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

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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 (Albertão 1991). It is obvious that Earth is an open system subjected to any sort of interactions with other corpses 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 EPISTEMOLOGICAL AND HISTORICAL INTRODUCTION

"Catastrophes are part and parcel of uniformity" – This was certainly T. H. Huxley's final statement (1869, p.xlvii) 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 of 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 attachment to the [doctrine of uniformity], which excluded [catastrophes as meaningful events] in whole Earth's history. Early XIX century researchers accepted the catastrophic point of view as one basic principle for geological sciences. The Phaenerozoic 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 non-sense.

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 concerned with truth. Marvin (1990) indicates some illustrations on this question: (i) in 1891, Gilbert's self-control concerning the interpretation of Meteor crater in Arizona (USA) as a derived impact crater restrained Impact Geology for almost 60 years although D. M. Baringer had collected evidences for impact in this same crater by 1905; (ii) Ralph B. Baldwin found difficulty in publishing papers on lunar craters; (iii) The scablands geomorphology in Oregon State was recognised as a catastrophic event of basalt extrusion inside a thick blanket of ice of the last glacial episode. The results of the author's conclusions on the scablands morphology were certainly painful for him who suffered exclusion from the community of geologists. A social fact like this is very important to remind us of the dangers of any sort of authoritarian thinking in science and in whatever human activities. Inadequate social control and self-imposed control are two faces of the same authoritarian aspect in human affairs.

The Tunguska event in Siberia in 1908 offered an occasion for a long history of research looking for a comprehension of the meaning of an usual event. Some Russian researchers achieved a recent successful modelling of the event – a 30º entry of a bolide in the atmosphere with the explosion occurring high in the atmosphere. In Brazil a similar event happened in Amazonas State near São Paulo de Olivença, Rio Curaçá a tributary of Rio Javari, itself a tributary of Rio Solimões (August 13th 1930). Three bolides struck into/over or above the forest – a Tunguska average size bolides of 10-100 m as lately reported in Daily Telegraph (6 March, p. 9, 1931) from a previously report in L'Osservatore Romano by Father Fidello (1930).

Man arrival on Moon with the Apollo flight mission in the early 1970 permitted to recognise that the Moon's craters are definitely impact-derived products. So must be with Earth's many craters no matter if they are partially preserved, non preserved at all or eventually underlying some thick sedimentary deposit. Alvarez *et al*. (1980) 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 geological processes during time having present day geological processes as the only ones in whole Earth's history [3] the *actional principle* considers the invariance of geological processes energy ratios around averages throughout the whole history [4] the *configurational principle* is Lyell's theory alleging temporal uniformity of crust and life as a steady-state view of geological conditions through time (Austin 1979). Of course the 4th sub-principle is denied by the very geological facts. Notwithstanding many geologists still keep in mind the strict mental habit of rigorously applying this 4th principle to whatever model of crustal evolution. An example is the systematic application of plate tectonics typically a Mesozoic-Cainozoic event structuring to times as older as the Proterozoic. Of course Tectonics is Tectonics but as a broad phenomenon it underwent different phases with different styles and different energy involved in the geological processes.

Not every school of thought in Geology agrees with the validity of the totality of the four sub-principles (Austin 979). 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 Élie de Beaumont (1798-1874), L. Frapolli (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-neocatastrophist 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.

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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 Table 1 presents some fairly good probabilistic estimations of impact ratios in Archean, Proterozoic and Phaenerozoic Eons.

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

Probability density of impacts on Earth	Age or phase	Craters diameters Dc	Possible number of craters	Authors
$1.4 \times 2.45 \times 10^{-4}$ km^{-2}		> 16 km		Barlow 1990
	4.6-3.9 Byr	> 100km	2500-3000	Grieve 1980
		>1000 km	25	
	3.8-3.2 Byr	> 30km	>3190	
	3.2-1.1 Byr	>30 km	>1650	Wilhelms 1987
	[1.1 Byr	>30 km	825	
$0.45 (\pm 0.2) \times 10^{-14}$ yr^{-1} km^{-2}	Proterozoic	>20 km		Shoemaker and Shoemaker 1990
$0.35 (\pm 0.13) \times 10^{-14}$ yr^{-1} km^{-2}	Phaenerozoic	> 20 km		Grieve 1982

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*-] 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 Termier and Termier 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.

