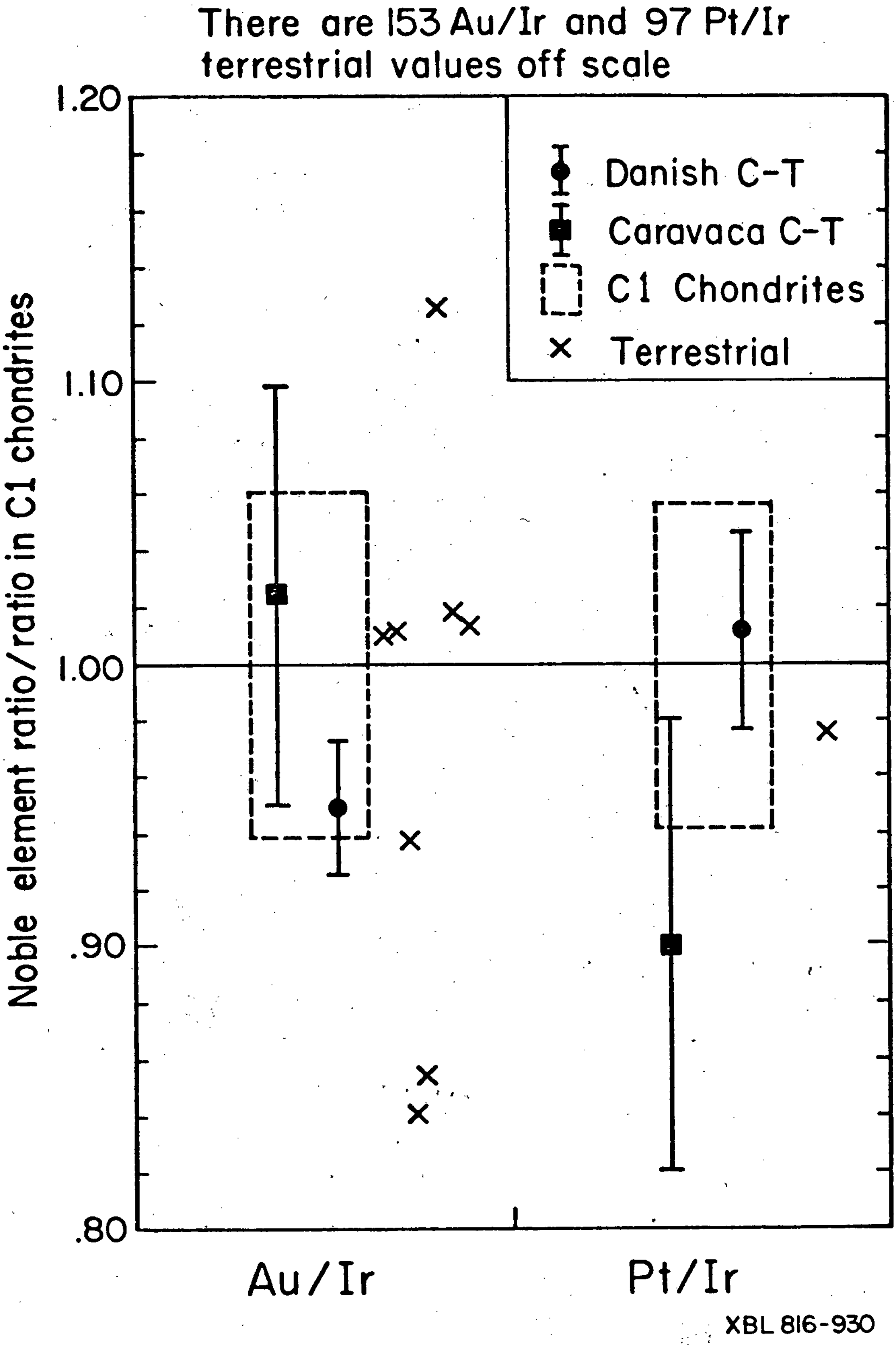

There are 153 Au/Ir and 97 Pt/Ir terrestrial values off scale
Noble element ratio/ratio in C1 chondrites
1.20
1.10
1.00
.90
.80
Danish C-T
Caravaca C-T
C1 Chondrites
Terrestrial
Au/Ir
Pt/Ir
XBL 816-930

