BASICS OF IMPACT CRATERING & GEOLOGICAL, GEOPHYSICAL, GEOCHEMICAL & ENVIRONMENTAL STUDIES OF SOME IMPACT CRATERS OF THE EARTH

IAP 2008 12.091 Special Topics Course
January 8 – 22, 2008

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SESSION 2: January 10, 2008

COURSE OUTLINE

1. Introduction to Terrestrial Impact Cratering
2. Review of Some Major Research Studies of Terrestrial Impact Craters
3. Tools of Analysis
4. Impact Crater: Chesapeake Bay Well Logging and Geochemical Studies
5. Impact Cratering: Economic Potential and Environmental Effects
6. Conclusion

DETAILED COURSE WORK

The course work involves the following:

- January 8, 10, 15, 17, 22 10 AM to Noon
- 5 sessions each of 2 hours - 25%
- Study/work assignments – 4 - 20%
- Project

  Literature Survey &

  Writing a report - 30%
- Project Presentation - 25%
- Required percentage to pass this course is 95%
- Grading: P/F

On completion of this course

You will gain knowledge of

- Criteria for identification of terrestrial impact craters
- Evaluation of parameters such as size, impactor velocity, ….
- Research studies of age determination and correlation with events such as mass extinction,
- Economics of geological ore formation
- Effects of ejected deposits on the surrounding environment that creates an interest to pursue a career in medical geology.

SESSION 2

Review of
Some Major Research
Studies of
Terrestrial Impact Craters

SESSION 2 OBJECTIVES

Impact Crater Studies

1. Chicxulub
2. Mjolnir
3. Sudbury
4. Vredefort

INTRODUCTION

What are the topics of research studies?

- What are the satisfactory identification criteria?
- What type of crater – simple or complex?
- What is the size?
- What is the age?
- What is composition in and around the crater?
- What happened to the environment?
- What are the significant events correlated?
- …

All these comprise the research studies of several groups of different/multi disciplines.

INTRODUCTION …

Currently, more than 160 impact craters are identified on the Earth. New impact craters are getting identified; many research scientists are conducting studies like further developing detailed concepts of impact cratering and impact crater structures; the global and local effects, historical aspect of the earth, economic potential of the craters, numerical modeling of the impact cratering and impact hazard and so on. Well documented web sites are providing excellent references and images of most of the impact craters.

For this session, I selected 4 impact craters. My focus is to provide introduction and outline salient features of these craters.

The study assignments enable familiarity of the geological, geophysical, geochemical and environmental research studies conducted on these craters.

Chicxulub, Chesapeake Bay, Sudbury, Mjolnir, Vredefort Impact Craters Location, Size and Age

Crater Name	Chicxulub	Chesa -peake Bay	Sudbury	Mjølnir	Vredefort
Location	Yucatan, Mexico	Virginia, USA	Ontario, Canada	Barents Sea, Norway	South Africa
Latitude	N 21° 20'	N 37° 17'	N 46° 36',	N 73° 48'	S 27° 0'
Longi -tude	W 89° 30'	W 76° 1'	W 81° 11'	E 29° 40'	E 27° 30'
Diameter (km)	170	90	250	40	300
Age (My)	64.98 ± 0.05	35.5 ± 0.3	1850 ± 3	142.0 ± 2.6	2023 ± 4

Based on
http://www.unb.ca/passc/ImpactDatabase/essay.html

CHICXULUB IMPACT CRATER

Location	Yucatan, Mexico
Latitude	N 21° 20'
Longitude	W 89° 30'
Diameter (km)	170
Age (My)	64.98 ± 0.05

CHICXULUB IMPACT CRATER RESEARCH

- 1981 – recognition of the gravity and magnetic anomalies centered on the village of Chicxulub, at the tip of the Yucatan peninsula in Mexico, resemblance to those identified at large impact structures. - Penfield and Camargo.
- 1991 – proposition of the long sought KT crater lied buried under 1000 m of Cenozoic sediments at the tip fo the Yucatan peninsula - Hildebrand et al.
- 1992 -93 demonstration of the crater origin of the structure by geophysical and lithological studies and its KT age determination by radiometric dating . - Swisher et al. 1992; Sharpton et al. 1993.
- 1993 – multi-ring basin of impact crater – Sharpton et al.
- 1996 - markings of cenotes on Onshore crater rim, northwestern part of the crater is on Offshore the Yucatan peninsula. - Pope et al.
- 1997 - indication that the structure is a most likely a multi-ring basin with a diameter around 200 km by offshore seismic studies Morgan et al. (1997)
- 1997 – studies climate effects of the Chicxulub Cretaceous/Tertiary boundary impact – Pope et al.

CHICXULUB IMPACT CRATER RESEARCH …

- 1998 Hydrocode simulation of the Chicxulub impact event and the production of climatically active gases – Pierazzo et al.
- 1990s – Prominent satellite data and ground studies allowed most scientists to postulate the impact event responsible for mass extinction of more than 70 percent of Earth's living species 65 million years ago.
- 2003 - NASA's righ-resolution map from Shuttle Radar Topography Mission (SRTM).

  SRTM has provided the most strikingly visible evidence to date of a 180-kilometer (112-mile) wide, 900-meter (3,000-foot) deep impact crater .

CHICXULUB IMPACT CRATER RESEARCH …

- 2004 -2005 - 3D Modelling of Chicxulub crater - P. M. Vermeesch and J. V. Morgan (2004)

  C. W. Borst and G. L. Kinsland (2005)
- 2004 – Impactite studies of Chicxulub Structure Tuchscherer et al.
- 2007 - Chicxulub impact event and its environmental consequences at the Cretaceous-Tertiary boundary - D. A. Kring
- 2007 - Numerical modeling of impact-induced hydrothermal activity at the Chicxulub crater

  - O. Abramov and D. A. Kring

CHICXULUB IMPACT CRATER …

http://photojournal.jpl.nasa.gov/catalog/PIA03377

CHICXULUB IMPACT CRATER …

Original caption released with Image:

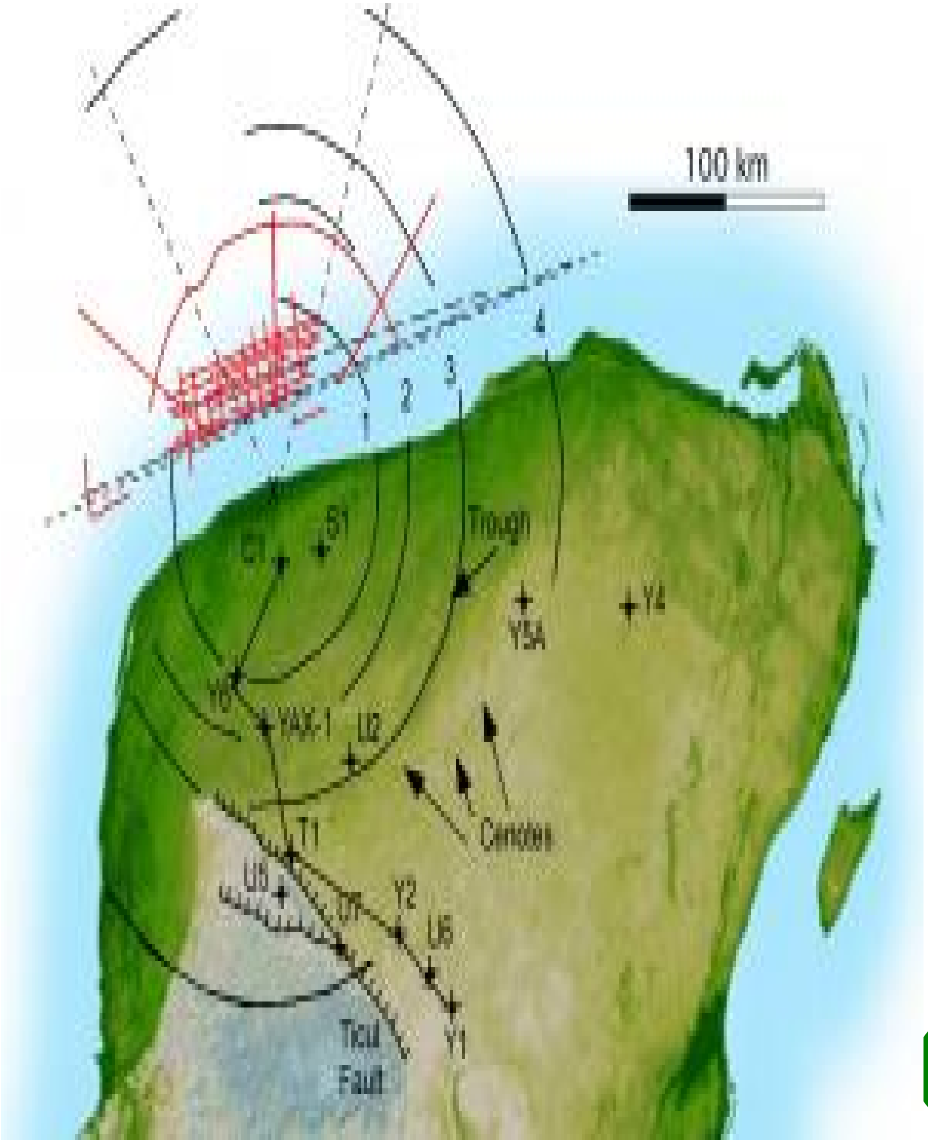
This shaded relief image of Mexico's Yucatan Peninsula show a subtle, but unmistakable, indication of the Chicxulub impact crater.

