THE CRETACEOUS-TERTIARY BOUNDARY IN THE CONTEXT OF IMPACT GEOLOGY AND SEDIMENTARY RECORD - AN ANALYTICAL REVIEW OF 10 YEARS OF RESEARCHES IN BRAZIL

PAULO PEREIRA MARTINS JR.1, GILBERTO ATHAYDE ALBERTÃO2 AND RENATO HADDAD3

ABSTRACT The question of the Cretaceous-Tertiary (K-T) boundary is here considered in a more wide sense, considering its importance for Impact Geology. The first two sub-principles of uniformitarianism can be seen as similar to the actualist principle and can be both merged with catastrophism as a renewed view of geosciences [as two principles in dialectical opposition for working with regime x rupture processes in Earth Sciences]. Examples from Brazilian basins, especially Pernambuco-Paraíba (PE-PB) basin, are considered with their face value for the study of the K-T boundary. Most of their characteristics also give support to Impact Geology Theory. It is also considered the importance of the initial works on the Brazilian K-T sedimentary boundaries (in a Impact Geology context), which begun 10 years ago giving support to present time trends of researches. At present with the actual state of knowledge in Geosciences it is no longer possible to consider the Earth System as a closed one (Alberto 1991). It is obvious that Earth is an open system subjected to any sort of interactions with other corpuses and fields within the Cosmos as many geological and biological evidences indicate everywhere.

Keywords: K-T boundary, sedimentary record, epistemology, Historical Geology, catastrophes, Pernambuco-Paraíba basin, Campos basin, iridium anomaly, impact craters.

AN EPSTEMOLOGICAL AND HISTORICAL INTRODUCTION Catastrophes are part and parcel of uniformity – this was already T. H. Huxley’s and scientists mentioned (Lyell 1869, p.345) concerning Lyell’s principle of uniformity (Lyell 1830-1833). Also J. Le Conte (apud Hooykaas 1970) declared “Catastrophism and uniformitarianism are opposite extremes which must be combined and reconciled”. Both are statements of a comprehensive understanding of Earth’s history and vicissitudes all along its whole existence. Lyell’s understanding with these questions (letter of 1829) corresponded to a “steady state conception” for Earth history – “no causes whatever have ... ever acted, but those now acting” (in Lyell 1881, p.234).

For more than 150 years a significant part of the community of people of science, mostly geologists of the Anglo-Saxon tradition, maintained loyalty to a rather rigorous attitude to the [doctrine of uniformity], which excluded [catastrophes as meaningful events] in whole Earth history. In the second half of the 20th century researchers accepted the catastrophic point of view as one basic principle for geological sciences. The Phaenoreozioc geological standard column was established with this sort of view sometime before and a little later than Lyell’s publication of his “Principles of Geology” in 1830. Lyell denied any sort of catastrophic event and considered it practically nonsense.

In spite of some discordant voices the geological community followed the uniformitarian view with orthodoxy presenting sometimes very bad examples of what should not be done with science and with scientific colleagues within a project of knowledge which is really characterized by orthodoxy. Marvin (1969) presented a definite proof for this long run epistemological problem in Geology with their discovery of the final event, which gave an end to the whole phase of evolution of the Mesozoic Era. Lyell’s [uniformitarian principle] is recognised as divided in [four sub-principles]: [1] the methodological principle considers the invariance of matter and energy properties and natural laws in time (Gould 1965) [2] the causal principle considers the invariance of the types of Early-XIX century researchers accepted the catastrophic point of view as one basic principle for geological sciences. The Phaenoreozioc geological standard column was established with this sort of view sometime before and a little later than Lyell’s publication of his “Principles of Geology” in 1830. Lyell denied any sort of catastrophic event and considered it practically nonsense.

