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

PILLALAMARRI ILA

Department of Earth Atmospheric &Planetary Sciences

Massachusetts Institute of Technology

Cambridge, MA 02139

SESSION 5, January 22, 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. Well Logging and Geochemical Studies of Chesapeake Bay Impact Crater
5. Economic Potential and Environmental Effects of Impact Craters
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**

SESSION 5

Economic Potential & Environmental Effects of Impact Craters

OBJECTIVE

- Economic Potential
- Environmental effects of terrestrial impact cratering
- Modeling of impact hazard and response
- Conclusion

Economic Potential

25% of the known terrestrial impact craters are associated with economic potential such as

- mineral ores,
- hydrocarbons,
- evaporite minerals
- fresh water.

Ref: Mazur, Stewart and Hildebrand (2000)

Economic Potential ...

Impact cratering involves

- **immense formative energies interactions between the projectile and the target rocks,**
- **resulting shock wave interactions**
- **that can lead to the redistribution, formation and/or the concentration of economic deposits**

Thus the crater formation processes could become conducive to economic potential.

Ref: Masaitis, V.L., 1989; Grieve, R.A.F. and Masaitis, V.L., 1994.

Economic Potential ...

Deposits of materials formed near impact structures can be categorized (Masaitis, 1989) as

- **progenetic**
- **syngenetic**
- **epigenetic**

- **Progenetic deposits**
- **redistribution of easily retrievable deposits by impact effect.**

Examples:

- **gold and uranium deposits of the Vredefort structure in South Africa (valued at $7 billion dollars per year),**
- **uranium deposits at Carswell, Saskatchewan (valued about $1 billion worth of uranium ore).**

Ref: Westbroek and Stewart (1996)

Economic Potential ...

- **Syngenetic deposits**

  originate during or shortly after an impact event,
  direct deposition of energy into the target rocks
  causing phase changes and melting.
  Ex: The Cu-Ni deposits at Sudbury, Ontario
  ($2 billion dollars over the last five years).

- **Epigenetic deposits**

  form after the impact ,
  hydrothermal alteration,
  formation of enclosed basins
  with isolated sedimentation,
  flow of fluids into structural traps of the crater.
  Ex: Hydrocarbon accumulations

Economic Potential ...

- **Cu-Ni ore Sudbury, Ontario**

  $2 billion dollars over the last five years.
- **North American deposits: $5 billion year**
- **Gold and uranium ores of the Vredefort structure in South Africa: $7 billion per year).**
- **Hydroelectric power 4000 GWh/a from the reservoir at Manicouagan, Quebec,**

  $200 million per year.
- **Building materials (e.g. cement and lime products) Ries, Germany: $70 million per year**

Ref:

Naldrett, A. J. (2003)

Westbroek H .-H., and Stewart, R. R. (1996)

Environmental Effects of Terrestrial Impact Cratering

Impact structures of the Earth have potential important environmental effects on the local ecology.

Factors that cause environmental effects

- impactor size,
- impactor mass,
- energy released.

These should be determined as accurately as possible.

Environmental Effects of Terrestrial Impact Cratering …

Mjolnir crater

estimated impact parameters

- Impactor size: 1-3 km in diameter,
- Impactor mass: 0.2 – 14 (1 – 33) billion tons,
- Released energy at impact: 6E4 – 1E6 megatons TNT.

Dissipation of the energy released during the Mjølnir impact is sufficient to have caused environmental effects.

For actual values:

Ref: Gudlaugsson, S. T, (1993), Tsikalas, F., Gudlaugsson, S.T., Faleide, J.I., (1998)

Environmental Effects of Terrestrial Impact Cratering …

Mjolnir crater estimated impact effects:

- several short, near-field perturbations
- large magnitude earthquake
- considerable displacement of material from the impact site
- high-amplitude tsunami waves.
- as far as 10 crater diameters away from the impact site.

Ref: Dypvik, H., Smelror, M., Sandbakken,P. T., Salvigsen O., Kalleson, E., (2006)

Environmental Effects of Terrestrial Impact Cratering …

Mjolnir crater impact effects ..

- The estimated energy release during the Mjølnir impact can trigger
  - earthquake magnitude: **7.7-8.7**,
  - slumping on nearby sedimentary slopes.
- The estimated volume of the displaced material:
  - of the order of **140-180 km^3**
  - causing major upheaval of the sea.

Environmental Effects of Terrestrial Impact Cratering …

Mjolnir crater impact effects ..

The impact of the Mjølnir projectile into a shallow shelf environment

with water depths of **300-500 m**

and the subsequent collapse of the impact-generated water cavity is expected to have given rise to large-amplitude tsunami waves.

Environmental Effects of Terrestrial Impact Cratering …

Mjolnir crater estimated impact effects:

The impact effect in sea is generation of huge amplitude tsunami waves.

Crater age: 142 Ma

Structure period: Upper Jurassic-Lower Cretaceous

A paleogeographic reconstruction for early Cretaceous time indicates:

Possible coastal erosion of the region of the shores of northeastern Greenland, northern Fennoscandia, Novaya Zemlya.

These regions are within the 400 km radius from the impact site and could be affected by tsunami waves with amplitudes greater than 5-10 m.