Most scientists now agree that this impact was the cause of the Cretatious-Tertiary Extinction, the event 65 million years ago that marked the sudden extinction of the dinosaurs as well as the majority of life then on Earth.

Ref: http://photojournal.jpl.nasa.gov/figures/PIA03379-fig1.jpg

CHICXULUB IMPACT CRATER …

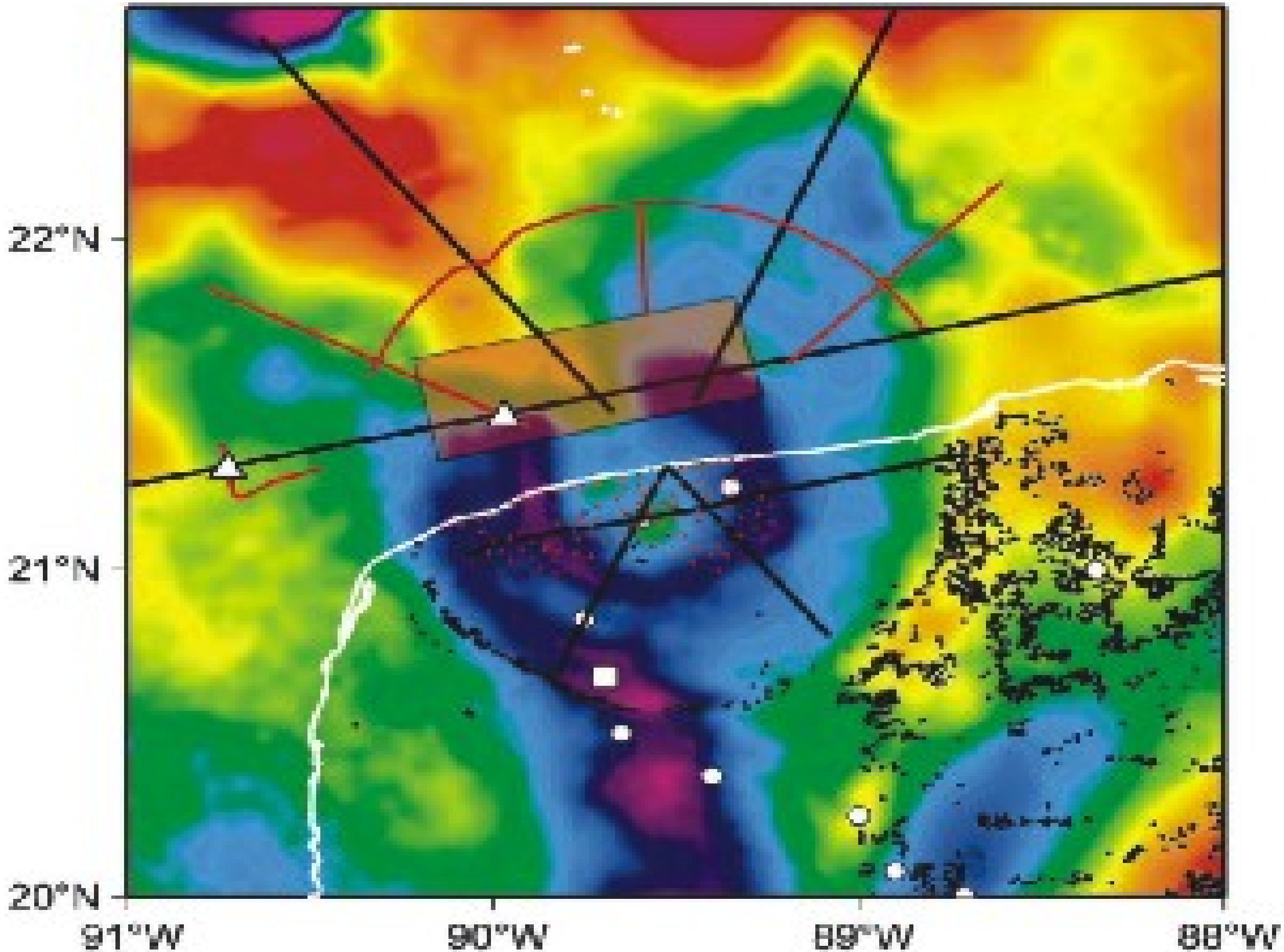
- Shaded relief of the Yucatan Peninsula generated by data from the Space Shuttle Radar Topography Mission.
- Image also illustrates the position of the Yaxopoil-1 (Yax-1) well and other subsurface drill cores, and crater rings based on gravity data (Sharpton et al., 1993).
- 2005 seismic lines are illustrated in red,
- Pre-2005 are indicated by dashed black lines.
- Radar image courtesy of NASA.



CHICXULUB IMPACT CRATER SOURCE CREDITS

Shuttle Radar Topography Mission (SRTM) aboard
Space Shuttle Endeavour (2000).
SRTM utilized the
Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR).
SRTM was designed to collect
3-D measurements of the Earth's surface.
200-foot mast, and additional C-band and X-band
antennas improved tracking and navigation devices.
The mission is a cooperative project of
NASA, DOD, NIMA
National Imagery and Mapping Agency (NIMA) of
U.S. German and Italian space agencies
http://www.jpl.nasa.gov/srtm/

CHICXULUB IMPACT CRATER …



Radar image courtesy of NASA.

CHICXULUB IMPACT CRATER …

The Yucatan plateau

- consists mostly limestone,
- is an area of very low relief
- elevations vary by less than few hundred meters

The computer-enhanced image is an exaggerated topography highlighting

- the semicircular trough,
- the darker green arcing line

at the upper left corner of the peninsula.

CHICXULUB IMPACT CRATER …

Scientists believe the impact was

- centered just off the coast in the Caribbean
- altered the subsurface rocks
- the overlying limestone sediments formed later
- erode very easily on the vicinity of the crater rim.