Not every school of thought in Geology agrees with the validity of the totalty of the four sub-principles (Austin 1979). In continental Europe the actualist principle (Prévost 1825, 1845) has a correspondence only to the first two sub-principles. Actualism (Hooykaas 1970) is considered here as the guiding principle which can comprise together both the actualist principle in a dialectical opposition with a catastrophist principle with all its modern variations like episodic sedimentation (Dott 1983). Actualism constitutes with the regime vs. rupture aspects a true and definitive principle for Geosciences. Amidst traditional actualist catastrophists were Elie de Beaumont (1798-1874), L. Frappolli (1846-47) and Charles Saint Claire Deville (1814-1881) (apud Hooykaas 1970). Dott (1983) himself is an example of a man of science still reacting to prejudices against catastrophism in his paper’s item “Why not catastrophic sedimentation? “Catastrophic ... should be purged from our vocabulary because its use feeds the creationist-neocatastrophic cause.” (in Dott 1983, p.9). There is no sensible way of purging this word out from our vocabulary for there is not in any western language a better word than this Greek one – it means exactly what it means.

1 - Fundação CETEC, Av. J. C. da Silveira 2000, Horto, 31170-000 Belo Horizonte, MG and Univ. Fed. de Ouro Preto, Escola de Minas, Morro do Cruzeiro, 35400-000 Ouro Preto, MG, Brasil. E-mail: pmartin@cetec.br
2 - PETROBRAS/EPBC, Av. Elias Agostinho, 665- Ponta da Inhambú, 27913-350 Macaé, R.J. Brasil. E-mail: albertao@ep-bc.petrobras.com.br
3 - Fundação CETEC, Av. J. C. da Silveira 2000, Horto, 31170-000 Belo Horizonte, MG
The year of 1995 was a decisive one with Shoemaker-Levy comet impact on Jupiter. Theoretical and practical approaches to Impact Geology became a definitive scientific branch of science from then on (decade of 1990). It was witnessed that the comet Shoemaker-Levy, which was divided in nine enormous pieces by the extraneous shearing gravitational force of planet impacted on it one by one. One of those impacts produced a disturbance in Jupiter atmosphere as bigger as planet Earth. This historical aspect is very old in Solar System and impacts produced a disturbance in Jupiter atmosphere as bigger as gravitational force of planet impacted on it one by one. One of those impacts produced a disturbance in Jupiter atmosphere as bigger as gravitational force of planet impacted on it one by one. One of those impacts produced a disturbance in Jupiter atmosphere as bigger as gravitational force of planet impacted on it one by one.

Impact evidences inside any of the Western Atlantic marginal basins became a defying aspect, which interested us mostly. Historicity-aspects like fossils extinction, Ir-anomaly, sediments evidences of a crisis, faunal/pollens change from underlying and upper strata in K-T boundary, spherulids/tektites and shocked quartz were expected to be recorded in this Brazilian and eventually other sedimentary basins within the K-T boundary. In a calculated risk at that time we started working with this subject in the M.Sc. degree programme of Ouro Preto Federal University (School of Mines). A non-prejudiced researcher must expect to witness that some of the transformations on Earth’s crust and/or within the biospheres (in the sense of Terrier and Terrier 1986; Table 2) must have also been recorded in this Brazilian and eventually other sedimentary basins within the K-T boundary. In a calculated risk at that time we started working with this subject in the M.Sc. degree programme of Ouro Preto Federal University (School of Mines). It was a well-succeeded effort focusing on the K-T boundary matter. It’s also important to quote Sircilli Netto’s work (1986), who was the first one trying to determine an Ir-anomaly in Brazilian marginal basins although unsuccessfully. Since 1978 on, an epistemological effort for Historical Geology teaching and researches (at Ouro Preto Federal University) evolved step by step determining a philosophy and a structure for a research programme [empirical and epistemological].

