**THERMAL AND DYNAMIC CONSEQUENCES OF IMPACT – LESSONS FROM LARGE IMPACT STRUCTURES.** Roger L. Gibson and W. Uwe Reimold, Impact Cratering Research Group, School of Geosciences, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa (E-mail: 065rlg@cosmos.wits.ac.za, reimoldw@geosciences.wits.ac.za).

**Introduction:** In the early years following the recognition of meteorite impact cratering as an important geological process within the Solar System, impact researchers were largely confined to inferring cratering mechanics from studies of surface crater morphologies and small-scale experiments. With the advent of sophisticated computer-based numerical simulations and high-resolution geophysics, however, researchers have begun to explore more fully the detailed 3-D structure of craters and the processes that give rise to them. This paper examines some of the issues raised by the model simulations from the perspective of the field evidence presented in impact structures, with particular reference to the Vredefort structure in South Africa.

**Reality vs simulation:** Impact is a short-term catastrophic process driven by the transfer of the kinetic energy of a hypervelocity projectile into a target. At a first-order approximation, the cratering process varies as a function of energy released by the impact – small impacts create simple craters whereas larger events create complex craters with central uplifts, peak rings or multiple rings. Projectiles of varying sizes, densities and velocities can effectively release similar amounts of energy and, thus, create similar structures. Additional levels of complexity can be added by varying, inter alia, the shape of the impactor, the angle of impact, and the structure and composition of the target. To a large extent, numerical simulations have allowed researchers to experiment with a wide range of input parameters and to examine the consequences of changing these variables (e.g. [1], [2]). The question remaining, however, is whether direct observation of impact structures in the field and laboratory-based experimental work can facilitate further refinement of such simulations.

**The Vredefort impact structure:** The 2.02 Ga Vredefort impact structure in South Africa is the world's oldest impact structure. It may lay claim to being the largest as well, however, substantial erosion (by between 7 and 10 km) has obliterated the original crater rim and impact breccias. Like the similarly large 1.85 Ga Sudbury structure, Vredefort has attracted the attention of numerical modelers (e.g. [3], [4]) in part because the high levels of erosion require indirect estimation of the size of the respective impact events and craters. In the Vredefort structure, the root zone of the central uplift – the ~90-km-wide Vredefort dome – is the best-preserved part, although impact-related structural and hydrothermal effects are evident up to radial distances of at least 100 km from the center, and possibly further afield as well. Shock effects (shatter cones, planar deformation features, high pressure quartz polymorphs and textures suggestive of diaplectic glass and mineral melt formation) are confined to the dome, and display a distribution consistent with a broad increase in maximum shock pressure radially inwards ([5], [6]). A similar broad increase in the grade of shock-induced thermal metamorphism is observed towards the center of the dome ([6]-[8]). In addition, dykes of impact melt and voluminous pseudotachylitic breccias are present in the rocks. Therriault et al. [9] estimated an original crater diameter of 270 to 300 km based on the distribution of the shock features. Henkel and Reimold [10] obtained a similar estimate from geophysical modeling. Numerical simulations by Turtle and Pierazzo [4, 11], however, have suggested a diameter as small as 120-160 km. These scaling simulations used the distribution of common shock effects such as PDFs in quartz, and the distribution of post-shock isotherms, respectively, as a basis for reconstructing the impact crater. Clearly, such a wide discrepancy requires further scrutiny. A critique of the modeling parameters and assumptions is beyond the scope of this paper. Instead, we wish to focus on the geological evidence within impact structures such as Vredefort that can assist in understanding the cratering process.