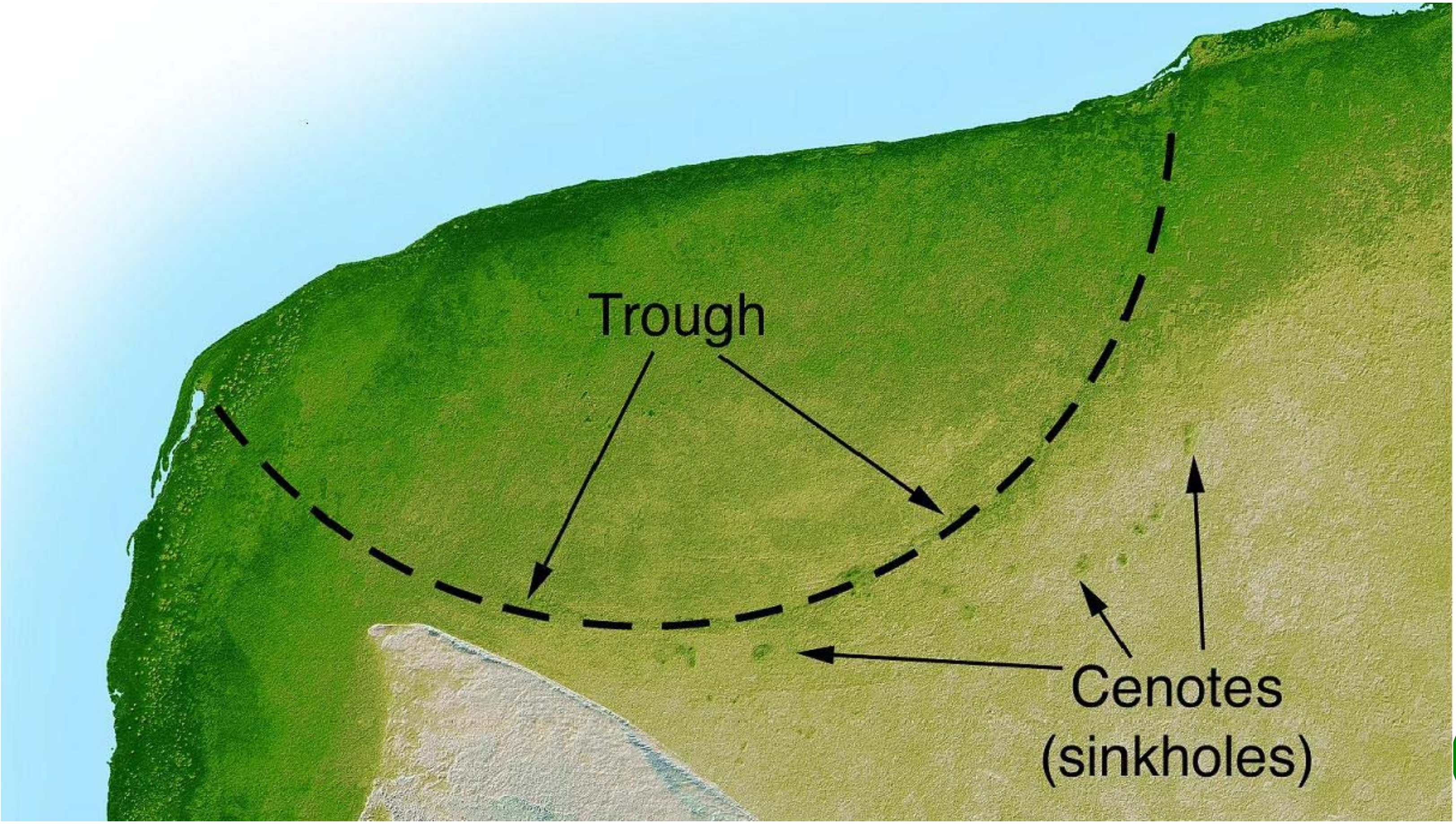
Formation of trough and cenotes:

- the trough as well as numerous sinkholes called cenotes are visible as small circular depressions
- the trough is about 3 to 5 meters deep and is about 5 km wide

CHICXULUB IMPACT CRATER …

- The North America and Yucatan Peninsula images created from the map are available on the JPL Planetary Photo journal

  http://photojournal.jpl.nasa.gov/figures/PIA03379-fig1.jpg



PICTURE CREDITS

- **Picture File Name:** PIA03379.jpg
- **Target Name:** Earth
- **Is a satellite of:** Sol (our sun)
- **Mission:** Shuttle Radar Topography Mission (SRTM)
- **Spacecraft:** Space Shuttle Endeavour
- **Instrument:** C-Band Interferometric Radar
- **Product Size:** 18001 samples x 11438 lines
- **Produced By:** JPL
- **Orientation**: North toward the top, Mercator projection
  Image Data: shaded and colored SRTM elevation model
  Original Data Resolution: SRTM 1 arcsecond (about 30 meters or 98 feet)
  Date Acquired: February 2000

CHICXULUB IMPACT CRATER …

Chicxulub impact played a major role in the Cretaceous-Tertiary (KT) boundary mass extinction event.

- Presence of strong iridium anamolies

  Example of Environmental effect
- Thin section of the uppermost Cretaceous layer shows abundant and diversified foraminifera
- Very basal Paleocene, fauna has been replaced by small opportunistic and undiversified organisms. Two faunas are separated by less than a cm of dark KT clay rich in ejecta material
- Image of A. Montanari can be viewed at

  http://we.vub.ac.be/~dglg/Web/Claeys/Web-Chix/ICDP-Chix/chixintro.html

CHICXULUB IMPACT CRATER …

Chicxulub impact ejecta

– evidence found in Belize and Cuba

- Chicxulub ejecta blanket in Yucatan and Belize composed of dolomite blocks ranging in size from a few mm to several decimeters - Pope et al. (1999)
- Upper Cretaceous to lower Paleogene section at Loma Capiro (central Cuba) provided new evidence for a Cretaceous-Paleogene boundary age for the Chicxulub impact. - Alegret et al. (2005)

CHICXULUB IMPACT CRATER …

- The ejecta plume of an impact crater consists of
  a highly dynamic mixture of vaporized and
  melted target rock and projectile material and
  solid rock debris.

  It forms from extreme starting conditions
  with pressures of several 100 GPa
  with temperatures of >10,000 °C in the first
  phase of the impact cratering process
- The ejecta plume
  accelerates in its early phase with a velocity of >5 km/s
  decelerates, and finally collapses.
  (Melosh, 1991; Pierazzo et al.,1998),
- Products of this collapse are suevite rocks on the terrestrial planets geologic recorders of this fundamental process (Kieffer and Simonds, 1980).

CHICXULUB IMPACT CRATER …

Exploration of the Chicxulub crater,Yucatán Peninsula will provide information on

- impact induced environmental perturbations
- the structure of large craters
- controlling groundwater flow in Yucatán state
- producing proximal deposits that produce hydrocarbons.

The Chicxulub study

- quantify the amount of CO_2, SOx and H_2O injected in the atmosphere,
- refine current climate models
- provide better understanding of the engendered perturbation of the global Earth System.

Chicxulub Impact Crater …

- **Stratigraphic and mineralogic studies of Cretaceous-Tertiary (K-T) boundary sections provide the information that the offshore oil-producing breccias and seals from oil fields in the Campeche marine platform are of K-T boundary age and probably formed due to the K-T impact event at Chicxulub.**

  \- Grajales-Nishimura et al (2000)

CHICXULUB IMPACT CRATER …

Seismic and aeromagnetic data indicate that crater-floor exhalative(cfe)

- deposits exist on the crater floor at potentially economic depths of ~1.1 km
- deposits may contain metallic sulfide deposits analogous to those found on the Sudbury crater floor
- a new type of exhalative sulfide deposit be recognized, the crafex category (crater-floor exhalative)

- Grajales-Nishimura et al (2000)

CHICXULUB IMPACT CRATER …

Chicxulub crater’s economic potential:

Estimated sulfide tonnages :

- **Sulfides might be produced by crystallizing / cooling Chicxulub melt volumes of 10,000 and 20,000 km^3**
  with estimated yield of 230 - 2,000 x 10^6 tonnes of sulfides.

- **An estimation of 50 sizeable mounds / deposits on Chicxulub’s crater floor yields average sizes of 4.5 to 40 x 10^6 tonnes.**
  A log normal distribution model prohects that the largest deposits equal or exceed 50 x 10^6 tonnes.

- **Predictions of hydrothermal halo (e.g. Mn, Fe, Ba, Ni, Re, Pd, Co, Cr, Cu, Zn, Pb, V, S and As) associated with the crafex deposits.**

  - Grajales-Nishimura et al (2000)