Since 1978 in Historical Geology classes for the undergraduate course of Engineering Geology of Ouro Preto Federal University (School of Mines), students’ attention was stimulated to the important fact that Geology is a [pro-historical] science [pro-historical] in a strict epistemological sense and historical in an [analogous sense] but not in a strict similar sense to human historical sciences (Martins Jr. 1999). A non-prejudiced researcher must expect to witness that some of the transformations on Earth’s crust and/or within the biospheres (in the sense of Terrier and Terrier 1986; Table 2) must have also been provoked by catastrophic events of widespread importance in spite of Lyell’s idiosyncratic denial of them. The traces of these many transformations are evident in the geological record. These various types of evidences are [attributes of historicity] of the geological record. Epistemologically a “historicity-attribute” means any significant and conspicuous aspect as registered in the geological record, which permit to decide about the evolutionary direction of events and their styles.

### Table 1 – A broad view on the probabilities of catastrophic impacts craters-yielding on Earth [4.6 Byr-Recent].

<table>
<thead>
<tr>
<th>Probability density of impacts on Earth</th>
<th>Age or phase</th>
<th>Craters diameters</th>
<th>Possible number of</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 x 10^-2 x10^-1 km^-2</td>
<td>&gt; 16 km</td>
<td>&gt; 16 km</td>
<td>Barlow 1990</td>
<td></td>
</tr>
<tr>
<td>4-3 Byr</td>
<td>&gt; 100km</td>
<td>&gt;3190</td>
<td>Wilhelm 1987</td>
<td></td>
</tr>
<tr>
<td>3.2-1 Byr</td>
<td>&gt; 50 km</td>
<td>&gt;825</td>
<td>Shoemaker and</td>
<td></td>
</tr>
<tr>
<td>0.25 km</td>
<td>&gt; 20 km</td>
<td>Shoemaker and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 x 10^-14 yr^-1 km^-2</td>
<td>&gt; 30 km</td>
<td>&gt;1650</td>
<td>Shoemaker and</td>
<td></td>
</tr>
</tbody>
</table>

### BRAZILIAN MESOZOIC-CAINOZOIC TRANSITION SEDIMENTARY RECORD - TEN YEARS OF RESEARCHES (1990 – 2000) The first complete works dealing with the stratigraphy and biostratigraphy of the outcrops of PE-P basin were those of Tinoco (1967), Beurlen (1967), Mabesoone et al. (1968) and more recently Stinnesbeck (1989). They can be considered the pioneers on the K-T boundary matter. It’s also important to quote Sircilli Netto’s work (1986), who was the first one trying to determine an Ir-anomaly in Brazilian marginal basins although unsuccessfully. Since 1978 on, an epistemological effort for Historical Geology teaching and researches (at Ouro Preto Federal University) evolved step by step determining a philosophy and a structure for a research programme [empirical and epistemological].

Only by the year of 1990 the search for a possible K-T boundary impact evidences inside any of the Western Atlantic marginal basins became a defying aspect, which interested us mostly. Historicity-aspects like fossils extinction, Ir-anomaly, sedimentary evidences of a crisis, faunal/pollens change from underlying and upper strata in K-T boundary, spherulids/tektites and shocked quartz were expected to be recorded in this Brazilian and eventually other sedimentary basins within the K-T boundary. In a calculated risk at that time we started working with this subject in the M.Sc. degree programme of Ouro Preto Federal University (School of Mines). It was a well-succeeded research by 1993 (Albertão 1993). This effort opened a new prospect of researches in Brazil.

### PERNAMBUCO – PARAÍBA (PE-PB) BASIN IN NORTH-EASTERN BRAZIL (PERNAMBUCO STATE) Impacts can provoke systemic phenomena on Earth’s surface, which can only be well understood with an interdisciplinary approach. In this respect the Final Mesozoic planetary event is focused from its “local historicity-aspects” in coastal PE-PB basin (Fig. 1) and submarine Campos basin. Many detailed studies were conducted concerning micropalaeontology [plankton and pannonmorphs], stratigraphy, Ir-anomaly, geochemistry (stable isotopes, rare-earth and other elements distribution), palaeoecology, palaeosurface dynamics, climatology and diagenesis in PE-PB basin, especially the areas of Ponta do Funil and Poty Quarry (Albertão 1993, Albertão et al. 1993, Albertão et al. 1994a, 1994b, Albertão and Martins Jr. 1996a, 1996b).

