Earth and Planetary Science Letters 408 (2014) 285–295

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Liquefaction of sedimentary rocks during impact crater development

J.P. Hippertt [a], C. Lana [a,*], R.F. Weinberg [b], E. Tohver [c], M. Schmieder [c], R. Scholz [a], L. Gonçalves [a], J.F. Hippertt [d]

[a] Departamento de Geologia, Universidade Federal de Ouro Preto, Ouro Preto, Minas Gerais, 35400-000, Brazil
[b] School of Earth, Atmosphere and Environment, P.O. Box 28E, Monash University, Melbourne, Victoria 3800, Australia
[c] School of Earth and Environment, University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia
[d] Instituto de Bio y Geociencias del NOA (IBIGEO), Universidad Nacional de Salta, CONICET, Av. Bolivia 5150, 4400 Salta, Argentina

ARTICLE INFO

Article history:
Received 7 December 2013
Received in revised form 5 September 2014
Accepted 29 September 2014
Available online 31 October 2014
Editor: C. Sotin

Keywords:
impacts
liquefaction
meteorite
Araguainha
sandstone
microbrecciation

ABSTRACT

Impact crater development on every planetary body requires catastrophic movement of large volumes of crustal rocks. The process produces well-known features such as brecciation and frictional melting, but a mechanism that explains how rocks accommodate the strain during the cratering flow remains unclear. Here, we investigate target rocks from the Araguainha impact crater (central Brazil) that typify what happens to a consolidated, fluid-saturated sedimentary rock at ∼2 km below the surface prior to the impact event. Sandstone units record a pattern of chaotic large-scale folds and pervasive microscopic (grain-to-grain) brecciation that result from rock strength degradation triggered by the impact. Field mapping and extensive textural observations indicate that these sandstones experienced initial microstructural damage from the shock wave and that this process may have weakened grain-to-grain bonds and started the process of pervasive microbrecciation. Accompanying heating and decompression lead to vaporization and expansion of fluids in the sandstone pores, magnifying the process of brecciation by effectively liquefying the rock mass and allowing for chaotic folding (at a range of scales up to blocks 100 m in length) in the central uplift. This is a vaporization-assisted microbrecciation, and it may have inhibited the formation of pseudotachylites, because energy was dissipated by pervasive microcracking, vaporization of pore fluids, and large scale chaotic folding, rather than localized displacement on brittle faults and frictional heating. We suggest that impact liquefaction of sedimentary rocks depends on whether the presence of pore-fluids and related micro-brecciation are sufficient to dissipate most of the impact energy.

1. Introduction

The formation of large impact craters involves highly energetic/destructive processes that include rock vaporization, melting and pseudotachylitic brecciation (Melosh, 1989; French, 1998; Ivanov et al., 2010). Shock waves emanating from the collision may reach speeds up to 10 km/s and set rocks into a flow motion to form a bowl-shaped transient cavity within seconds of the collision. For complex craters, the rock flow is highly effective in that the rim of the initial cavity expands kilometers away from the impact point and seconds later it collapses back to form the final crater structure (e.g., Lana et al., 2006). The nature of this process is unknown to any tectonic environment operative on Earth and, consequently, the mechanism that best explains the sudden reduction in rock strength remains obscure. One explanation is that violent acoustic vibrations could temporarily reduce the internal frictional strength of the rocks, allowing them to behave like fluids (Melosh, 1979; Melosh and Ivanov, 1999). This model is convenient because liquefied debris has an effective viscosity sufficiently low to permit collapse within the required time-scale. Other physical models propose that rocks lose internal cohesion through thermal softening due to extreme temperatures released upon impact (O'Keefe and Ahrens, 1993), but direct evidence for these theoretical models have not been fully documented in nature. While there are many studies of the characteristic effects of shock deformation on target rocks, the phenomenon that causes loss of cohesion in target rocks around large impact structures has not been fully documented. Here we show that the structural integrity of fluid-saturated sedimentary rocks is destroyed at grain scale by shock damage and pore-fluid expansion during the impact.