CHICXULUB IMPACT CRATER

- **The key question that remains is how the gigantic energy released affected**

  the atmosphere,

  the climate,

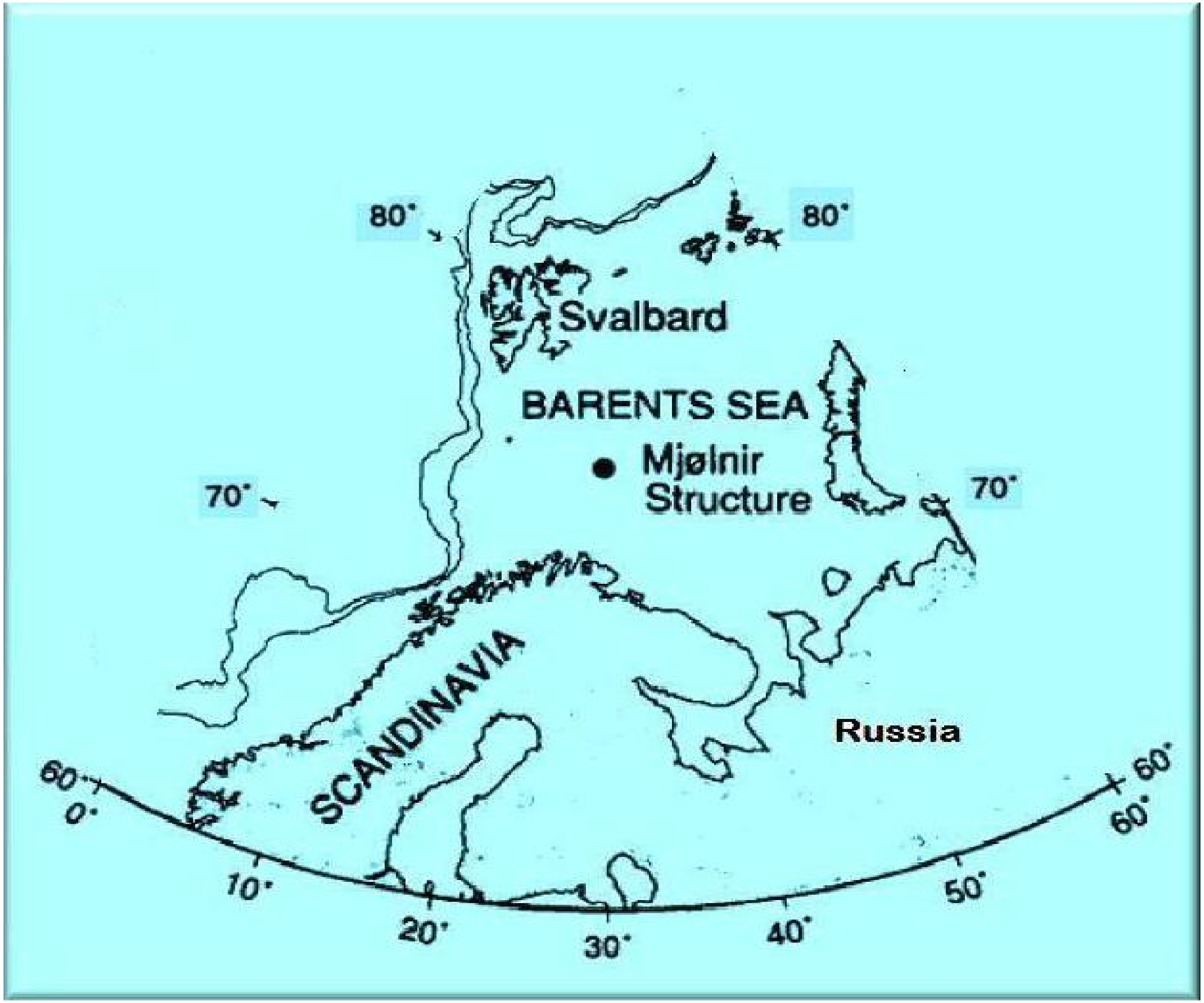
  the oceans and

  the organisms.

MJOLNIR IMPACT CRATER

Location	Barents Sea, Norway
Latitude	N 73° 48'
Longitude	E 29° 40'
Diameter (km)	40
Age (My)	142.0 ± 2.6

MJOLNIR IMPACT CRATER …



Based on image p. 291, Ref. Geology 21(1993)291-294.

MJLONIR CRATER INTRODUCTION

Mjlonir impact crater

- Well preserved submarine impact crater

  providing wealth of information about impact cratering event and effects in marine environment
- Search for hydrocarbon potential
- Numerical modeling studies
- Environmental effects

MJOLNIR IMPACT STRUCTURE

40 km in diameter

Age 142 Ma

Jurassic and Early Cretaceous period

Formed by an asteroid or comet 0.7-2.5 km in diameter

Shallow sea , > 5 km of sedimentary section

one of the well preserved terrestrial submarine craters

MJLONIR CRATER
MARINE TARGET IMPACT

Geological features are particular to craters formed at sea. The features are most likely a result of the influence of the target on the cratering process.

Marine-target craters form only if the target sea is shallow enough to absorb sufficient kinetic energy into the sea bed.

When the crater diameter is large compared to the water depth, the crater's appearance resembles the crater formed on land.

MJLONIR CRATER
MARINE TARGET IMPACT

Melosh (1989) divides the formation of an impact crater into three main stages:

- contact and compression,
- excavation,
- modification.

These stages grade into one another, however, can be crudely distinguished

MJLONIR CRATER
MARINE TARGET IMPACT

Differences in the geology and morphology between the impact craters formed on land and at sea are:

Craters formed in shallow water environment:

- at shallow target water depths, the resulting crater features resemble those of a land-target impact,
- in shallow marine environment, a weak rim wall may develop with high water pressure,
- collapse of such a wall may lead to an early intrusion of the open sea.

Craters formed in deeper water environment:

- are concentric,
- often lack melt sheets and rim walls,
- have deposits and radial gullies formed by the resurge of the sea
- impacts on the deep shelf are probably much more energetic than is suggested by the dimensions of the preserved crater.

MJLONIR CRATER
MARINE TARGET IMPACT …

- At greater target water depths, the resulting crater
  often lacks a melt sheet and a rim wall,
  is concentric,
  has a fining-up resurge sequence,
  has the outer parts cut by radial gullies
  that have been eroded by resurge.
- The concentric shape is most probably
  the result of the layered target,
  in combination with the higher position of
  the explosion in relation to
  the preserved part of the crater in the sea floor.
- Formation of the inner rim wall of the crater by uplift of the basement by breccia injections.
- Formation of the outer rim wall in the marine-target structure in the water mass.

MJOLNIR IMPACT CRATER …

Search for Hydrocarbons

- The hypervelocity impact contributes to the soot formation with possible initial distribution similar to that of the accompanying ejecta.
- The paleogeographic position impact site at the time of occurrence determined to be hundreds of km from the closest forest. Thus there would not be any ignition of wildfires on the surrounding environment.
- Thus, the soot particles must have originated from pyrolysis and combustion heating of the organic rich, partly volatile, dark clays of the sea bed (Hekkingen Formation).
- This heating should have occurred during shock wave propagation through the target sediments together with ignited sea bed before the return of the pre-impact sea level.
- Soot analysis of Barents sea core samples revealed concentrations in the range <1 ppm to 32,000 ppm.

MJOLNIR IMPACT CRATER

Core- log- seismic data integration for high-resolution seismic stratigraphy

Core-log-seismic data integration method is an interdisciplinary strategy, integrating core measurements,

- logging data
- seismic 2D or 3D mapping of reflecting regional geologic structure
- downhole logging

  (continuous information in intermediate scale surrounding of the borehole),
- core data physical properties and
- core data geologic age information

SUDBURY IMPACT CRATER

Location	Ontario, Canada
Latitude	N 46° 36',
Longitude	W 81° 11'
Diameter (km)	250
Age (My)	1850 ± 3

SUDBURY IMPACT CRATER INTRODUCTION

- There are many studies (for more than five decades) on Sudbury impact structure and Sudbury igneous complex. There are more than 400 references listed to date in the Sudbury impact crater database.
- I will be outlining the salient features of the crater. Sudbury impact is notorious for generating the vast economic wealth of Ni-Fe ores and Platinum Group Elements (PGE).

