thermal metamorphic features with the thermal model may improve our knowledge of the geologic process connected with impact cratering.

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THERMOBAROMETRIC STUDIES ON THE LEVACK GNEISSES—FOOTWALL ROCKS TO THE SUDBURY IGNEOUS COMPLEX. R. S. James[1], W. Peredery[2], and J. M. Sweeny[3], [1]Geology Department, Laurentian University, Sudbury, Ontario P3E 2C6, Canada, [2]INCO E.T.S., Copper Cliff, Ontario P0M 1N0, Canada, and [3]Falconbridge Limited (Exploration), Falconbridge, Ontario P0M 1S0, Canada.

Granulite and amphibolite facies gneisses and migmatites of the Levack Gneiss Complex occupy a zone up to 8 km wide around the northern part of the Sudbury Igneous Complex (SIC). Orthopyroxene- and garnet-bearing tonalitic and semipelitic assemblages of granulite facies grade occur within 3 km of the SIC together with lenses of mafic and pyroxenitic rock compositions normally represented by an amphibole ± cpx-rich assemblage; amphibolite facies assemblages dominate elsewhere in this terrain. These 2.711-Ga gneisses were intruded by (1) the Cartier Granite Batholith during late Archean to early Proterozoic time and (2) the SIC, at 1.85 Ga, which produced a contact aureole 1–1.5 km wide in which pyroxene hornfelses are common within 200–300 m of the contact.

A suite of 12 samples including both the opx-gt and amphibole-rich rock compositions have been studied; typical mineral compositions are OpxXmg = 0.55–0.60, GtXpyr = 0.12–0.32, PlgAn = 0.25–0.40 in the felsic and pelitic rocks; in the mafic gneisses Cpx has Xdi = 0.65–0.77 and Al-Tsch = 0.036–0.043 and amphibole compositions are Edenite with (Na+k) = 0.52–0.77 and Si(iv) = 6.4–6.9. Garnets in the semipelitic gneisses are variably replaced by a plg-bio assemblage. Thermobarometric calculations using a variety of barometers and thermometers reported in the literature suggest that the granulite facies assemblages formed at depths in the 21–28-km range (6–8 kbar). Textures and mineral chemistry in the garnet-bearing semipelitic rocks indicate that this terrain underwent a second metamorphic event during uplift to depths in the 5–11-km range (2–3 kbar) and at temperatures as low as 500°–550°C. This latter event is distinct from thermal recrystallization caused by the emplacement of the SIC; it probably represents metamorphism attributable to intrusion of the Cartier Granite Batholith. These data allow two interpretations for the crustal uplift of the Levack Gneisses: (1) The gneisses were tectonically uplifted prior to the Sudbury Event (due to intrusion of the Cartier Batholith); or (2) the gneisses were raised to epizonal levels as a result of meteorite impact at 1.85 Ga.

THE CRETACEOUS-TERTIARY (K/T) IMPACT: ONE OR MORE SOURCE CRATERS? Christian Koeberl, Institute of Geochemistry, University of Vienna, Dr.-Karl-Lueger-Ring 1, A-1010 Vienna, Austria.

The Cretaceous-Tertiary (K/T) boundary is marked by signs of a worldwide catastrophe, marking the demise of more than 50% of all living species. Ever since Alvarez et al. [1] found an enrichment of Ir and other siderophile elements in rocks marking the K/T boundary and interpreted it as the mark of a giant asteroid (or comet) impact, scientists have tried to understand the complexities of the K/T boundary event. The impact theory received a critical boost by the discovery of shocked minerals that have so far been found only in association with impact craters [2]. One of the problems of the K/T impact theory was, and still is, the lack of an adequate large crater that is close to the maximum abundance of shocked grains in K/T boundary sections, which was found to occur in sections in Northern America. The recent discovery of impact glasses from a K/T section in Haiti [3,4] has been crucial in establishing a connection with documented impact processes. The location of the impact-glass findings and the continental nature of detritus found in all K/T sections supports at least one impact site on or near the North American continent.

