ENVIRONMENTAL PERTURBATIONS CAUSED BY THE SERRA DA CANGALHA IMPACT CRATER STRUCTURE, NORTHEASTERN BRAZIL

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Abstract

This paper includes a discussion on the effects a meteorite impact had on the Serra da Cangalha region in northeastern Brazil and the resultant environmental perturbations that occurred in the region. These environmental perturbations were large enough to seriously affect the earth's global environment after the impact. The effects of such an impact on both the land and the atmosphere constitute the focus of this paper. Such effects include ejecta dispersal, shock wave, landslides, global wildfires, clouds of dust, and overall atmospheric cooling. The result of these effects had in the past been and would in the future be the devastation of many of the organisms living at the time of the impact. Such a major and sudden change in the conditions of the planet would result in a huge depletion of biomass. Using the Pi-scaling relations, we deduced that the impactor propably came from a northwest-to-southeast trajectory at a low angle of 25° to 30°. The geodynamic interpretation indicates that an impact energy equivalent to about 1.8×10^4 Megatons of TNT was released during impact. This energy is well below the stipulated nominal threshold for global disaster (3×10^5 Megatons of TNT), but is within the range described as subglobal disasters. A ground impact of the projectile would have set up an atmospheric blast wave that delivered key peak pressure at a maximum radius of 156 km. This could have resulted in an earthquake surface-wave magnitude (M_s) of 9.2, a rough proxy for Richter magnitude leading to a substantial damage in the region. Also, a peak shock pressure of about 47 GPa was generated during the impact. This peak shock pressure is well below the levels necessary for generating melts which explains the low melt volume found. Based on our research findings, we deduce that the impacts from earth-crossing objects (asteroids and comets) that struck the Serra da Cangalha region about 300 million years ago is enough to have devasted the local ecosystem and biota leading to a high mortality rate at that time.

Keywords: Perturbations, impact, Serra da Cangalha, disaster, shock

Introduction

Of recent, the interest in studying impact processes on earth has increased tremendously because it has been recognized that these processes are important geologic events. Besides, the evolution of life on earth has also been severely affected by the impact of large extraterrestrial projectiles (asteroids and comets). The earth and its inhabitants are in constant danger of earth-crossing objects (ECO) impacting on the earth as the earth lies at the center of a cosmic shooting gallery consisting of asteroids and comets. These objects race through space at velocities relative to the earth of up to 75 times the speed of sound. These extraterrestrial objects are materials left over from the formation of the solar system and are basically materials that never coalesced into planets (Tyson, 1995). As the earth revolves around the sun, it periodically passes close to orbiting asteroids and comets, producing near-earth-object (NEO) situations which on impact in the earth usually leave behind fingerprints called impact craters. Impact craters contain ecosystems that are often very different from the surrounding ecosystems. Impact events are unique in that they are the only extraterrestrial mechanism capable of disrupting an ecosystem locally in space and time (Cockhell and Lee, 2002).

Kring, (1997) showed that the biological consequences of impact cratering depend on many factors. These include the energy of the impact event, the type of target materials, the type of projectile, and the ambient conditions on earth at the time of impact. The consequences may range from the death of individual organisms to the complete extinction of species. While the former can be the direct result of an impact event (e.g., shock wave-induced hemorrhaging and edema in an animal's lungs, the former is the indirect result of impact events caused by the shutdown of photosynthesis by a global cloud of impact debris and production of very harmful gases and dust that eventually led to their extinction (see Alvarez *et al.* 1980). When the environmental effect is largely regional, the changes must overwhelm the migratory capacity of a species or last longer than its dormant capacity. When the effect transcends geographical boundaries and becomes global, the change must be rapid relative to the time scale of evolutionary adaptation or, last longer than the dormant capacity of a species. Many environmental effects that could lead to extinction have been identified of recent. (e.g., Alvarez *et al.*, 1980; Bohor *et al.*, 1984; Venkatesan and Dahl, 1989; Hilderbrand and Boynton, 1990; Izett *et al.*, 1991; Cheetham and Jackson, 1996; Smith and Jeffery, 1998, 2000).