SUDBURY IMPACT CRATER

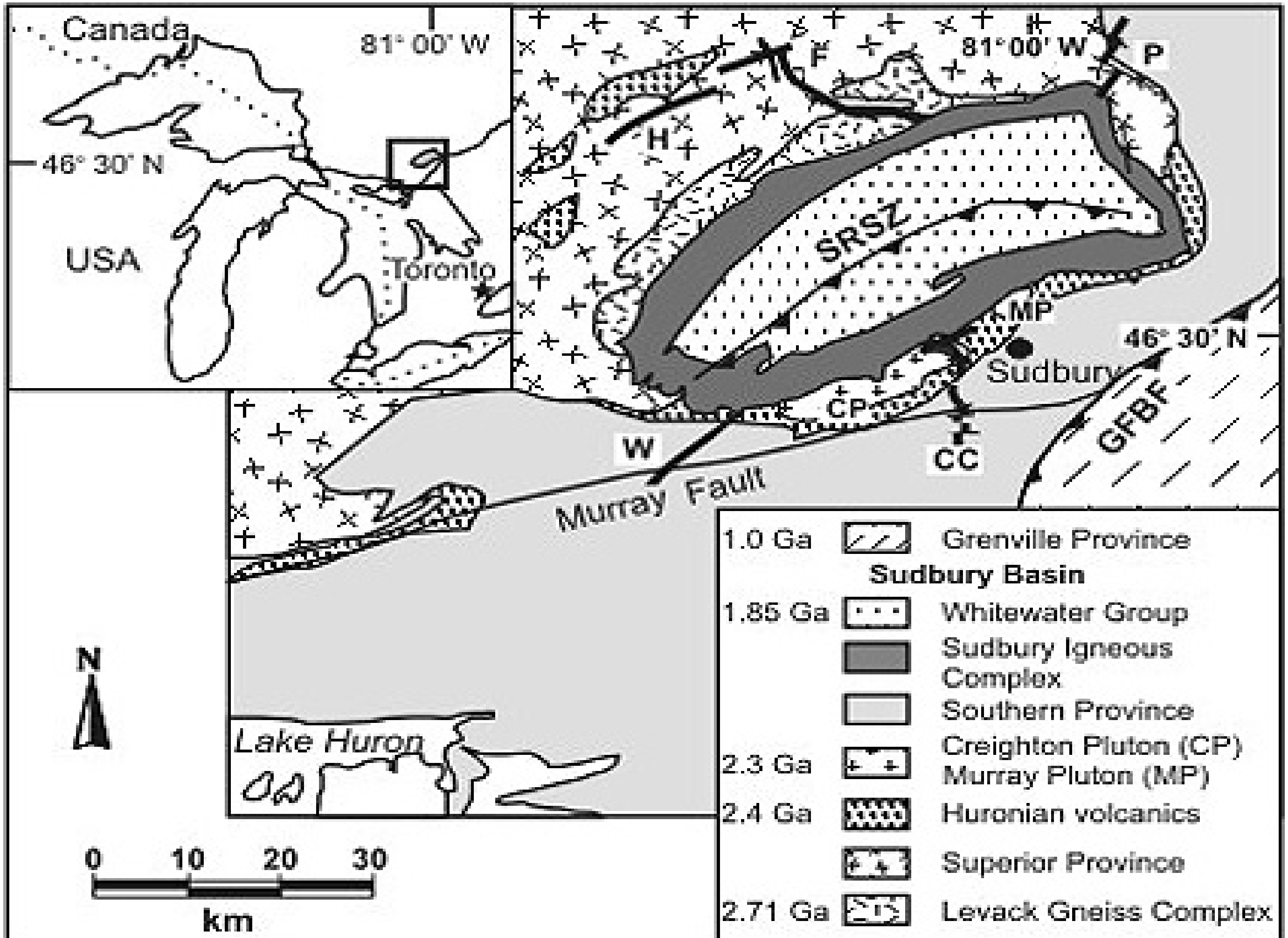


Photo image courtesy of NASA

http://rst.gsfc.nasa.gov/Sect18/Sect18_5.html

SUDBURY IMPACT CRATER …

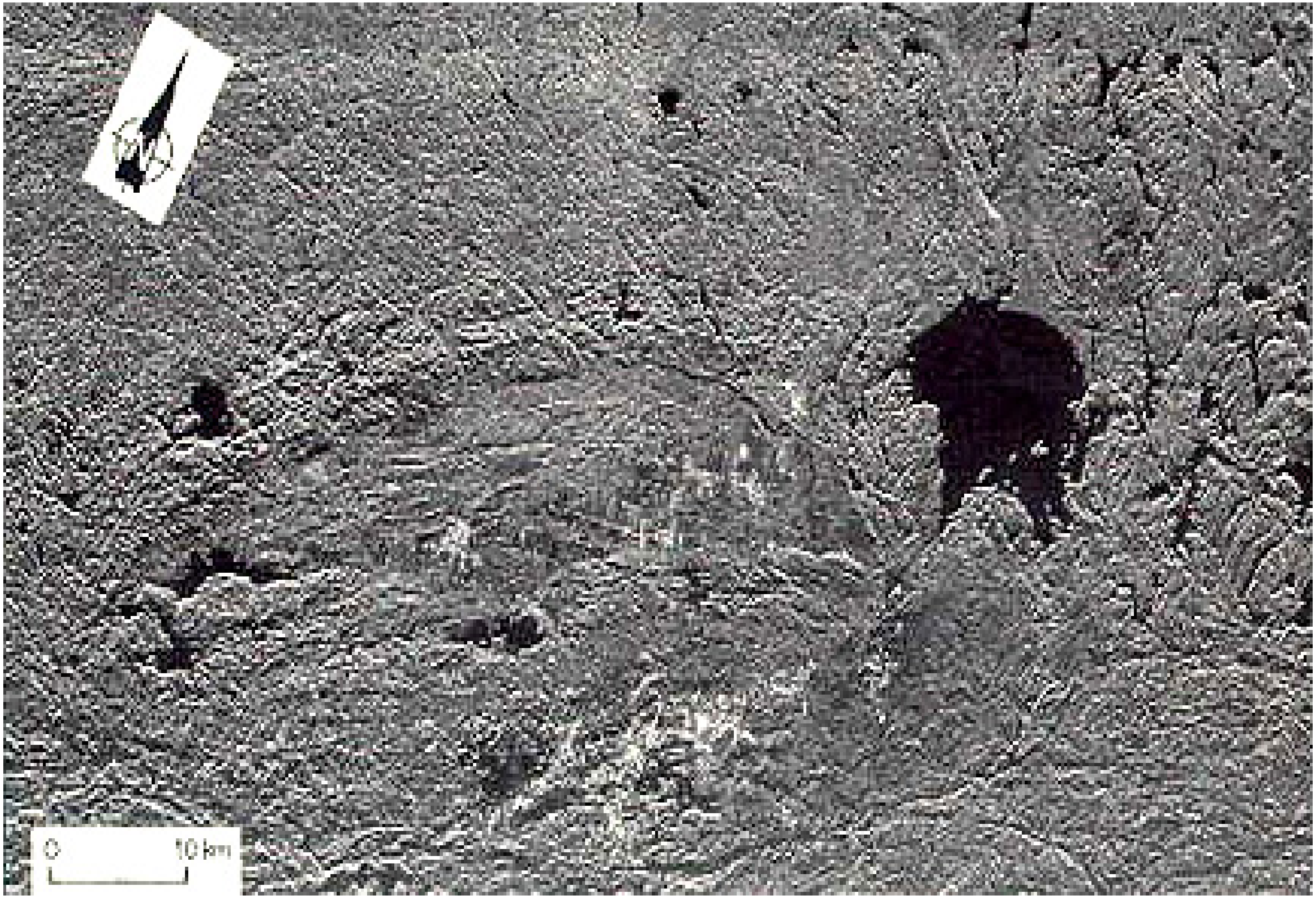


Photo image courtesy of NASA
http://rst.gsfc.nasa.gov/Sect18/Sect18_5.html

SIR-B image legend next slide

SUDBURY IMPACT CRATER …

Image legend:

Shuttle Imaging Radar Mission B (SIR-B)

SIR-B radar image of the Sudbury impact structure.

The Structure is elliptical because of deformation by Grenville thrusting and the near by Wanapitei crater filled much later.

Ref:

http://rst.gsfc.nasa.gov/Sect18/Sect18_5.html

SUDBURY IMPACT CRATER …

- The Sudbury Basin is the site of one of the oldest and the largest impact craters found on the Earth.
- Sudbury Meteorite Crater is a Multi ring Basin:
  - Age: 1850 +/- 50 Ma
  - Diameter: 250 Km (estimated)
  - Location: Ontario, Canada. N 46° 36' W 81° 11'
- Distinctive features

  1. Shatter cones (up to 3 m in length);
  2. PDF in quartz, feldspar and zircon grains;
  3. Overturned collar rocks of South Range structure
  4. Brecciation of country rocks occurring up to 80 km from the Sudbury Igneous Complex.

SUDBURY IMPACT CRATER …

- The Sudbury Igneous Complex occurs within the Sudbury structure.
- The Sudbury Igneous Complex
  - is a 2.5- to 3.0-km-thick,
  - ~60- × 27-km elliptical igneous-rock body, which consists of four major lithologies

    (from top to bottom)
  - granophyre,
  - quartz gabbro
  - norite," and
  - contact sublayer"

    (sulfide- and inclusion-bearing noritic rock).