### The K-T boundary and micropalaeontology Micro-palaeontology was determinant to characterise the alterations from
lower level/upper level contact zone of the K-T boundary (Table 3). Pollens are more conspicuously different than foraminifera from lower level to upper level. Foraminifera seems to have undergone some transport from lower level to the upper level through erosion (Albertão et al. 1993, Albertão et al. 1994a, 1994b, 1994c, Stinnesbeck and Keller 1995, Koutsoukos 1995).

Ir-anomaly Ir-distribution in sediments points out to an anomaly characterised biostratigraphically (Albertão and I et al. 1994a, 1994b, 1994c, Stinnesbeck and al. 1994). At the same level (bed I) a TOC (Total Organic Carbon) anomaly was also observed (Fig. 2).

Spherules Microtektite-like microspherules (Fig. 3a) and shattered fragments of shocked-like quartz grains (Fig. 3b) are common immediately underneath and at bed I (Albertão et al. 1994c, Albertão 1997, Delício et al. 1998). Microspherules are better

<table>
<thead>
<tr>
<th>Names of Biospheres</th>
<th>Age By bil. years</th>
<th>Most Important Characteristics</th>
<th>Events and/ dated craters and/or tektites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-biosphere</td>
<td>4.5 - 3.8 By</td>
<td>Intensive pitting; Small emerging continental areas; 2 atmospheres; the 1st atmosphere ejected by solar T-Tauri event; 2nd atmosphere was r educive</td>
<td>[4.6-1.1] most intensive Impact Era on Earth and Moon</td>
</tr>
<tr>
<td>1st biosphere</td>
<td>3.5 – 3.0 By</td>
<td>Consolidation of the 1st crust under anoxic conditions; procharyonts micro-organisms; anaerobiosis; archaeabacteria.</td>
<td>Idem</td>
</tr>
<tr>
<td>2nd biosphere</td>
<td>3.0 – 1.75 By</td>
<td>Crust undergoes 2 types of consolidation; shields and fold belts connecting from one pole to other with bacterial life; photosynthesis; revolution of the atmospheric free O2 production</td>
<td>Sudbury Canada</td>
</tr>
<tr>
<td>3rd biosphere</td>
<td>1.75 – 0.8 By</td>
<td>Tectonic introduction to Pangea. Two super continents with a fracture zone almost coincident as the great circle of Tethys; protocharyonts; pluricellular algae, sexuated reproduction; eucaryonts chloroplasts; cyanobacteria; mitochondrides; photosynthesis; free oxygen</td>
<td>Idem</td>
</tr>
<tr>
<td>4th. biosphere</td>
<td>700 - 330 By</td>
<td>Diversification of pluricellular animals; marine eumetazoans; pelagic ecosystems</td>
<td>—</td>
</tr>
<tr>
<td>5th biosphere</td>
<td>530 By</td>
<td>Warmer seas with reefs. 10 % free O2. Pelagic ecosystems, stromatolites; cyanobacteria, spongiarcheates; eumetazoans (mollusks, brachiopods, echinodermata, etc.) trilobites. Erosion; sedimentation after Assintic movements.</td>
<td>—</td>
</tr>
<tr>
<td>6th - 7th biosphere</td>
<td>±500 - 400 By</td>
<td>Opening of the proto-Atlantic, collision orogenesis; Saharan glaciation; South pole in Africa; Caledonian suture originates North Atlantic continent; pelagic ecosystems with acritarchs; reefs, porifera, carnivore cephalopods, Tethyan migration of trilobites.</td>
<td>—</td>
</tr>
<tr>
<td>8th - 9th. biosphere</td>
<td>400 till ± 240 By</td>
<td>Pangea continent; end of mise en place of the Caledonides; intracratonic South American basins; Permian massive extinction; modern atmosphere since then; Variscan orogenesis; sauropsids, therapsids, reptiles with amniotic eggs; forests; vertebrate tetrapods, etc.</td>
<td>Permian-Triassic; Araguaiunha 40km, Brazil. 365 ± 7 Siljan (52km), Sweden.</td>
</tr>
<tr>
<td>10th. biosphere</td>
<td>220 - 100 By</td>
<td>Opening of Tethys ocean; Atlantic rupture; appearance of placental mammals; angiosperms; archaeoepxy lithographica; birds; great basalt effusion, etc.</td>
<td>Serra da Cangalha 220 My 210 ± 4. Manicougan (70km) Canada; 183 ± 3. Puchezh-Katunki (80km) Russia</td>
</tr>
<tr>
<td>End of the 10th biosphere</td>
<td>80 – 60 By</td>
<td>End of Mesozoic Era with meteorite impact in Chixculub Yucatan Peninsula; global ecological catastrophe; massive extinction of Mesozoic fauna and flora; continuous plate tectonics.</td>
<td>Chixculub event Mesozoic Era ends. Dc = 300km</td>
</tr>
<tr>
<td>11th biosphere</td>
<td>60 – 6 By</td>
<td>Continuous Alpine, Andes and Himalayan tectonics; oceans increase; earth’s magnetic field oscillates; biogeographic expansion of mammals, birds and angiosperms; plates separation; extensive new habitats on whole Earth.</td>
<td>Pliocene 14.7 ± 07; Moldavites; 28.6 ± 2 Libyan desert glass; 34.7 ± 2 Bediasite; 38 ± 9 Popigai (100km); 57 Kara (50km) Russia</td>
</tr>
<tr>
<td>12th biosphere</td>
<td>From 6 By – to present time</td>
<td>Present day geology and geography; maximum biodiversity; presence of humans</td>
<td>0.77 ±0.1 Australites; 088 ± 0.13 Ivory Coast Hoyle’s (1984) impact - Pleist. glacial; Impacts 9700 yr. B.P (Tollman and Tollman 1994)</td>
</tr>
</tbody>
</table>