Large-scale "ductile" fold structures are observed in and around central uplifts of a number of craters including the Spider and Lawn Hill craters in Australia, the Vredefort Dome in South Africa

* Corresponding author. Tel.: +55 31 98483538; fax: +55 31 35591606.
E-mail address: cristianodeclana@gmail.com (C. Lana).

http://dx.doi.org/10.1016/j.epsl.2014.09.045
0012-821X/

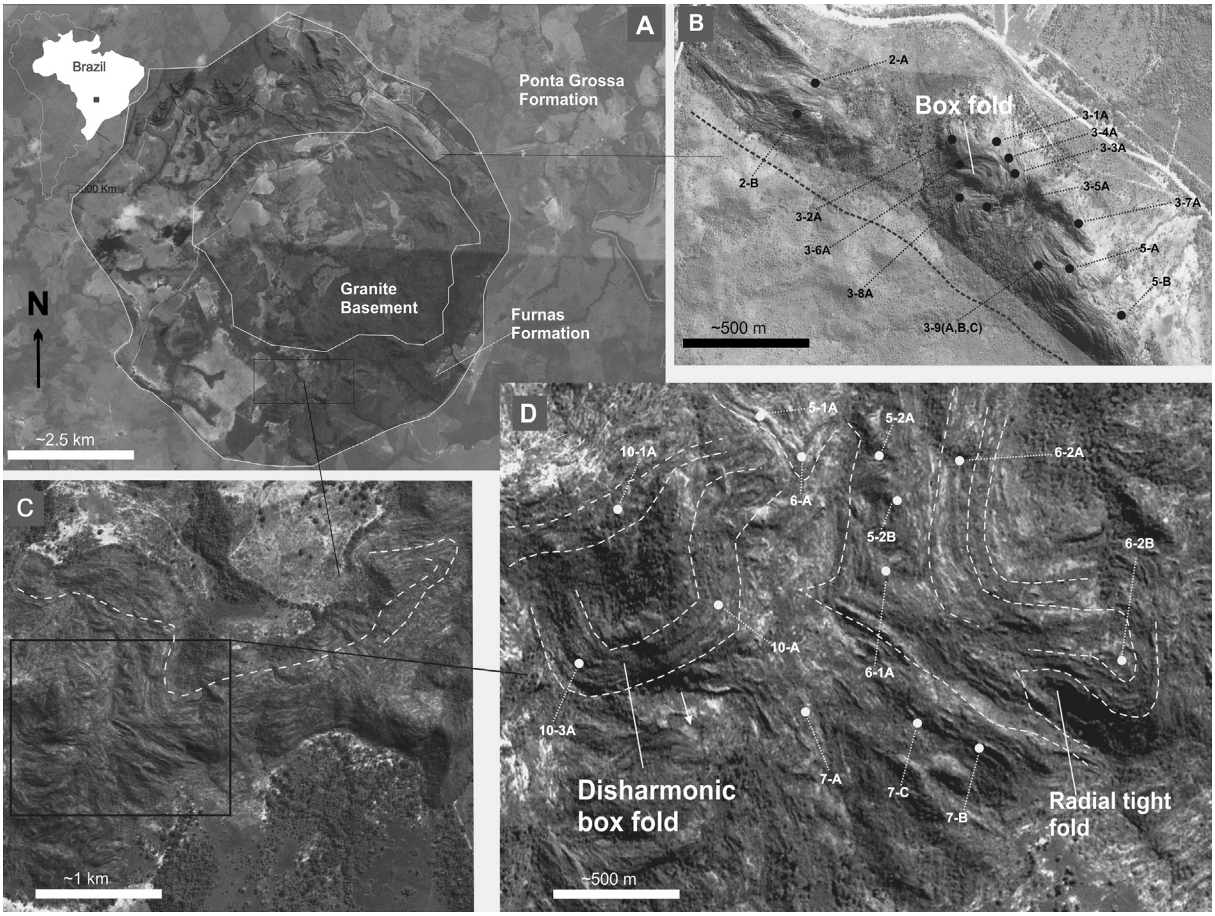

Fig. 1. A: Satellite image of the uplift with the distributions of the different formations marked (the granite core and surrounding Furnas and Ponta Grossa Formations). B: Enlarged image of the northeastern ridge of the central uplift in A. C: Aerial photograph of the southeastern ridge. White dashed line highlights the contorted nature of the bedding at the granite/sandstone contact. D: Enlarged image of southern ridge, depicting km-scale fold geometries in the Furnas Formation. White dashed lines mark the trend of bedding. The numbers are sample localities.

and the Araguainha structure in central Brazil (Lana et al., 2003a, 2004, 2006, 2008; Abels, 2005; Wieland et al., 2005; Salisbury et al., 2008; Tohver et al., 2013). These folds are the best expression of extreme compressional strain recorded in central uplifts of a number of complex craters in sedimentary and mixed (sedimentary+crystalline) target rocks (e.g., Lana et al., 2003a, 2006; Wieland et al., 2005). Their contorted nature seems to require a prodigious change in bulk-rock strength that suggests either ductile or fluid-like behavior. In addition, folded sedimentary strata in and around central uplifts seem to be devoid of pseudotachylite. Pseudotachylites are more commonly described in crystalline rocks of large impact structures (e.g., the Vredefort Dome) whereby the deformation is thought to occur through intense fracturing/faulting and frictional shearing (Melosh, 2005; Spray, 1995, 2010; Lana et al., 2003b, 2004).