SUDBURY IMPACT CRATER …

Geologic History of the Sudbury Basin summarized by S. I. Dutch (2001)

- 2500-2300 Ma

  Deposition of the Huronian Supergroup on Archean basement. Initial volcanism was followed by deposition of a thick pelitic sequence followed by three cycles of glacio-marine sediments interbedded with other clastic rocks

- 2300 Ma

  Blezardian crustal deformation event (Riller and others, 1999). An as yet poorly defined event manifested by folding, unconformities, and syntectonic granitic magmatism. The basal Huronian rocks were probably tilted to near vertical before the emplacement of the granitic plutons (Dutch, 1976).

- 2150 Ma

  Intrusion of dikes and sills of Nipissing Diabase

- 1900-1750 Ma

  Penokean Orogeny. Deformation and metamorphism of the Huronian rocks, also deformation, metamorphism and igneous activity in Wisconsin, Michigan, and Minnesota.

- 1850 Ma

  Sudbury impact event. Formation of a crater and central uplift, widespread brecciation of Huronian and Archean rocks, and formation of the Sudbury Igneous Complex and Whitewater Group crater fill units

Ref:

Dutch, S.I., 2001. "Significance of back-to-Back Facing Directions Along the South Range of the Sudbury Igneous Complex." Ontario, Geologic Society of America National Meeting, Boston, MA, November 7, 2001.

SUDBURY IMPACT CRATER …

- The Sudbury Igneous Complex of Ontario, Canada, is the remnant of a voluminous melt sheet produced in a few minutes by impact of a massive meteorite into continental crust 1.85 Ga ago.

- The transient cavity and melting zone reached.
  instantly (~2 min)
  relaxed to form a more familiar large,
  shallow crater holding a thick,
  superheated (~1700 °C)
  melt sheet covered by ~2 km of breccia.

- Originally had a diameter of 200 to 250 km.

SUDBURY IMPACT CRATER …

- Schematic illustrations of the critical stages in the dynamics of evolution leading to the final petrologic structure of the Sudbury

are provided in

“The Sudbury Igneous Complex: Viscous emulsion differentiation of a superheated impact melt sheet”

M. J. Zieg, B. D. Marsh.

GSA Bulletin; November/December 2005; v. 117; no. 11/12; p. 1427–1450

SUDBURY IMPACT CRATER ECONOMIC IMPORTANCE

- This igneous rock (called an "irruptive") is host to vast deposits of nickel and copper. This impact structure is continuously providing a 500 billion dollar source of ore and minerals since mining began in the last century.

Ref:

From Impact to Riches: Evolution of Geological

Understanding as Seen at Sudbury, Canada

A. J. Naldrett

GSA Today, Volume 13, Issue 2 (February 2003) Article: pp. 4–9.

SUDBURY IMPACT CRATER …

- Mungall, Ames and Hanley inferred (2004) that:
  - the **melt sheet** preserved as the Sudbury Igneous Complex is derived predominantly from the lower crust,
  - the hypervelocity impact caused a **partial inversion** of the compositional layering of the **continental crust**.
  - the matrix of the Onaping Formation is a mixture of the original **surficial sedimentary strata**, shock-melted **lower crust** and the **impactor** itself.

Ref:

Mungall, J.E., Ames, D.E.,& Hanley, J. J.,

Geochemical evidence from the Sudbury structure for crustal redistribution

by large bolide impacts,

Nature 429, 546-548 (3 June 2004).

COMPARISON OF SUDBURY AND CHICXULUB IMPACT CRATERS

Pope et al (2004) compared the structure and stratigraphy of Sudbury and Chicxulub impact craters.

- Chicxulub: well-preserved morphologic state

  Sudbury: highly-exposed (~ 8 km erosion) state.
- Both craters have 5 structural rings with diameters of about 85, 120, 150, 200, and 250 km with similar character and dimensions.
- Chicxulub has a sixth peak ring (~ 80 km)

  Sudbury does not have (probably due to erosion).

COMPARISON OF SUDBURY AND CHICXULUB IMPACT RATERS …

- Both Sudbury and Chicxulub are structurally similar 200 km diameter craters.
- Sudbury and Chicxulub craters are stratigraphically dissimilar.

  Suevite (melt volume) of Sudbury in the central basin is seven times the Chicxulub.
- Modeling of velocity contrast between a comet and asteroid impact explained the difference in melt volumes.

Ref:

Pope, K.O, Kieffer, S. W., Ames, D. E.,

Empirical and theoretical comparisons of the

Chicxulub and Sudbury impactstructures

Meteoritics & Planetary Science ,January 2004,

39(1):97-116

VREDEFORT IMPACT CRATER

Location	South Africa
Latitude	S 27° 0'
Longitude	E 27° 30'
Diameter (km)	300
Age (My)	2023 ± 4

VREDEFORT IMPACT CRATER

Space shuttle image STS51I-33-56AA, courtesy of NASA.

VREDEFORT IMPACT CRATER

- The Vredefort crater in South Africa is the circular remnant of an impact event happened on the Earth about 2 billion years ago.
- The Vredefort structure in the Archean Kaapvaal craton of South Africa is regarded as
  - the oldest with an estimated age of 2.02 Ga (Spray et al., 1995)
  - the largest terrestrial impact structure, with an estimated diameter of 300 km. (McCarthy et al., 1990; Therriaultet al., 1997).

VREDEFORT IMPACT CRATER …

- The Vredefort structure is located near the center of the Witwatersrand basin in the 2.7 Ga to 3.6 Ga Kaapvaal craton.

  Study of Moser (1997) showed that

  the combined heating effects of the shock wave and impact-triggered magmas are considered to generate a 300 km^2 thermal imprint of the asteroid collision with Kaapvaal craton, and account for the nearly coeval timing relationship between core metamorphism and shock.

VREDEFORT, CHICXULUB AND SUDBURY IMPACT CRATERS

Grieve and Therriault (2000) compared the available data on the Vredefort, Sudbury, and Chicxulub craters and summarized as follows:

- Vredefort, Sudbury, and Chicxulub are the largest known terrestrial impact structures.
- All have multi-ring basins.
- All have some form of multiple-ring attributes.
- All have many common structural features.
- There are also commonalities in the structural and lithological features of Vredefort and Sudbury.
- It is feasible to construct a generalized compilation of the character of 200-300 km diameter terrestrial (Earth) impact basins
- Vredefort, Sudbury, and Chicxulub impact events generated world-class mineral and hydrocarbon deposits.

IAP 2008 12.091 ASSIGNMENT 2

1. Review the Chicxulub Impact Crater facts

- Discovery

  Attention to: A paleogeographic reconstruction of the continents 65 Ma.

- KT Boundary Mass Extinction
- Regional Effects
- Global Effects

Suggested site:

http://www.lpl.arizona.edu/SIC/news/chicxulub1.html

and the related links.

Suggested reading:

The Chicxulub impact event and its environmental consequencesat the Cretaceous–Tertiary boundary

David A. Kring,

Palaeogeography, Palaeoclimatology, Palaeoecology 255 (2007) 4–21

IAP 2008 12.091 ASSIGNMENT 2 …

2. Review the Sudbury Impact Structure

- Shatter cones of Sudbury impact structure

http://www.uwsp.edu/geo/projects/geoweb/participants/dutch/Sudbury/SCMorphGSA99.htm

- Deformation studies of Sudbury impact structure

  http://gdcinfo.agg.nrcan.gc.ca/app/app4_e.html

- Map of the horizontal gravity gradient over the Sudbury Structure

  http://gdcinfo.agg.nrcan.gc.ca/app/sudbury1_e.html

- Map of the horizontal gravity gradient over the Sudbury Structure as it may have looked shortly after formation.

  http://gdcinfo.agg.nrcan.gc.ca/app/sudbury2_e.html

IAP 2008 12.091 ASSIGNMENT 2 …

Suggested book:

- French, B. M., and Short, N. M.,

  Sudbury Structure, Ontario: Some petrographic evidence for an origin by meteorite impact, pp.383-412.; in

  Shock metamorphism of natural materials,

  Proceedings of the First Conference held at NASA, Goddard Flight Center,

  Maryland, 1966,

  French, B. M., and Short, N. M., (Eds.)

  Mono Book Corp, Baltimore, 1968

  Library of Congress Catalog No. 68-59422.