A meteorite falling to the earth can have many disastrous effects on the land. Some of these effects are discussed briefly. Kring, (2000) suggested that in the immediate vicinity of the impact crater, a shock wave, an air blast and heat are usually produced by the impact explosion that will eventually affect the entire ecosystem. A meteor entering into earth's atmosphere will first send a shock wave into the air. The friction the meteor creates while traveling through the air will cause its temperature to dramatically increase. The airblast will cause impact winter. The winter occurs through dust blasted into the stratosphere blocking out sunlight, and plunging the earth into darkness and refrigeration. This refrigeration will offset greenhouse warming via volcanic CO_2 release into the atmosphere that triggered climatic warming. The high temperature often causes smaller meteorites to completely burn up before they reach the earth (Nelson 2000). Even when meteorites actually hit the ground, they are hard to find. Most meteorites that fall in tropical areas are destroyed on a time scale which is short compared to the rate of infall (Bland *et al.*, 2000). As the ECO strikes the earth, massive amounts of dust and small pieces of rock are sent up into the atmosphere. This cloud of dust and rock is distributed across the earth. The consequences of this are extremely serious for the biota of the planet. The dust and rock will block sunlight, keeping it from getting through the atmosphere. Day thus becomes as dark as night for months at a time. Freezing conditions occur in the oceans, away from the coastlines. Without sunlight, the life-supporting process of photosynthesis ceases in plants (Paine, 1999). Dott and Prothero (1994) also suggested that the cold and darkness would cause the collapse of the food chain. The disappearance of plants would break the food chains and the carnage would begin (Courtillot, 1999). Toon *et al.*, (1994) showed another major effect of ECO impacting on the earth is global wildfires or firestorms. Firestorms are perpetuated by massive amounts of methane gas that are released from the earth by the collision. Lightning can ignite the released methane gas. When the ECO strikes, it shakes up the earth, thereby rupturing the pockets of methane that are trapped in gas hydrates. As this fire is fueled by extraordinary levels of methane gas, the atmosphere itself would also be on fire. The fires would incinerate global flora and fauna. The blaze would also decrease oxygen supplies and increase levels of carbon dioxide instigating a run-away greenhouse effect, a major, overall heating of the planet (Paine 1999).

Over 150 surviving impact craters have been found so far on earth ranging in age from under one million years to more than 2000 million years (Cockell and Lee 2002). Only 11 impact craters are known in South America and eight of them are located in Brazil. These are, Domo de Araguainha, Serra da Cangalha, Riachão, Vargeão, São Miguel do Tapuio, Colônia, Cerro Jarau and Piratininga (Crósta, 1987, Hachiro *et al.*, 1996). Two other craters are located in Argentina (Campo del Cielo and Rio Cuarto) and Monturaqui is the only one located in Chile (Fig. 1). They all range from small simple craters (ranging from less than 2 km to 4 km in diameter) to the large complex craters (Pilkington and Grieve, 1992). A size and impact versus frequency graph is shown in Fig. 2.

During the twentieth century, several impacts and near misses were recorded on earth. For example, in 1908 a stony asteroid of approximately 50 meters in diameter exploded in the air above the Tunguska River in Siberia, producing an equivalent TNT yield of 15-30 megatonnes (MT) and leveling over 2,000 square miles of dense forest. Had the Tunguska event occurred over a populated city, the results would have been catastrophic. In 1937 and again in 1989, large asteroids passed uncomfortably close to the earth. The 1989 asteroid would have unleashed the equivalent of more than 40,000 megatonnes of TNT had it impacted. More recently, in 1994, astronomers cautiously watched as a small asteroid missed the earth by only 60,000 miles. In 1996 comet Hyakutake passed within nine million miles of earth [0.1 astronomical units (AU)], the nearest comet approach in six centuries. Yet this body was discovered only three months prior to its closest approach to earth (Hyakutake 1996). The Hiroshima weapon was estimated to have had an explosive power equivalent to 18,000 tonnes of TNT. The destructive power of these weapons are both enormous and horrific. However, they provide the only cognitive benchmark useful to conceptualize the environmental impact effects of the energy of the earth impactor (asteroids) that struck the Serra da Cangalha region about 300 Ma ago.