In this paper, we focus on the highly contorted sedimentary strata from the 10–12 km-wide central uplift of the 254.7±2.5 Ma Araguainha impact structure (Tohver et al., 2012) in central Brazil (Fig. 1A). The Araguainha central uplift comprises a 5 km-wide granitic core surrounded by a collar of upturned to overturned strata of the Furnas and Passa Dois Formations (e.g., Lana et al., 2007, 2008). The highest intensity of impact-related folding is in the older stratigraphic units (inner collar strata) that have been thickened by a factor of 3 to 5 (Lana et al., 2006, 2008). Thickening is particularly evident for the Devonian sandstone unit of the central uplift (Furnas Formation), which is exceptionally thick to the north, west, and southwest sectors of the core–collar contact (Figs. 1A–D). On the scale of the crater, rocks of the Furnas Formation comprise 400 m to 800 m wide, fault-bounded blocks of highly folded strata (e.g., Fig. 1B). The blocks themselves are marked by highly contorted fold structures (Figs. 1B–D) and represent an excellent natural laboratory to investigate large-scale flow of target rocks during impact events.

2. Background

The Araguainha structure is located in the northern margin of the Paraná Basin (Lana et al., 2006, 2007, 2008). It is morphologically marked by a 10–12 km diameter central uplift surrounded by a 15–20 km wide annular trough, with two concentric rings and the crater rim (Lana et al., 2007). The central uplift is divided into a 2 km-thick collar of Devonian to Carboniferous clastic sedimentary rocks of the Paraná Basin (Furnas and Ponta Grossa Formations) and a 4 km-wide core of late Cambrian granitic basement (Figs. 1A–D) (Engelhardt et al., 1992; Tohver et al., 2012, 2013). The annular trough exposes Devonian pelites/sandstones of the Ponta Grossa Formation and Carboniferous red sandstones/conglomerates of the Aquidauana Formation.

Elsewhere in the Paraná basin, the Furnas sandstones are known as flat-lying, predominantly undeformed, medium- to coarse-grained, quartzarenite to subarkose sandstones, with 80–90% quartz, 2–10% feldspars and minor accessory minerals. Oil- and gas-related studies show that the sandstone porosity ranges from 2 to 15% across the Furnas Formation. Pore connectivity may be limited due to replacement of feldspars and diagenetic precipitation of kaolinite or illite (De Ros, 1998; Melo and Giannini, 2007).