The Manson Impact Structure is the largest recognized in the United States, 35 km in diameter, and has a radiometric age indistinguishable from that of the Cretaceous-Tertiary (K/T) boundary [5]. Although the Manson structure may be too small, it may be considered at least one element of the events that led to the catastrophic loss of life and extinction of many species at that time. The Manson crater is completely covered by Quaternary glacial sedimentary deposits that are underlain by flat-lying carbonate sediments of Phanerozoic age as well as Proterozoic red clastic, metamorphic, volcanic, and plutonic rock sequences. In the 35-km-diameter zone that marks the extension of the crater the normal rock sequence is disturbed due to the impact, and at the center of the structure granitic basement rocks are present that have been uplifted from about 4 km depth. The Manson structure was established as an impact crater on the basis of its geomorphology (circular shape, central uplift), the presence of shock metamorphic features in minerals (e.g., multiple sets of planar lamellae in quartz), Bouguer gravity data, aeromagnetic and ground magnetic data, as well as seismic surveys [6].

Detailed studies of the geochemistry of Manson target rocks (approximated by the drill core samples of the Eischeid #1 well, near the crater) and impact melt rocks and breccia samples [7] have shown that it is possible to reproduce the chemistry of the melt rocks and breccias by mixing various basement rocks. The elemental abundances in the black glasses found at the Haiti K/T boundary section are not incompatible with the ranges observed for target rocks and some impact glasses found at the Manson crater [7]. Most elemental abundances measured in the black glasses are within the range for the Manson rocks, and elemental ratios such as Th/U and La/Th are also compatible. The Rb-Sr and Sm-Nd isotopic signatures of the black glass are compatible with a continental crustal source [3]. In principle, this would apply for Manson rocks, but no definite conclusion can be made as the isotopic characteristics of the Manson rocks are not yet known. The yellow glasses, on the other hand, may require a different source material, as no rocks with such high Sr or S content have been observed in sufficient quantities in the Manson target rock stratigraphy. However, the target rock stratigraphy at Eischeid indicates abundant carbonates. I suggest that a more definitive answer can be obtained in the near future, when the samples from the newly drilled cores at the Manson structure are analyzed in more detail. These cores are just now becoming available for studies.

A second candidate for the K/T boundary crater is the Chicxulub structure, which was first suggested to be an impact crater more than a decade ago. Only recently, geophysical studies and petrological (as well as limited chemical) analyses have indicated that this buried structure may in fact be of impact origin [8]. The impact origin was recently confirmed by the discovery of unambiguous evidence for shock metamorphism, e.g., shocked quartz and feldspar [9]. The stratigraphy of the crater and the exact succession and age of rocks are not entirely clear at this time, largely because the structure is now buried under about 1 km of Tertiary sediments, mainly limestone, and because of limited sample availability due to the destruction of core samples in a fire. The sedimentary sequence (composed mainly of carbonates and evaporites) overlies a basement at 3–6 km depth that is inferred to be composed of metamorphic rocks. If Chicxulub was formed by impact at a time at or before the end of the Cretaceous, the preimpact surface consisted largely of rocks for the carbonate-evaporite sedimentary sequence, probably releasing large quantities of CO_2 and SO_2 into the atmosphere.

Chicxulub contains abundant carbonate, limestone, and evaporite rocks, and the presence of andesitic rocks has been reported (which would make it a candidate for the source of the Haiti glasses), although it is not clear if the "andesite" is a real andesitic bedrock, or makes up the proposed melt sheet. There are some problems with Chicxulub being the source for the Haiti impact glasses (and therefore for parts of the claystones at some K/T boundaries). For this discussion, we need to review the origin of tektites and impact glasses. Rb-Sr and Sm-Nd isotopic systematics of tektites show that the source material was Precambrian crustal terrane (from Nd model ages), and that the sediments that were later melted to form tektites were weathered and deposited at (for the Australasian tektites, for example) about 167 Ma ago and probably comprised Jurassic sediments. Further evidence for a sedimentary precursor comes from the study of cosmogenic radionuclides. Pal et al. [10] first reported that the ^{10}Be content of Australasian tektites cannot have originated from direct cosmic ray irradiation in space or on Earth, but can only have been introduced from sediments that have absorbed ^{10}Be that was produced in the terrestrial atmosphere. This is an extremely important observation. The recent discovery of Glass and Wu [11], that impact debris is present in the same deep sea core layers as microtektites, gives further proof of an impact event leading to the production of tektites.