Fig. 1. Publisher: Pls Insert from Pdf file

Fig. 2. Insert too

A better understanding of the environmental effects resulting from impacts would assist in having a realistic assessment of the danger that ECOs pose to mankind. The principal objective of this paper is to contribute to the scientific knowledge of the environmental problem caused by the ECO impact that occurred in the Serra da Cangalha region (State of Tocantins) northeastern Brazil about 300 Ma ago. It also gives an insight into the geodynamic formation processes of the crater through Pi-scaling relations and the impact event energy (Megatons of TNT) released in the region.

Regional and Local Geology of the Study Area

The South American continent was classified into three tectonic provinces: the South American platform, the Patagonian platform and the fold belt by Schobbenhaus *et al.*, (1984). Brazil is located within the South American platform with its basement rocks formed by the Archean rocks and the Late Proterozoic mobile belts. Furthermore, Cordani and Neves, (1982) characterised the geology of Brazil into four groups: the cratonic areas and smaller cratonic fragments mobilized during the Brasiliano cycle (700 – 500 Ma), mobile belts of the Brasiliano cycle, and the Precambrian and Phanerozoic sedimentary cover.

The cratonic areas of Brazil are subdivided into four groups. These are the Amazonian craton situated in the northern area, the São Francisco craton located at the northeastern margin, São Luis craton northeast and the Luís Alves cratons in the south. The Brasiliano cycle mobile belt in Brazil is divided into the Tocantins province, the Goías massif and the Brasília belt. Cordani and Neves (1982) described the Goías massif as a mosaic of old cratonic fragments of different origins now juxtaposed and overprinted by the orogenic cycles during the Middle and Late Proterozoic era. Borborema province in the northeast is composed of gneissic-migmatitic-granitic massifs and metavolcanic-metasedimentary fold belts. The Ribera and Dom Feliciano belts occur in the southeast (Fig. 3).

The Paleozoic intracratonic sedimentary basins within the oldest geological provinces of Brazil are represented by the Amazon, Solimões, Parnaíba, Parecis and Paraná basins. França *et al.*, (1995) and Tankard *et al.* (1995) observed that many of the Paleozoic and Mesozoic rift basins of South America exploited the pre-existing basement structures avoiding Archaean cratons. The study region, Serra da Cangalha is located within the Parnaiba basin. A brief description of the regional and local geology of the study area is given below.

The Serra da Cangalha meteorite impact crater structure (Fig. 4) is located on longitude 46°52' W and latitude 8°05' S in northeast Brazil. It occurs within the intra-cratonic Parnaiba basin consisting of Upper Silurian to Cretaceous sedimentary covers. The structure is one of the eight known impact craters in Brazil (Crósta, 1987). It is the second largest impact crater in Brazil with a 13 km diameter estimated from satellite imaging (McHone 1979). Santos and McHone (1979) provided strong evidence that supports a meteoritic origin for this crater through the discovery of shatter cones in the quartzite boulders of the Poti Formation. Crósta (1987) recognized features due to shock metamorphism at the center of the crater, such as shatter cones, shock lamellae, and impact breccia. A distinct uplifted annular trough and a circular central ring that has a diameter of 5 km and reaching a height of about 300 m characterize this crater (De Cicco and Zucoloto 2002). The geologic evidence seen at the site rules out an endogenic origin due to igneous intrusion or salt diapir. Igneous rocks are entirely absent in this region and the sediments underlying the structure do not contain significant carbonate or salt units. The crater´s shape (semi-circular, open on northwest quadrant) suggests oblique impact on a northwesternly trajectory (Fig. 4). The horseshoe-shaped structure (Fig. 4) also provides morphological evidence for identifying the Serra da Cangalha feature as an impact crater. The rimless northwestern part of the structure is the result of the impactor that struck that region. An impactor having a low-angle trajectory is consistent with the arcuate rather than circular form of the Serra da Cangalha impact structure. The NNE - SSW trending faults on the western flank of the structure close to the open quadrant in the northwest are interpreted to have resulted from extensional rebound and gravitational sliding of sediments in the central area. Series of concentric or arcuate bounding faults (CPRM 1972) have been observed on the outside margins of the structure and may represent detachment surfaces commonly found in association with crater impacts (Melosh 1989).