Figure 3

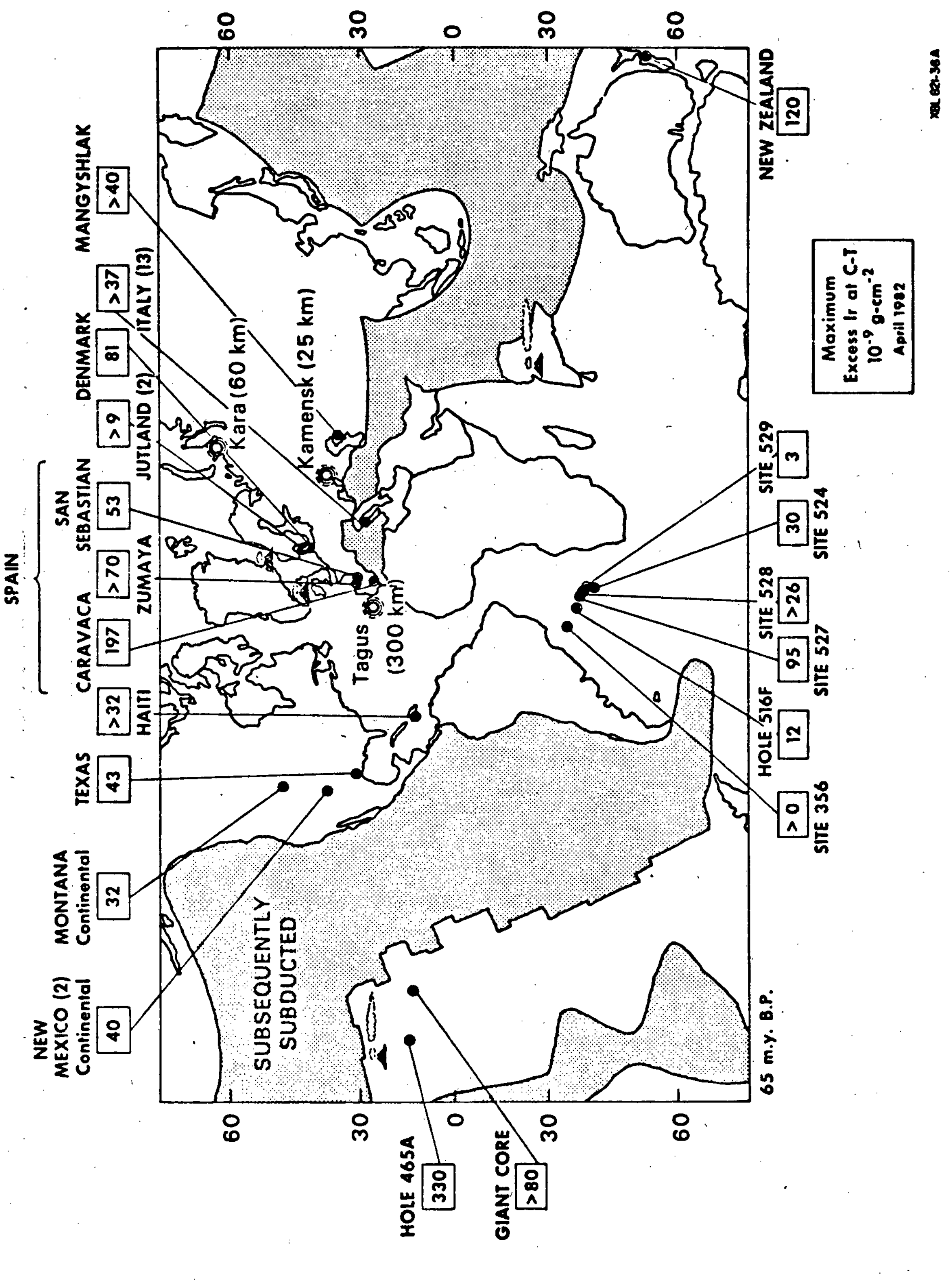

SPAIN
NEW MEXICO (2) Continental
40
MONTANA Continental
32
TEXAS
43
HAITI
>32
CARAVACA
197
ZUMAYA
>70
SAN SEBASTIAN
53
JUTLAND (2)
>9
DENMARK
81
ITALY (13)
>37
MANGYSHLAK
>40
Kara (60 km)
Kamensk (25 km)
Tagus (300 km)
SUBSEQUENTLY SUBDUCTED
60
30
0
30
60
HOLE 465A
330
GIANT CORE
>80
65 m.y. B.P.
SITE 356
>0
HOLE 516F
12
SITE 527
95
SITE 528
>26
SITE 524
30
SITE 529
3
NEW ZEALAND
120
Maximum
Excess Ir at C-T
10^{-9} g-cm^{-2}
April 1982
XBL 821-38A