BRAZILIAN MESOZOIC-CAINOZOIC TRANSITION SEDIMENTARY RECORD - TEN YEARS OF RESEARCHES (1990 – 2000) The first complete works dealing with the stratigraphy and biostratigrapy 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 pallinomorphs], stratigraphy, Ir-anomaly, geochemistry (stable istopes, 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 Micropalaeontology was determinant to characterise the alterations from

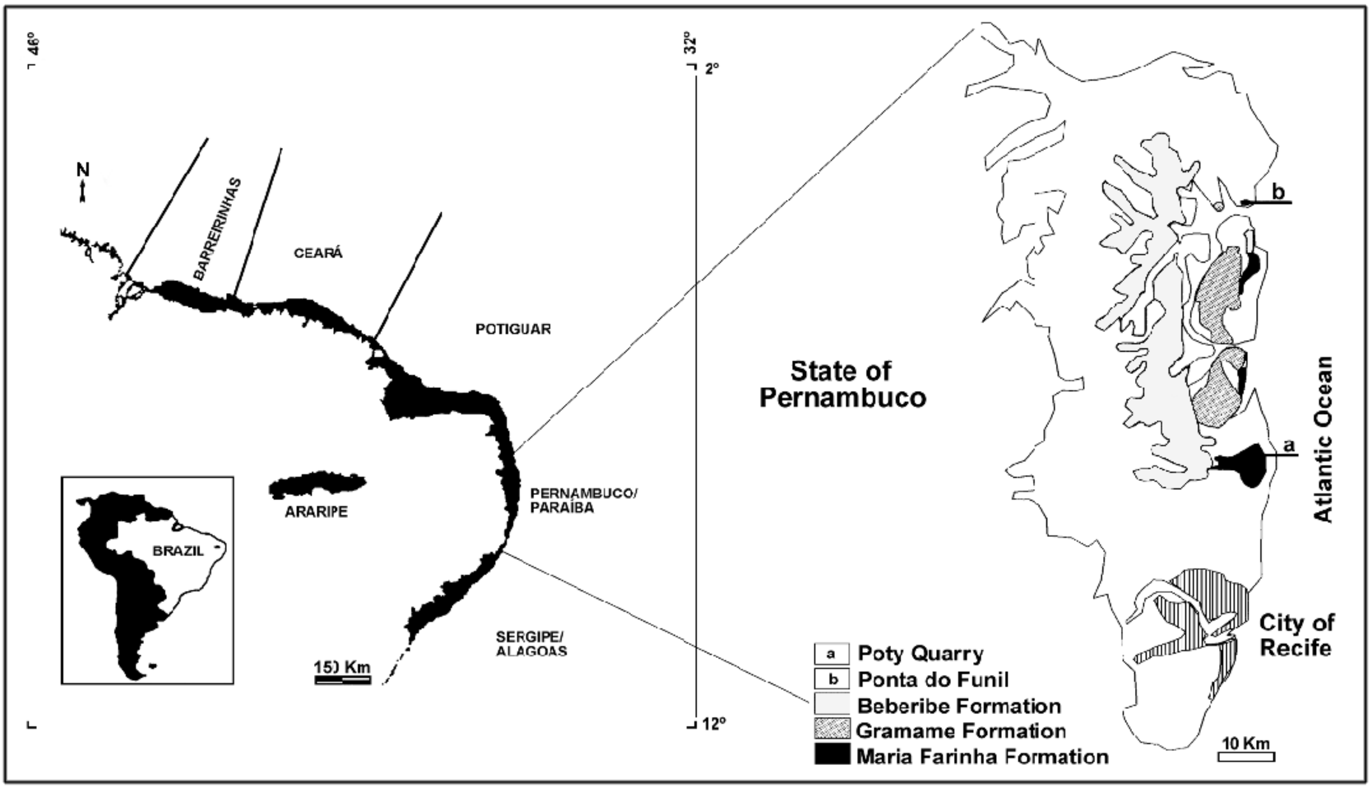

Figure 1 - Location map for Pernambuco-Paraíba basin. Poty quarry is indicated.

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.