For Chicxulub, a major problem is the production of impact glasses (or "tektite-like" glasses), which originate, as I have just mentioned, from the surface layers of the target area. However, any "andesitic" rock or other basement rocks at Chicxulub were obviously covered by carbonates and evaporites of up to several kilometers thickness. We therefore cannot conclude, at least not with the data presently available, that Chicxulub is the most logical source for the Haiti glasses. Although the "andesite" present at Chicxulub is similar in composition to the black glasses [8], other rocks that will be mixed in upon impact have trace-element signatures that are not compatible with any glass composition. Another problem is the obvious lack of quartz-bearing rocks at Chicxulub, which poses problems for the explanation of the abundance of shocked quartz at almost all K/T boundaries. This has led some researchers [e.g., 12] to propose that two impacts, involving Chicxulub and Manson, might be responsible for the K/T event. In view of the preliminary nature of some data we refrain from speculating on such an origin. Other proposed impact locations, such as near Kara Crater, which was suggested by Russian scientists to be of K/T age, have not been confirmed. Precise Ar-Ar ages of Kara show that it is most probably too old to be associated with the K/T boundary, and it is also situated on the wrong side of the Earth, as it was inferred (see above) that the impact crater(s) are most likely near the North American continent. At present we can conclude that the Manson crater is the only confirmed crater of K/T age, but Chicxulub is becoming a strong contender; however, detailed geochemical, geochronological, and isotopic data are necessary to provide definitive evidence.

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TEKTITE ORIGIN BY HYPERVELOCITY ASTEROIDAL OR COMETARY IMPACT: THE QUEST FOR THE SOURCE CRATERS. Christian Koeberl, Institute of Geochemistry, University of Vienna, Dr.-Karl-Lueger-Ring 1, A-1010 Vienna, Austria.

Impact Origin of Tektites: Tektites are natural glasses that are chemically homogeneous, often spherically symmetrical objects several centimeters in size, and occur in four known strewn fields on the surface of the Earth: the North American, moldavite (or Central European), Ivory Coast, and Australasian strewn fields. Tektites found within such strewn fields are related to each other with respect to their petrological, physical, and chemical properties as well as their age. A theory of tektite origin needs to explain the similarity of tektites in respect to age and certain aspects of isotopic and chemical composition within one strewn field, as well as the variety of tektite materials present in each strewn field.

In addition to tektites on land, microtektites (which are generally less than 1 mm in diameter) have been found in deep-sea cores. Tektites are classified into three groups: (1) normal or splash-form tektites, (2) aerodynamically shaped tektites, and (3) Muọng Nong-type tektites (sometimes also called layered tektites). The aerodynamic ablation results from partial remelting of glass during atmospheric passage after it was ejected outside the terrestrial atmosphere and quenched from a hot liquid. Aerodynamically shaped tektites are known mainly from the Australasian strewn field where they occur as flanged-button australites. The shapes of splash-form tektites (spheres, droplets, teardrops, dumbbells, etc., or fragments thereof) are the result of the solidification of rotating liquids in the air or vacuum.

Mainly due to chemical studies, it is now commonly accepted that tektites are the product of melting and quenching of terrestrial rocks during hypervelocity impact on the Earth. The chemistry of tektites is in many respects identical to the composition of upper crustal material [1,2]. Trace elements are very useful for source rock comparisons: the ratios of, e.g., Ba/Rb, K/U, Th/Sm, Sm/Sc, Th/Sc, K vs. K/U in tektites are indistinguishable from upper crustal rocks. The chondrite-normalized REE patterns of tektites are very similar to shales or loess, and have the characteristic shape and total