Fig. 3. *Publisher: Pls insert*

At the Serra da Cangalha impact site, the target rock consists of thick Paleozoic sedimentary rock. The crater structure is buried under about 1200 m of Devonian-Carboniferous sedimentary country rocks. These consist of the Pennsylvanian Piauí Formation (323 – 290 Ma), Mississippian Poti Formation (354 – 323 Ma) and the Upper Devonian-Mississippian Longá Formation (365 - 354 Ma). Outside the crater, and within the annular inner depression of the structure, these sequences reach a greater thickness than above the buried rim that surrounds this depression. Borehole data (CPRM, 1972) showed that the crater´s annular inner depression is filled with impact-derived materials (consisting of allochtonous monomict breccia) as well as minor impact melt bodies.

Fig. 4. *Publisher: Pls insert.*

Methods

The geophysical environmental impact assessment was performed using the Holsapple and Schmidt, (1982) Pi-group scaling relations contained in Melosh (1999). Also, the environmental pertubations caused by the impact of ECO in Serra da Cangalha region was studied using the various relations proposed in Toon *et al.* (1994). These two relations formed the framework within which environmental geophysical impact assessment of the Serra da Cangalha structures was studied. The most significant environmental perturbations were the direct and indirect result of ejected debris that rained through the atmosphere, as first postulated by Alvarez *et al.* (1980). This material was carried in a vapor-rich plume that rose through the atmosphere into space. Once above the atmosphere, it expanded on ballistic trajectories, enveloping the whole Earth as it fell back into the atmosphere. In addition to the dust in the vapor-rich plume of ejecta, several important gas species were entrapped.

In this study, an asteroid ECO was assumed to be the most probable impactor in the study area. The Holsapple and Schmidt (1982) Pi-group scaling law was used to calculate the size of the bolide, impact energy, angle and crater formation time and the transient and final crater diameters.

Results and Discussion

The results obtained from the modeling using the Pi-scaling relation are shown in Table 1. Impact-crater melange, at least 50 m thick, was likely formed by mass movement from the transient crater rim commencing after the first 10 to 20 sec. The results suggest 30° as the most favourable angle at which a 13 km final impact crater having a typical scenario like the Serra da Cangalha could have formed. The impactor is estimated to have been about 535 m in diameter. The results (Table 1) indicate that the asteroid that struck the study area released, on impact, energy equivalent to 1.8×10^4 Megatons of TNT (or 7.53×10^{26} erg). It was thus opened a 6.50 to 8.45 km-diameter transient crater within approximately 16 sec. It is noted that such sudden energy release is well below the nominal threshold for a global disaster. That threshold was estimated to be 3×10^5 Megatons of TNT (or 8.4×10^{27} erg) by Toon *et al´*s (1994) calculations. However, it is within the range that Morrison *et al.* (1994) describe as subglobal disasters. Most of the energy of impact is created by the conversion of hypervelocity into excavation of target materials.