Table 2 – “The many biospheres” concept and the biospheres characteristics accordingly to Termier and Termier (1980), modified by the present authors; geological dating are from various sources.
Table 3 - Palaeontological evidences of the K-T boundary in Poty Quarry, and some geochemical characteristics of transitional layers in PE-PB basin, Brazil.

<table>
<thead>
<tr>
<th>Lower part of the contact zone</th>
<th>Cretaceous Foraminifera</th>
<th>Extinction of Palynomorphs</th>
<th>Contents in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>base of layer D.</td>
<td>Rugoglobigerina, Pseudoguembelina palpebra e caryae Globotruncanca aegyptiaca, Pseuda guembelina exocolata, etc.</td>
<td>Dinogynium, Deinandrea diebetti, Ariadnaesporites sp.</td>
<td>Lu = 0.4, Dy = 6.5</td>
</tr>
<tr>
<td>contact of upper Gramame fm. / lower Maria Farinha fm.</td>
<td></td>
<td></td>
<td>Hi = 2.7, Sm = 6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>U = 30, Ce = 118.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yb = 3.8, Se = 5.0</td>
</tr>
</tbody>
</table>

preserved in bed D, the conspicuous probable tsunamiite which occurs under bed I (Albertão and Martins 1996a, Martins and Albertão 1996a, Martins and Albertão 1988), probably due to the low permeability, which avoided recrystalization, devitrification and/or weathering in bed D. Their composition, shapes, internal and surface textures are similar to those reported elsewhere like those of Caravaca/Spain and Raton basin/USA. Most are 150 mm across and develop as spheres, or less frequently as oblate spheroids; few as teardrop like. Many have crater-like pits and protruding mounds of various sizes and shapes (Fig. 3a). Their morphic features are similar to those of well-known tektites and micro-tektites (McNamara 1985, Wang 1992). Their outer-surface is similar to the main mineral components of the layers they are found within (limestone and marls reworked with phosphate grains of microgastropods, foraminifera and small brownish, oval faecal pellets – microprolites). Diagenetic process has necessarily worked on the spherule outer-surfaces. Spherules can be divided in three distinct classes (Marini et al., in press): ¾ (1) resistant class (2) white class (3) brittle class. Most of them are composed mainly by F-rich apatites and differ notably from Al- and Fe-rich phosphate types described elsewhere in the world (Albertão et al., in press). Finally bed D, especially its base not yet fully studied, is the best candidate in holding tektites as a “historicity-attribute” of the K/pre-T impact event as locally recorded.