Names of Biospheres	Age By bil. years	Most Important Characteristics	Events and/ dated craters and/or tektites
Pre-biosphere	4.5 - 3.8 By	Intensive pitting; Small emerging continental areas; 2 atmospheres; the 1^t atmosphere ejected by solar T-Tauri event; 2^d atmosphere was reductive	[4.6-1.1 [most intensive Impact Era on Earth and Moon
1^t biosphere Archean	3.5 – 3.0 By	Consolidation of the 1t crust under anoxic conditions; procharyonts micro-organisms; anaerobiose; archaebacterias.	Idem
2^d biosphere Upper final Archean	3.0 – 1.75 By	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 O_2 production	Sudbury Canada
3^d. biosphere Proterozoic; Ante-cambrian	1.75 – 0.8 By	Tectonic introduction to Pangea. Two super continents with a fracture zone almost coincident as the great circle of Tethys; protocharyonts; pluricellular algae, sexuated reproduction; eucharyonts chloroplasts; cyanobacterias; mitochondries; photosynthesis; free oxygen	Idem
4^{th} . biosphere Ediacarian-Vendian	700 - 530 By	Diversification of pluricellular animals; marine eumetazoans; pelagic ecosystems	—
5^{th} biosphere Lower Cambrian – Tommotian	530 By	Warmer seas with reefs. 10 % free O_2. Pelagic ecosystems, stromatolites; cyanobacterias, spongiarcheates; eumetazoans (mollusca, brachiopoda, echinodermata, etc.) trilobites. Erosion; sedimentation after Assintic movements.	—
6^{th} - 7^{th} biosphere Middle-upper Cambrian; Ordivician; Silurian	± 500 - 400 By	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	—
8^{th} – 9^{th} . biosphere Upper Palaeozoic; Lower Triassic	400 till ± 240 By	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.	Permian-Triassic; Araguainha 40km, Brazil. 365 ± 7 Siljan (52km), Sweden.
10^a. biosphere Triassic middle-lower Cretaceous	220 - 100 By	Opening of Tethys ocean; Atlantic rupture; appearance of placentary mammals; angiosperms; archaeopteryx lithographica; birds; great basalt effusion, etc.	Serra da Cangalha 220 My 210 ± 4. Manicougan (70km) Canada; 183 ± 3. Puchezh-Katunki (80km) Russia
End of the 10th biosphere Senonian; final Cretaceous	80 – 60 By	End of Mesozoic Era with meteorite impact in Chicxulub Yucatan Peninsula; global ecological catastrophe; massive extinction of Mesozoic fauna and flora; continuous plate tectonics	Chicxulub event Mesozoic Era ends. D_c = 300km
11^{th} biosphere Palaeocene - Miocene	60 – 6 By	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.	Pliocene 14.7 ± 07; Moldavites; 28.6 ± 2 Libyan desert glass; 34.7 ± 2 Bediasite; 38 ± 9 Popigai (100km); 57 Kara (50km) Russia
12^{th} biosphere	From 6 By – to present time	Present day geology and geography; maximum biodiversity; presence of humans	0.77 ± 0.1 Australites; 088 ± 0.13 Ivory Coast Hoyle's (1984) impact - Pleist.glac.; Impacts 9700 yr. B.P (Tollman and Tollman 1994)

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 in the named bed **I** characterised biostratigraphicaly (Albertão and Martins 1992, Albertão *et al*. 1992, Albertão 1993) as the last Cretaceous level in Pedreira Poty (quarry) within the basis of Maria Farinha formation. Ir-content is around 26 times bigger than the average values of all other samples. This anomaly was also confirmed when considered the ratio with clay minerals (Fig. 2). Other recognised world occurrences present similar low values of Ir-anomaly (Donovan *et al*. 1988, Bourgeois *et al*. 1988). 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 3 - Palaeontological evidences of the K-T boundary in Poty Quarry, and some geochemical characteristics of transitional layers in PE-PB basin, Brazil.

Lower part of the contact zone	**Cretaceous Foraminifera**	**Extinction of Pallinomorphs**	**Contents in ppm**	
base of layer **D**; contact of upper Gramame fm. / lower Maria Farinha fm.	***R****ugoglobigerina,* ***P****seudoguembelina palpebra e* carseyae ***G****lobotruncana aegyptiaca,* ***P****seudo guembelina excolata,* etc.	***D****inogymnium,* ***D****eflandrea diebeli,* ***A****riadnaesporites* sp.	Lu ≅ 0,4 Hf ≅ 2,7 Th ≅ 13 U ≅ 30 Yb ≅ 3,8	Dy ≅ 6,5 Sm ≅ 6,3 Nd ≅ 39,8 Ce ≅ 118,0 Se ≅ 5,0
Upper part of the contact zone	**Tertiary Foraminifera**	**New palinomorphs**	**Content intervals in ppm**	
Base of overlying layer to stratum **D**	*G.M.****t****rinidadensis G.[M.]****p****seudobul- loides, G.[P.]****e****ugubina, G.[E.]* ***f****ringa, G.* ***m****inutula*	***E****chitriporites trianguliformis,* ***S****chizeoisporites eocenicus,* ***P****roxaperetites cursus* and pollens of *palmaceae*	Lu ≅ 0,1- 0,25 Hf ≅ 0,3- 2,0 Th ≅ 1,0- 12,0 U ≅ 1,0- 15,0 Yb ≅ 0,4-a 1,8	Dy ≅ 0,3-0,4 Sm ≅ 0,2-3,5 Nd ≅ 1,0-18,0 Ce ≅ 1,0- 39,0 Se ≅ 0,2- 5,0

preserved in bed **D**, the conspicuous probable tsunamite 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 recrystallization, 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.