To put the energy released at Serra da Cangalha in perspective and answer the question of the effect that the impactor had when it struck the study area required the use of Morrison *et al´*s (1994) formular. The formular relates average number of fatalities (N) with the impact's megaton yield (Y): $N = 10^3 Y^{0.666}$. With Y value of 1.8×10^4, the number of fatalities is 682,356. According to Morrison *et al,.* (1994), the area of forest devastation and destruction of buildings is given approximately by $A = 10^4 Y^{0.666}$, where A is the devastated area in hectares and Y is the yield in MT equivalent of TNT. On a vegetated plain, both atmospheric peak-overpressure wave and infrared flash-burn combustion due to impact would have devastated a region estimated to have comprised 6.82×10^6 hectares (or 2.63×10^4 mi^2) in the Serra da Cangalha (where $Y = 1.8 \times 10^4$). The calculation of the land devastation effect and the environmental impact the meteorite (ECO) probably had in the State of Tocantins in Brazil where the Serra da Cangalha is located, are explained as follows: The State of Tocantins has a land area of 2.87×10^7 hectares (or 1.1×10^5 mi^2). The meteorite would thus have destroyed 24% of the land-mass of the State of Tocantins. The approximate economic loss from impacts below global threshold values is computed by the formula: $V_\$ = 6\ [\ln (D_{max}/50)]$, where D_{max} is the maximum estimated fatalities (same as larger N previously computed) and $V_\$$ is economic loss in millions of dollars (Morrison *et al.*, 1994). Using the foregoing formula, an economic loss suffered from an impact like Serra da Cangalha is estimated as \$57.1 million if such an impact had happened in recent times.

Table 1. Results showing the Pi-Scaling Relation at Serra da Cangalha impact site

Impact	Impactor	Transient	Final

angle	Energy (MT)	crater diameter (km)	crater diameter (km)
90°	1.8 x 10^4	8.42	17.10
45°	1.8 x 10^4	7.50	14.90
40°	1.8 x 10^4	7.27	14.30
35°	1.8 x 10^4	7.00	13.70
30°	1.8 x 10^4	6.68	13.00
25°	1.8 x 10^4	6.32	12.20
20°	1.8 x 10^4	5.89	11.20
15°	1.8 x 10^4	5.37	10.00
10°	1.8 x 10^4	4.70	8.57
5°	1.8 x 10^4	3.73	6.54

As with nuclear weapons, maximum damage is inflicted by a blast wave generated not on the ground, but rather at a critical altitude (h_o) which equals 2.3($E^{0.333}$) km, where E is explosion energy in MT (Toon *et al.*, 1994). We obtain a blast wave generated at a critical altitude, h_o equal to 47.7 km. Impact blast waves have an abrupt pressure pulse followed immediately by a substantial wind (Toon *et al.*, 1994). Also, peak over-pressure, defined as the difference between ambient pressure and pressure of the shock front, characterizes shock waves. Key peak overpressure, for a ground impact occurs in an area having a maximum radius equal to 5.08($E^{0.333}$) km, where E is the adjusted impact energy in Megatons of TNT. E is adjusted according to E = qY, where q is an empirically determined constant, (0.5), and Y the kinetic energy yield in MT (Toon *et al.*, 1994). At Serra da Cangalha, a ground impact would have set up an atmospheric blast wave that delivered key peak pressure at a maximum radius (r) of 105 km. The Toon *et al.*, (1994) equation for maximum radius (r) of key peak-pressure contour after an atmospheric detonation at altitude h (in km) is: $r = [2.09h - 0.449h^2(E^{-0.333}) + 5.08E^{0.333}]$. For Serra da Cangalha, impactor detonation with maximum adjusted yield (E) equal to 9000 MT and at critical altitude, h_o equal to 47.7 km, the maximum radius of key peak pressure would have been 156 km. At Serra da Cangalha, intra-asteroid shock-wave traverse time was 1.38×10^{-3} seconds.