**The problem with impact structures:** The fundamental problem with impact structures is that their large-scale order and symmetry disguises the chaotic nature of their constituent features at smaller scales. The heterogeneous nature of shock wave interaction with rocks at the grain scale has long been known from experimental and field studies, yet the principal aim of integrating observational data from partially eroded structures such as Vredefort and Sudbury with simulation results is to obtain a match between the large-scale morphology and the spatial distribution of peak shock isobars and post-shock isotherms, on the one side, and the model results on the other. Model predictions for complex impact structures (e.g., [3], [12]) are that the shock effects are largely confined to the central uplift and that the radial inward movements that accompany central uplift formation modify the original hemispherical pattern of shock isobars into an elongate bulbous shape with a vertical long axis. As post-shock temperatures are directly proportional to the magnitude of the shock, they will display a similar elongate bulbous pattern, enhanced by interaction between the shock heating and the heat already present in the rocks due to the pre-impact geotherm [3]. At the large scale, results from the Vredefort dome have confirmed the simulation predictions. In fact, Melosh and Ivanov's [12] and Ivanov and Deutsch's [3] results were instrumental in directing geological investigations to the central parts of the dome where the models predicted shock pressures as high as 60 GPa and post-shock temperatures in excess of 1000 °C. Whereas a previous study based on quartz PDFs in the dome by Grieve et al. [13] had been unable to confirm shock pressures of more than 10-15 GPa in these rocks, but had speculated that pressures may have been as high as 25 GPa, these studies confirmed widespread shock metamorphism of feldspars and hydrous ferromagnesian silicates at pressures in excess of 30 GPa and possibly as high as 50 GPa ([5], [6]), and post-shock temperatures of between 1000 and 1350 °C ([6], [8]). These results confirmed Grieve et al.'s [13] original contention that post-shock annealing in the core of the dome had selectively annealed PDFs, rendering the pressure estimation technique useless.

Whilst the modeling predictions and direct observations concur on the broad scale, it is important to note that Ivanov and Deutsch's [3] models are for a 200-250 km diameter structure whereas [4, 11] maintain that they have achieved good agreement with a 120-160 km diameter structure. Apart from the heterogeneous grain-scale response to shock noted from experimental studies and many other impact structures, our group has recently established larger-scale heterogeneity in the formation of pseudotachylite veins in the dome that suggests that shock pressures varied by as much as a factor of 2-3 on scales ranging from millimeters to tens of meters. This finding, which is attributed to complex reflection and refraction of the impact shock wave through the target rocks as a result of pre-existing heterogeneities, not only makes the immediate geological context in which samples for "average" peak pressure calculations are chosen of extreme importance, but also questions whether such an "average" pressure approach is realistic. The link between peak shock pressure and post-shock temperature means that this also has implications for "average" post-shock isotherms. Gibson [8] has noted highly variable post-shock metamorphic textures in rocks in the dome and widespread evidence of disequilibrium that confirm localized thermal heterogeneity. A similar conclusion was drawn by [14] from the deep borehole through the Puchezh-Katunki central uplift.

A further issue with estimation of peak shock pressures in impact structures relates to the reliability of shock experimental data in constraining peak shock pressures in natural events. [15] have recently reviewed the problems in extrapolating data from experiments to natural rocks. They caution that, because of the short duration of experiments relative to natural events, and even the design of some of these experiments, threshold pressures for the formation of certain shock effects may be considerable overestimates. Such a breakdown in basic knowledge would have fundamental implications when attempting to use shock isobar patterns to refine numerical simulations.

In addition to the shock and thermal patterns generated by an impact cratering event, numerical simulations are attempting to explain how, on a gross scale, a well-ordered structure evolves. The Vredefort dome provides a rare opportunity to access large areas of rock from deep levels within the central uplift and to test whether models such as acoustic fluidization [12] or the block model [3] can explain central uplift formation. Preliminary data from the dome by our group have failed to identify pervasive block rotation, even where substantial pseudotachylitic melts are likely to have existed during central uplift formation. Most movements appear to reflect late-stage extensional collapse of the structure along faults at a variety of scales. Further from the central uplift, impact-related deformation involves brittle-ductile folding and extensional faulting on scales of tens of meters to kilometers that also appears to be related to the latter stages of central uplift formation.

**Summary:** At present, numerical modeling of large impact events provides a good first-order indication of the distribution of impact-related features. However, the low spatial resolution of the models (typically of the order of kilometers) hampers full integration of the modeling results with the observed geological features and does not allow the latter to be used to refine model parameters. More work is needed to understand the local-scale interaction between a shock wave and its target rocks to assist resolution of this problem.

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