CAMPOS BASIN – RIO DE JANEIRO SHELF – PREVIOUS AND NEW INVESTIGATIONS  The initial efforts to study the submarine basin of Campos offered only a relative contribution to understand the K-T boundary (Albertão 1993, Albertão and Martins Jr. 1995, Martins Jr. and Albertão 1996b). The sedimentary record permitted to identify distinct behaviour of elements and minerals in the analysed drilling wells suggesting identical sedimentary sources but distinct sedimentary processes. Cyclic deposition of elements is evident (alkaline, earthy alkaline, metals and rare earth – of a total of 46 elements).

Studies based on samples from Campos permitted to identify the K-T boundary with calcareous nanofossils and associated spherules (Grassi, in press, Grassi and De Ros 1999). A 2.5-cm thick layer of spherules was interpreted as tektites derived from the Chicxulub Event. Tektites are dark-grey to black with 0.3 to 1.4 mm of diameter. Calcite and pyrite extensively substituted them. Some of them display internal textures of flow and devitrification textures of the original glass preserved as minor inclusions in only a few tektites. Eventually these tektites are the most faraway deposited material from the local impact crater of Chicxulub as far as ~7,800 km (Grassi and De Ros 1999, Albertão et al., in press).
PERPECTIVE OF FUTURE RESEARCHES

Future researches will give continuity to microtektite-like microspherules and to shattered fragments of shocked-like quartz grains investigations especially in the boundary layers D and J. Campos basin most certainly can still furnishes a lot of historicity-attributes such as spherules. Other coastal basins may eventually bring more light on this phenomenon as well. Other Brazilian investigators are studying known craters such as Araquainha astrolebre (Hippert and Lana 1998).

Detailed micropalaeontological studies (mainly for foraminera, nanofossils, pollens and ostracods) are at present being developed in Pb, D and M. Sc. theses under the supervision of Dr. Eduardo A. M. Koutsoukos (Petrobras/Cenpes). Very soon it will bring new data to the interpretation of the boundary events.

A software for KHOROS amnience is already developed. It is possible the automatic recognition of circular forms within the various types of remote sensing images. The program is capable of distinguishing impact craters (fig. 4) from those of volcanoes (Haday et al. 1998-2000, Araújo et al. 1996, 1998, in press). The program permits the recognition of objects in a scene, as a last step in a processing-chain, which can be described in four phases [i] reading, selection enhancement and registration of images [ii] data fusion and pattern detection [iii] pattern recognition and [iv] identification of the targets – the present time researches are being developed in Aymorés astrolebre in Minas Gerais State (Martins Jr et al., 2000) and presently research will be conducted for craters systematic identification.

CONCLUSIONS

Present time geological thought has been transformed with various paradigm revolutions [plate tectonics, cladist evolution, and catastrophism with its various branches]. Any sort of resistance to recognise the relative importance of the principle of catastrophism on equal basis with the principle of actualism is faded to bankruptcy.

Today we can repeat with more amplitude T.H. Huxley’s statement that “catastrophes are part and parcel of regime” (“periodic catastrophes” like earthquakes and turbidite formation, etc.) and also that “-non-range catastrophes are part of Earth’s history revolutions”.

Lyle’s idiosyncratic denial of catastrophes makes no sense. In a 1998 workshop of the Planetary Society on Impact Hazards Binzel’s (1999) ideas concerning a probability measure graphic for impacts on Earth is definitely accepted as the “Torino scale”. The Chickxubut Event is included in category 10 in Torino scale - “global/certain collision/ capable of causing a global climatic catastrophe – probability one per 100,000 years”.

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