To estimate the surface seismic effect of the Serra da Cangalha impact, we used the magnitude M_s in the Gutenberg-Richter scale formulation of Kanamori and Anderson (1975). This is given as $\log E_s = 4.8 + 1.5\ M_s$, where E_s is approximately 0.05 of the kinetic energy of the explosion (~7.53×10^{19} Joules). Thus, an earthquake surface-wave magnitude (M_s), a rough proxy for Richter magnitude, would have been ≈ 9.2. We infer that substantial damage must have occurred in the Serra da Cangalha region after the impact. This is comparable to the damage that occurred at the 1906 (San Francisco), 1964 (southern Alaska), and 1985 (Mexico City) earthquakes. For example, the 19 September 1985 Michoacán (Mexico) earthquake ($M \geq 8.1$) was the most severe natural disaster in Mexico's seismic history. It caused over 10,000 deaths in Mexico City and left an estimated 250,000 homeless (Astiz *et al.* 1987; Bolt 1993). A study by Melosh (1989) showed that the destructive effects of impact-generated seismic waves are not expected to be as severe as those of an earthquake of the same magnitude because an impact impact generated generates mostly P-waves, whereas an earthquake generates more destructive S-waves. A rule of thumb that he developed confirm that an impact-generated seismic disturbance is equal in destructiveness to an earthquake one magnitude less. That is the basis for our comparison. Moreover, Adepelumi (2003) employing 3D magnetotelluric modeling discovered a considerable reduction in the resistivity of the rock formations in the upper crust of the crater region. Similar observations were made by Masero *et al.*, (1997) for the Araguainha crater (Brazil), Zhang *et al.,* (1988) for the Siljan impact region (Sweden) and Cortes *et al.*, (2002) for the Azuara structure (Spain). Also, Grieve (1984) and Amir *et al.*, (2002) showed that the shock waves created by the impact event would normally fracture the crust possibly down to the upper mantle levels.

The origin of brilliant light flash accompanying a hypervelocity impact was first discussed by King, (1976). He attributed this phenomenon to the ionization of gasses at the instant of impact, as well as the ejection of incandescent molten material from the interface between target and projectile. Visible spectrum radiation would cause immediate flooding of the atmosphere with white light. Infrared wavelengths cause a thermal radiation impulse with fire-ignition effects that are subject to a scaling-law function. According to Adushkin and Nemchinov (1994), the threshold of fire ignition based upon nuclear weapons testing is 10^9 erg/cm^2. Therefore the maximum burn area (A_f) and maximum burn radius (R_f) can be calculated assuming a clear day. The energy budget of Serra da Canglha region is unknown. However, assuming a 25 percent thermal-radiation budget of Serra da Canglha maximum kinetic-energy yield (i.e., 1.8 x 10^4 MT), E_r, the energy budgeted to thermal radiation was 4500 MT. Adushkin and Nemchinov (1994) scale $A_f = 30E_r$ km^2 and $R_f = 3E_r^{0.5}$ km was also employed. For Serra da Canglha on a clear day, maximum burn area, A_f, would have been 135,000 km^2 (or 1.35 x 10^7 hectares), and maximum burn radius, R_f, 201 km.

The global atmospheric effects of Serra da Cangalha impact is not minimal since the obtained Y value is 1.8 x 10^4 Megatonnes of TNT. Numerical simulations in Melosh (1989) suggest that 150 MT is the threshold for a phenomenon called atmospheric blowout. Here the expanding gaseous fireball bursts through the top of the earth's atmosphere. It then releases rising gases with entrained ballistic material including glassy blobs (tektites and micro-tektites), shocked minerals, and dust particles into the vacuum of space. Kring (2000) suggested eight global and local atmospheric effects of any impact event large enough to register a crater equal to or exceeding 6.5 km. These are (i) cooling and photosynthetic suppression due to atmospheric dust loading, wafted soot from large-scale fires, shock pressure-generated nitrous-oxide, and target-generated SO_2; (ii) large-scale fires and associated atmospheric injection of pyrotoxins; (iii) acid rain from pollution by burning, nitrous-oxide generation, and SO_2 injections; (iv) ozone loss due to nitrous-oxide generation; (v) mechanical pressure effects due to shock waves; (vi) destruction and drowning due to tsunami; (vii) global warming due to H_2O and CO_2 injections; (8) and water, food, and soil poisoning due to heavy-metal dispersion (Toon *et al.,* 1994). Since the Serra da Cangalha impact structure is 13 km in diameter, it is concluded that the area would have undergone all these effects after impact as it is a typical terrestrial crater.