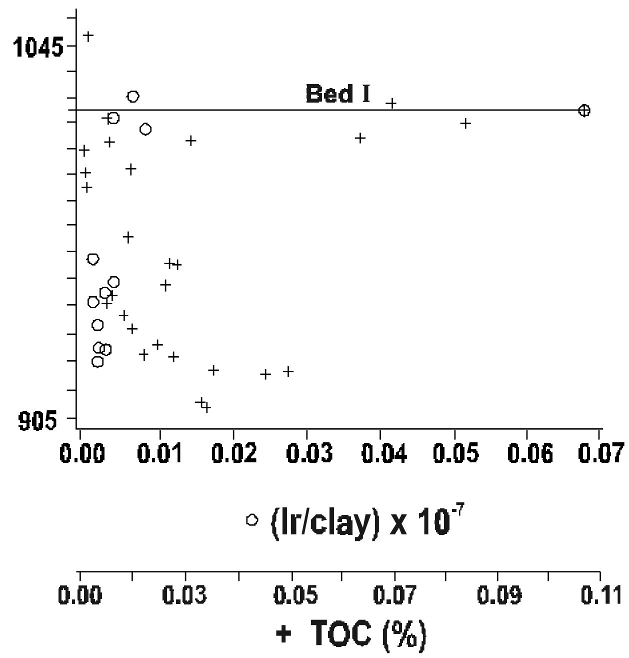

*Figure 2 - Distribution of Ir-content across the K-T boundary (neighbourhood of bed **I**); the ratio Ir/clay clearly indicates the presence or an anomaly; vertical scale is the thickness of outcrops in cm.; distribution of TOC (Total Organic Carbon) across the K-T boundary; here the anomaly is again characterised.*

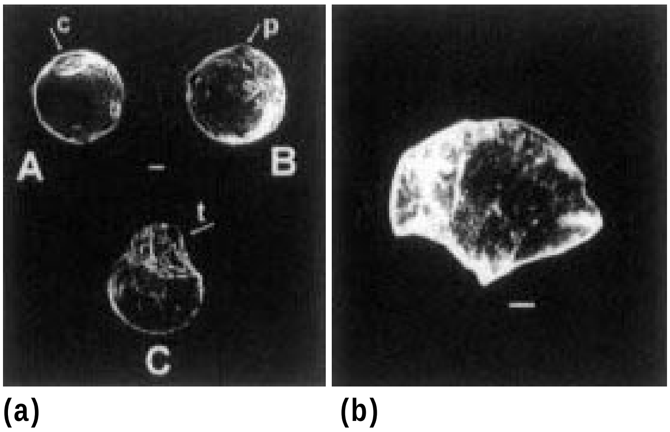

*Figure 3 - (a) - Scanning electron photomicrographs of three selected microspherules present at bed **I**; structures such as crater-like pits (c), protrusions (p) and tails (t) are present (scale bar = 20 mm); (b) photomicrography of a shock-metamorphosed quartz grain from bed D, exhibiting intersecting sets of sharp and straight planar lamellae (scale bar = 120 mm). Photographs (a) and (b) kindly ceded by E. A. M. Koutsoukos (Petrobras/Cenpes).*

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 nannofossils 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 features 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).

PERSPECTIVE 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 **I**. 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 Araguainha astrobleme (Hippert and Lana 1998).

Detailed micropaleontological studies (mainly for foraminera, nannofossils, pollens and ostracods) are at present being developed in Ph.D. and M.Sc. thesis 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 ambience 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 (Hadad *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 – models. At the present time initial researches are being developed in Aymorés astrobleme in Minas Gerais State (Martins Jr. *et al*., 2000) and presently research will be conducted for craters systematic identification.

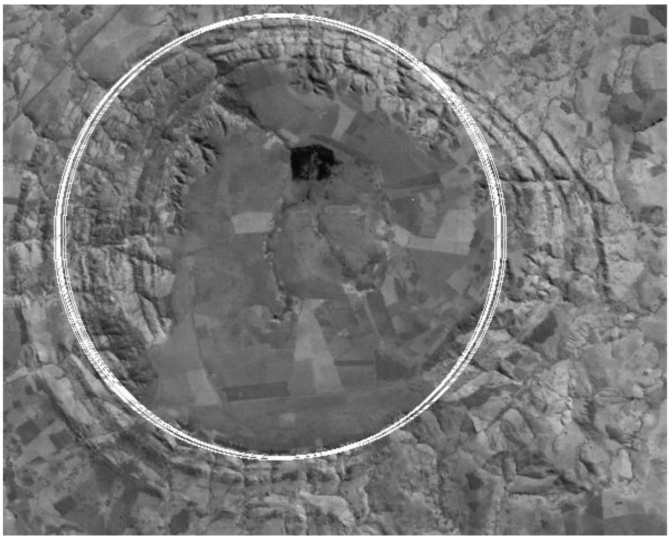

Figure 4 - An example of contour recognition of a crater (satellite filtered image track 220-73).

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-regime catastrophes are part of Earth's history revolutions". Lyell'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 was definitely accepted as the "Torino scale". The Chicxulub 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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