IAP 2008 12.091 ASSIGNMENT 2 …

3. Review the Mjolnir Impact Structure

   http://folk.uio.no/ftsikala/mjolnir/

   and browse the related links

   Suggested reading:

   Traces of the marine Mjølnir impact event

   H. Dypvik, M. Smelror, P. T. Sandbakken, O. Salvigsen, E. Kalleson,

   Palaeogeography, Palaeoclimatology, Palaeoecology 241 (2006) 621–636

4. Review the Vredefort Impact Structure

   http://www.unb.ca/passc/ImpactDatabase/images/vredefort.htm

   Suggested reading:

   Magnetic imaging of the Vredefort impact crater, South Africa,

   M. Muundjua, R. J. Hart, S. A. Gilder, L, Carporzen, A. Galdeano,

   Earth and Planetary Science Letters 261 (2007) 456–468.

IAP 2008 12.091 ASSIGNMENT 2 …

5. After visiting the (web) sites of the impact crater
   i. What are the main features by which the terrestrial impact craters are identified

ii. What is your understanding of the importance of the studies of Chicxulub, Sudbury, Mjolnir and Vredefort?

Write briefly about each crater.

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REFERENCES FOR FURTHER READING CHICXULUB IMPACT CRATER

- The Chicxulub crater

  http://we.vub.ac.be/~dglg/Web/Claeys/Web-Chix/ICDP-Chix/chixintro.html

- Terrestrial Impact Craters and Their Environmental Effects

  http://www.lpl.arizona.edu/SIC/news/chicxulub1.html

- Chicxulub Impact Crater references

  http://www.unb.ca/passc/ImpactDatabase/images/chicxulub.htm

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Abramov, O., and Kring, D. A.
  Numerical modeling of impact-induced hydrothermal activity at the Chicxulub crater,
  Meteoritics and Planetary Science, v. 42, pp. 93-112, *2007.*
- Alegret, L., Arenillas , I., Arz, J. A., Di´az, C., Grajales-Nishimura, J.M., Mele´ndez, A., Molina, E., Rojas,R., Soria, A. R.
  Cretaceous-Paleogene boundary deposits at Loma Capiro, central Cuba: Evidence for the Chicxulub Impact
  Geology; September 2005; v. 33; no. 9; p. 721–724
- Alvarez, L. W., Alvarez, W., Asaro, F., and Michel, H. V.
  Extraterrestrial cause for the Cretaceous/Tertiary extinction,
  Science, 208, pp. 1095–1008, 1980.

REFERENCES FOR FURTHER READING ... CHICXULUB IMPACT CRATER

- Dressler, B. O., Grieve, R. A. F., and Sharpton, V. L., (Eds.),

  Large meteorite impacts and planetary evolution, *Geological Society of America Special Paper 293*,

  pgs. 348, 1994.

  ISBN: 978-0813722931
- French, B. M., and Short, N. M., Editors,

  Shock Metamorphism of Natural Materials

  Mono Book Corp., Baltimore, Md., pgs. 644 1968.

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Grajales-Nishimura, J. M., Cedillo-Pardo, E., Rosales-Domínguez, C., Morán-Zenteno, D. J., Alvarez, W., Claeys, P., Ruíz-Morales, J., Padilla-Avila, P. , Sánchez-Ríos, A.,

  Chicxulub impact: The origin of reservoir and seal facies in the southeastern Mexico oil fields,

  Geology; April 2000; v. 28; no. 4; p. 307–310.
- Grieve, R. A. F.,

  Terrestrial Impact Structures, *Annual Reviews of Earth and Planetary Science, **15***, pp. 245–270, 1987.
- Hildebrand, A. R. and Penfield, G. T.,

  A buried 180-km diameter probable impact crater on the Yucatan Peninsula, Mexico,

  Eos, v. 71, p. 1424-1425, 1990.

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Kring, D. A.,
  The dimensions of the Chicxulub impact crater and impact melt sheet
  Journal of Geophysical Research (August 1995), 100(E8):16,979-19,986
- Kring, D. A.,
  The Chicxulub impact event and its environmental consequences at the Cretaceous-Tertiary boundary (*in* Cretaceous-Paleogene boundary events)
  Palaeogeography, Palaeoclimatology, Palaeoecology (November 2007), 255(1-2):4-21

REFERENCES FOR FURTHER READING ... CHICXULUB IMPACT CRATER

- Melosh, H. J.,
  Impact Cratering: A Geological Process,
  Oxford University Press, New York, 245 pp., 1989.
  ISBN 0 19 504284 0

- Melosh, H.J., 1991,
  Atmospheric impact processes,
  Advances in Space Research, v. 11, no. 6, p. 87–93,

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Morgan, J., and Warner, M.,

  Chicxulub: The third dimension of a multi-ring impact basin

  Geology; May 1999; v. 27; no. 5; p. 407–410.
- Morgan, J., Christeson, G., Gulick, S.,Richard Grieve, Urrutia, J., Barton, P., Rebolledo, M.,and Melosh J.,

  Joint IODP/ICDP Scientific Drilling of the Chicxulub Impact Crater

  Scientific Drilling, No. 4, March 2007, p. 42-44.
- Perry, E.,. Luis Marin, L., McClain J., Vela´ zquez, G.,

  Ring of Cenotes (sinkholes), northwest Yucatan, Mexico: Its hydrogeologic characteristics and possible association with the Chicxulub impact crater,

  Geology; January 1995; v. 23; no. 1; p. 17–20.

REFERENCES FOR FURTHER READING ... CHICXULUB IMPACT CRATER

- Pope K.O., Rejmankova, E., Paris J.F.,

  Spaceborne imaging radar-C (SIR-C) observations of groundwater discharge and wetlands associated with the Chicxulub impact crater, northwestern Yucatan Peninsula, Mexico

  GSA Bulletin; March 2001; v. 113; no. 3; p. 403–416.
- Pope K. O., Ocampo, A.C., Fischer, A. G. Walter Alvarez, W., Fouke, B. W., Webster, C. L., Vega, F. J., Smit, J.,A. Fritsche, E., and Claeys, P.

  Chicxulub impact ejecta from Albion Island, Belize, *Earth and Planetary Science Letters* , July 1999, 170(4):351-364

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Roddy, D. J., Pepin, R. O., and Merrill, R. B. (Eds.),
  Impact and Explosion Cratering: Planetary and Terrestrial Implications
  Pergamon Press, New York, 1301 pp., 1977.
  ISBN: 0080220509
- Sharpton, V. L., and Ward, P. D. , Editors,
  Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality
  Geological Society of America Special Paper ***247***, 631 pp., 1990.
  ISBN: 9780813722474
- Sharpton, V. L., Dalrymple, G. B. , Marín, L. E. , Ryder, G., Schuraytz, B.C., and Urrutia-Fucugauchi, J. ,
  New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary,
  Nature, ***359***, 819–821, 1992.

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Tagle, R., Erzinger, J. , Hecht, L. , Schmitt, R. T. , Stoffler, D. and Claeys, P., Platinum group elements in impactites of the ICDP Chicxulub drill core Yaxcopoil-1: Are there traces of the projectile? Meteoritics & Planetary Science 39, Nr. 6, P. 1009 - 1016. 2004.
- Tuchscherer, M. G., Reimold, W.U., Gibson, R.L., Koeberl,C., Petrographic observations and classification: impactites from the Yaxcopoil-1 borehole, chicxulub impact structure, Yucatan Peninsula, Mexico, Lunar and Planetary Science. 2003.
- Tuchscherer, M. G., Reimold, W.U., Koberl, C., Gibson,R.L., Geochemical characteristics of impactites from the Yaxcopoil-1 ICDP drip core, Chicxulub Imact Structure, Mexico, Lunar and Planetary Science XXXV. 2004

REFERENCES FOR FURTHER READING … CHICXULUB IMPACT CRATER

- Sharpton V. L., Burke, K., Camargo-Zanoguera, A., Hall, S. A., Lee D. S., Marín L. E., Suáarez-Reynoso , G., Quezada-Muñeton J. M., Spudis, P.D., and Urrutia-Fucugauchi, J.

  Chicxulub Multiring Impact Basin: Size and other

  characteristics derived from gravity analysis,

  Science, ***261***, pp. 1564–1567, 1993.
- Sharpton, V. L.

  Chicxulub Impact Crater Provides Clues to Earth's History

  Earth in Space Vol. 8, No. 4, December 1995, p. 7.
- Silver, L. T., and Schultz P. H., editors,

  Geological implications of impacts of large asteroids and comets on the Earth: An Intimate History

  Geological Society of America Special Paper 190, 128 pp., 1982.