Figure 4

TABLE 1. CRETACEOUS-TERTIARY BOUNDARY IRIDIUM SITES

Site	Location		Environment of deposition	Peak Ir abundance ppb	Peak Ir abundance ref	Maximum Integrated amount of iridium 10^{-9}g/cm^2	ref
Italy							
Contessa	43°22.6'N	12°33.7'E	Marine	5.0	1,2	>37	1
Bottaccione	43°21.9'N	12°35.0'E	Marine	3.9	1,2		1
Acqualagna	43°36.7'N	12°40.8'E	Marine	4.4	1,2		1
Petriccio	43°36.7'N	12°38.7'E	Marine	8.4	1,2		1
Gorgo a Cerbara	43°36.1'N	12°33.6'E	Marine	8.7	1,2		1
Pontedazzo	43°29.4'N	12°37.3'E	Marine	3.1			3
Frontale	43°21.0'N	13°05.6'E	Marine	4.5			3
Fornace	43°33.2'N	13°35.3'E	Marine	10.3			3
Cingoli	43°21'N	13°12'E	Marine	7.1			3
Colcanino	42°27.6'N	12°49.4'E	Marine	6.3			3
Ceselli	42°40.4'N	12°49.3'E	Marine	2.7			3
Maesta Confibio	43°27.2'N	12°45.0'E	Marine	6.0			3
Furlo Via Flaminia	43°38.3'N	12°42.6'E	Marine	1.2			3
Denmark							
Stevns Klint	55°16.7'N	12°26.5'E	Marine	87	4	81	1,5
Assens, Jutland	56°40'N	10°04'E	Marine	3.8	6	>9	7
Nye Kløv, Jutland	57°00'N	08°50'E	Marine	1.9	8	> 9	7
Spain							
Caravaca	38°03'N	1°54'W	Marine	44	4	197	2
Zumaya	43°18'N	2°16'W	Marine	4.0	9	>70	9
San Sebastian	43°19'N	2°00'W	Marine	6.8	9	53	9
New Zealand							
Woodside Creek	41°57'S	174°03'E	Marine	28	1,10	120	1,10
Haiti							
Béloc	18°24'N	72°32'W	Marine	2.3	11	>32	11
United States							
York Canyon, New Mexico	36°53'N	104°56'W	Continental	5.5	12	40	13
Raton, New Mexico	36°54'N	104°27'W	Continental	0.8	13	40	13
Brazos River, Texas	31°06'N	96°50'W	Marine	2.1	11	43	7
Russia							
Mangyshlak	43°39'N	51°12'E	Marine	6.5	8	>40	7
South Atlantic							
DSDP Leg 39, Site 356	28°17.22'S	41°05.28'W	Marine	0.16	2	>0.4	2
DSDP Leg 72, Site 516F	30°16.59'S	35°17.11'W	Marine	1.0	14	12	14
DSDP Leg 73, Site 524	29°29.06'S	3°30.74'E	Marine	3.6	15,16	30	15,16
DSDP Leg 74, Site 528	28°31.49'S	2°19.44'E	Marine	1.0	2	> 28	2
DSDP Leg 74, Site 529	28°55.83'S	2°46.08'E	Marine	0.8	2	3	2
North Pacific							
DSDP Leg 62, Site 465A	33°49.23'N	178°55.14'E	Marine	15	5,17	330	-
Giant piston core GPC-3	30°19.9'N	157°49.4'W	Marine	14	18	>80	18,19

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2) Berkeley Group, unpublished data.
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4) Smit, 1981a.
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8) Nazarov and others, 1982.
9) Michael A. Authur with Berkeley Group, unpublished data.
10) Dale A. Russell with Berkeley Group, unpublished data.
11) Florentin Maurrasse with Berkeley Group, unpublished data.
12) Orth and others, 1981.
13) Orth and others, 1982.
14) David A. Johnson with Berkeley Group, unpublished data.
15) Personal communication from U. Krähenbühl to F. Asaro, 1981.
16) Hsü and others, 1982.
17) Michel and others, 1981.
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19) Personal communication from F.T. Kyte to F. Asaro, 1982.

TABLE 2. IRIDIUM MEASUREMENTS MADE AT LAWRENCE BERKELEY LABORATORY

I. Low-sensitivity* measurements on clays and other geochemical materials, mostly in the form of ancient pottery sherds, 1970-1980. Total sherds analyzed:	6824		
A. Of these, sherds with Ir >31.5 ppb:		58	
The sherds with Ir >31.5 ppb include:			
1. Sherds contaminated during collection:			25
2. Glazed sherds with iridium probably in the glaze:			11
3. Sherds with unexplained high iridium levels:			22
II. High-sensitivity ($1\sigma \sim .3$ ppb) instrumental whole-rock measurements made on geochemical materials, June 1980-December 1981. Total samples analyzed:	288		
Of these,			
A. Samples with Ir values $> 2\sigma$:		81	
B. Samples with no detectable Ir (values $< 2\sigma$):		207	

---

* These measurements would have detected the Stevns Klint iridium anomaly (31.5 ppb: best current value for Berkeley standard sample of Stevns Klint boundary clay), but not the Italian iridium anomaly (3.6-5.0 ppb).

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