Impact melt is generally interpreted as a product of waste heat created by shock pressures exceeding 50 - 60 GPa (Engelhardt and Stöffler, 1968; O’Keefe and Ahrens, 1977). Also, the amount of heat produced and the resulting amount of melt vary roughly as a function of impact energy or crater diameter (O'Keefe and Ahrens, 1994). As impact angles decrease (referenced to the horizontal), peak shock pressures also decrease (Gault and Wedekind 1978; Schultz and Anderson, 1996). Using the planar impact approximation developed by Collins *et al.*, (2002) and considering a 25º to 30º impact angle, an assumed 25 km/s collision at the Serra da Cangalha region would result in a peak shock pressure of approximately 47 GPa generated by the passage of the shock wave at the impact contact zone. The peak shock pressure obtained by the model is well below the levels necessary for melting. We thus envisage low volume of melt developments in the Serra da Cangalha region.

Pierazzo and Melosh (2000) found that the volume of impact melt decreases by at most 20% for impacts from 90° down to 45°. Below 45°, the amount of melt in the target decreases rapidly with impact angle. The low impact angle obtained might also account for the low volume of melts that occurred in this region. The result of the most probable impact angle of 25° to 30° here deduced for the Serra da Cangalha region in relation to the extremely small volume of melt reported by CPRM (1972) leads to the obtained impact angle. This result is consistent with the suggestions of Pierazzo and Melosh (2000) that a low melt volume is expected for such an oblique angle impact. Kieffer and Simonds (1980) and Grieve and Cintala (1992) showed that the volume of melts found in craters impacting sedimentary targets is about two orders of magnitude less than for crystalline targets. This has been attributed to the formation and expansion of large quantities of sediment-derived H_2O and CO_2 that resulted in wide dispersion of the shock melted sedimentary rocks (Kieffer and Simonds, 1980). Manson and Lockne impact structures formed in environment similar to that of Serra da Cangalha show no defined melt sheets. Koeberl and Anderson (1996) and Sturkell and Ormo (1998) suggested that the very low melt volume found in this region is probably due to the occurrence there of the thick sedimentary sequence. Another reason can explain the low volume melts found in the study area. Situated within the Parnaiba Basin of northeast Brazil is a sedimentary sequence up to 3 km thick (Góes and Feijó, 1994; Melo *et al.* 1998). Such a thick sedimentary sequence at the impact site might have contributed to dispersal of the impact melt shortly after impact.

Conclusions

The results obtained from the geodynamic modeling of the Serra da Cangalha impact region show several facts. The first is that a small meteorite having a diameter of approximately 535 m and travelling at an impact velocity of 25 km/sec can release large quantity of energy that is capable of causing substantial damage to the environment on impacting the ground. Secondly, the Pi-scaling of Holsapple and Schmidt (1982) indicates 30º as the most favourable angle at which a 13 km final impact crater having a typical Serra da Cangalha scenario could have formed. Moreover, the impact energy (1.8×10^4 MT equivalents of TNT or 7.53×10^{26} erg) released is well below the nominal threshold for a global disaster estimated to be 3×10^5 MT or 8.4×10^{27} erg (Toon *et al.*, 1994). However, it is within the range that Morrison *et al.* (1994) described as subglobal disasters. More importantly, these results are useful in quantitatively understanding impact cratering. They also provide a better qualitative understanding of the processes involved. For Serra da Canglha on a clear day, maximum burn area, A_f, would have been 135,000 km^2 (or 1.35×10^7 hectares), and maximum burn radius, R_f, 201 km. The economic loss resulting from the impact would have been \$57.1 million if such an impact had happened in recent times while the fatality would have been 682,356 people. From the obtained energy of impact equivalent (1.8×10^4 Megatons of TNT), it is obvious that the global atmospheric effects of Serra da Cangalha impact could not have been minimal. Numerical simulations shown in Melosh (1989) suggest that 150 MT is the threshold for the atmospheric blowout phenomenon. The results of our environmental geophysical impact assessment studies of the Serra da Cangalha impact, suggest that the event had a devastating effect on the local ecosystem and its biota.

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