  ISBN: 978-0375706202

REFERENCES FOR FURTHER READING ...
CHICXULUB IMPACT CRATER

- Vermeesch, P. M., and Morgan, J. V. ,
  Chicxulub central crater structure; initial results from physical property measurements and combined velocity and gravity modeling *Meteoritics & Planetary Science* (July 2004), 39(7):1019- 1034

- Wittmann, A., Kenkmann, T., Hecht, L.,
  Stöffler, D.,
  Reconstruction of the Chicxulub ejecta plume from its deposits in drill core Yaxcopoil-1
  GSA Bulletin; September/October, 2007; v. 119; no. 9/10; p. 1151–1167

REFERENCES FOR FURTHER READING … MJOLNIR

- Dypvik, H., Gudlaugsson, S. T., Tsikalas, F., Attrep Jr. M., Ferrell Jr., R. E., Krinsley, D. H., Mørk, A., Faleide, J. I., Nagy, J.,

  Mjølnir structure: An impact crater in the Barents Sea,

  Geology, v. 24, no. 9, p. 779–782, September 1996
- Dypvik, H., and Moses Attrep, M.,
  Geochemical signals of the Late Jurassic, marine Mjolnir impact
  Meteoritics & Planetary Science, v. 34(3), p. 393-406 , May 1999.

REFERENCES FOR FURTHER READING ... MJOLNIR

- Dypvik, H., Ferrell, R. E., and Sandbakken, P. T., The clay mineralogy of sediments related to the marine Mjolnir impact crater *Meteoritics & Planetary Science*, 38(10):1437-1450,October 2003.
- Dypvik, H., Sandbakken, P. T., Postma, G.,and Atle Mork, A., Early post-impact sedimentation around the central high of the Mjolnir impact crater (Barents Sea, Late Jurassic) *Sedimentary Geology*,168(3-4):227-247. June 2004.

REFERENCES FOR FURTHER READING ... MJOLNIR

- Dypvik, H., Smelror, M., Sandbakken, P. T., Salvigsen, E. Kalleson, E., Traces of the marine Mjølnir impact event, *Palaeogeography, Palaeoclimatology, Palaeoecology 241 (2006) 621–636.*

- Gudlaugsson, S. T., Large Iimpact crater in the Barents Sea, *Geology, v. 21, p. 291-294, April 1993.*

REFERENCES FOR FURTHER READING … MJOLNIR

- Ormo, J., and Lindstrom, M.,
  When a cosmic impact strikes the sea bed,
  Geol. Mag. v. 137 (1), p. 67–80, 2000.
- Shuvalov, V., and Dypvik, H.,
  Ejecta formation and crater development of the Mjolnir impact
  Meteoritics & Planetary Science , v. 39(3),
  p. 467-479, March 2004.

REFERENCES FOR FURTHER READING … MJOLNIR

- Tsikalas, F., Gudlaugsson, S.T., and Faleide, J.I., Collapse, infilling, and post-impact deformation at the Mjølnir impact structure, Barents Sea

  Geological Society of America Bulletin, v. 110, p. 537-552, 1998.
- Tsikalas, F., Gudlaugsson, S.T., Eldholm, O., and Faleide, J.I., 1998, Integrated geophysical analysis supporting the impact origin of the Mjølnir Structure, Barents Sea,

  Tectonophysics, v. 289, p. 257-280, 1998.
- Tsikalas, F., Mjolnir Crater as a result of oblique impact; asymmetry evidence constrains impact direction and angle (*in* Impact tectonics, Impact studies ; Eds.:Koeberl, C; Herbert, H.; Springer Verlag, Berlin, p. 285-306, 2005.

  ISBN 978 3 540 24181 7.

REFERENCES FOR FURTHER READING … MJOLNIR

- **Mjolnir Crater, Norway**
  http://folk.uio.no/ftsikala/mjolnir/
- **3D Image of Mjolnir Crater**
  http://folk.uio.no/ftsikala/mjolnir/photo_gallery/html/location.html
- **Comprehensive list of references available at**
  http://www.unb.ca/passc/ImpactDatabase/images/mjolnir.htm

REFERENCES FOR FURTHER READING … SUDBURY CRATER

- Ames,D. E., Watkinson, D. H., Parrish, R.R.,

  Dating of a regional hydrothermal system induced by the 1850 Ma Sudbury impact event,

  Geology; May 1998; v. 26; no. 5; p. 447–450
- Dutch, S.I., 2001.

  Significance of back-to-Back Facing Directions Along the South Range of the Sudbury Igneous Complex. Ontario,

  Geologic Society of America National Meeting, Boston, MA, November 7, 2001.

REFERENCES FOR FURTHER READING ... SUDBURY CRATER

- French, B. M., and Short, N. M.,

  Sudbury Structure, Ontario: Some Petrographic Evidence For an Origin by Meteorite Impact, pp.383-412.; in

  Shock metamorphism of natural materials,

  Proceedings of the First Conference held at

  NASA, Goddard Flight Center, Maryland, 1966,

  French, B. M., and Short, N. M., (Eds.)

  Mono Book Corp, Baltimore, 1968

  Library of Congress Catalog No. 68-59422.

REFERENCES FOR FURTHER READING ... SUDBURY CRATER

- Mungall ,J.E., Ames D.E.,& Hanley ,J. J.,
  Geochemical evidence from the Sudbury structure for crustal redistribution by large bolide impacts,
  Nature 429, 546-548 (3 June 2004).
- Naldrett, A. J.
  From Impact to Riches: Evolution of Geological Understanding as Seen at Sudbury, Canada
  GSA Today, Volume 13, Issue 2, February 2003, Article: pp. 4–9.

REFERENCES FOR FURTHER READING ... SUDBURY CRATER

- Pope, K.O, Kieffer, S. W., and Ames, D. E., Empirical and theoretical comparisons of the Chicxulub and Sudbury impact structures, *Meteoritics & Planetary Science, January 2004, 39(1):97-116.*

- Zieg, M. J., Marsh.B. D.,
  The Sudbury Igneous Complex: Viscous emulsion differentiation of a superheated impact melt sheet,
  GSA Bulletin, November.December 2005, v. 117, no. 11/12; p. 1427–1450.

REFERENCES FOR FURTHER READING … SUDBURY CRATER

- **Sudbury crater**

  http://www.ottawa.rasc.ca/articles/odale_chuck/earth_craters/sudbury/index.html

- **Sudbury crater location map**

  http://rst.gsfc.nasa.gov/Sect18/Sect18_5.html

- **References**

A Comprehensive list of about 400 references from 1955 to 2006 are provided on the web site.

http://www.unb.ca/passc/ImpactDatabase/images/sudbury.htm

REFERENCES FOR FURTHER READING ... VREDEFORT CRATER

- Grieve, R., and Ann Therriault, A., Vredefort, Sudbury, Chicxulub; three of a kind? *Annual Review of Earth and Planetary Sciences* , 2000, 28 305-338
- McCarthy, T. S., Stanistreet, I. G., and Robb, L. J., Geological studies related to the origin of the Witwatersrand Basin and its mineralization: An introduction and a strategy for research and exploration, *S. Afr. J. of Geol., 1990, v. 93, p. 1–4.*

REFERENCES FOR FURTHER READING … VREDEFORT CRATER

- Moser, D.,
  Dating the shock wave and thermal imprint of
  the giant Vredefort impact, South Africa,
  Geology, January 1997, v. 25, no.1, p. 7–10.
- Muundjua,M., Hart, R.J., Gilder, S. A., Carporzen, L., Galdeano, A.,
  Magnetic imaging of the Vredefort impact crater, South Africa,
  Earth and Planetary Science Letters 261 (2007) 456–468.

REFERENCES FOR FURTHER READING ... VREDEFORT CRATER

- Spray, J. G., Kelley, S.P. and Reimold,W.U., Laser probe argon-40/argon-39 dating of coesite- and stishovite-bearing pseudotachylytes and the age of the Vredefort impact event.

  Meteoritics, v. 30, pp. 335-343. 1995.
- Therriault, A. M., Grieve, R. A. F., Reimold. W. U., Original Size of the Vredefort Structure: Implications for the Geological Evolution of the Witwatersrand Basin, Meteoritics Planet. Sci., vol. 32, p. 71-77. 1997.

- More references are also available on the web site

  http://www.unb.ca/passc/ImpactDatabase/images/vredefort.htm

KEY WORDS

Chicxulub crater, Sudbury strcuture, Mjlonir crater, Vredefort crater, impact sructures

SESSION 2 END