Ref: Environmental Effects

http://folk.uio.no/ftsikala/mjolnir/photo_gallery/html/environ_cons.html

Dypvik, H., Smelror, M., Sandbakken,P. T., Salvigsen O., Kalleson, E., (2006)

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay impact crater

estimated impact parameters

- Impactor size: 3.2 km diameter
- Impactor density: 2700 kg/m3
- Impact velocity: 17km/s
- Released energy at impact: of ~1.75×10^6 MegaTons

Ref: Collins, G. S., and Wünnemann, K. (2005)

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater:

The studies of meteor-impact structure beneath the lower Chesapeake Bay, provide accurate understanding of the ground-water reservoir system (Powars and Bruce, 1999; Powars, 2000).

These studies contribute to the environmental quality of ground water, which is of utmost importance to the millions of people living in the area along eastern shore of Virginia.

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater Effect on hydrogeology :
(Powars and Bruce, 1999; Powars, 2000; Gohn et al 2007):
"Marine, glauconitic, shelly sands of late Paleocene age compose the Aquia aquifer, which is regionally extensive but only a minor ground-water supply resource. Generally similar, but finer-grained sediments of late Paleocene to early Eocene age compose the overlying Nanjemoy-Marlboro confining unit. Both hydrogeologic units are truncated along the margin of the Chesapeake Bay impact crater."

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater Effect on hydrogeology: (Powars and Bruce, 1999; Powars, 2000; Gohn et al 2007): "Sediments of late Eocene age compose three newly designated confining units that overlie the Potomac aquifer within the Chesapeake Bay impact crater. These confining units include, from bottom to top, the impact-generated, lithologically distinctive but highly variable Exmore clast and Exmore matrix confining units and the marine, clayey Chickahominy confining unit. The three confining units collectively impede ground-water flow across the crater."

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater Effect on hydrogeology:
(Powars and Bruce, 1999; Powars, 2000; Gohn et al 2007):

- The Piney Point aquifer is regionally extensive, overlying most of the Chesapeake Bay impact crater and beyond, but is only locally significant as a ground-water supply resource across the middle reaches of Northern Neck and the Middle and York-James Peninsulas.

Acknowledgement:

A large amount of detailed information on the Chesapeake Bay impact crater was provided by the U.S. Geological Survey (USGS) Eastern Earth Surface Processes Team in support of understanding the effects of the impact crater

on ground-water resources. Conceptualization of geologic relations of the crater was particularly aided by David S. Powars of the USGS.

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater Effect on hydrogeology …

Edwards and Powars (2003) conducted scientific studies of microbial life present in the impact crater as part of intriguing recent studies of life in exotic environments:

- *The **entire marine** Cretaceous, Paleocene, and Eocene section that was once present at the site has been **excavated** and **redeposited** under extreme conditions of shock, heat, collapse, tsunamis, and airfall.*
- *The preserved **dinocysts** indicate these extreme conditions. They were the products of the impact, may be used as indicators for recognizing impact-related deposits elsewhere.*

Explanatory notes

- **Dinoflagellates** are single-celled organisms. They inhabit oceans, estuaries, lakes, and ponds. Some of them are bioluminescent , displaying a sparkling of the sea at night as the waves break.
- “Red tides," are caused by them, which can kill fish or poison humans who eat the fish or shellfish that have eaten the dinoflagellates.
- Many dinoflagellates have a complex life cycle that includes a **resting stage**. During this stage, the dinoflagellate may live in a sturdy capsule called a dinocyst.
- The dinocyst is studied by paleontologists using them as indicators.

Unlike many other fossils, the **dinocyst** looks like a **cocoon**.

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Cratering effect on marine organisms

- Dinocysts unaltered in non-impact area and altered by impact is given by Edwards and Powars (2003).

  Ref:

  Figure 4, p. 80, in

  Impact Damage to Dinocysts from the Late Eocene Chesapeake Bay Event

  L. E. Edwards and D. S. Powars

  PALAIOS, 2003, v. 18, p. 275–285

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater …

Use of discoaster nannofossils as indicators of wet impact:

- **Shock-wave–fractured calcareous Discoasters nanofossils were found in synimpact matrix materials. These represented tsunami or resurge sedimentation that followed impact.**
- **Evidence of shock-induced fracturing was not found in samples taken from cohesive clasts within the crater rubble.**
- **The data supports growing evidence that microfossils can be used successfully to estimate the intensity and timing of wet-impact cratering.**

Ref: Self-Trail, J. M. 2003

Environmental Effects of Terrestrial Impact Cratering …

- **Discoasters** are a group of calcareous nanofossils with distinctive 5- or 6-pointed star shape.
- **Discoasters are** extinct forms and may be closely related to the minute algae.

A good description (figure 1, p.697) and figures of discoasters (figure 4, p. 699), in the impacted region of Chesapeake Bay could be seen from the study of Self-Trail (2003).

Ref:

J. M. Self-Trail,

Shock-wave–induced fracturing of calcareous nanofossils from the Chesapeake Bay impact crater,

Geology, August 2003, v. 31, no. 8, p. 697–700;

Environmental Effects of Terrestrial Impact Cratering …

Chesapeake Bay Impact Crater …

According to the studies of Self-Trail (2003):

- **"Fractured calcareous nanofossils of the genus *Discoaster from synimpact sediments* within the Chesapeake Bay impact crater demonstrate that other petrographic shock indicators exist for the cratering process in addition to quartz minerals.**
- **Evidence for shock induced effect includes marginal fracturing of rosette-shaped *Discoaster species into*** pentagonal shapes **and**

  pressure- and temperature-induced dissolution of ray tips and edges of discoasters. "

Impact Hazard Modeling and Response Studies

- **Numerical modeling is a fundamental tool for understanding the dynamics of impact cratering, especially at planetary scales.**
- **In particular, processes like melting/vaporization and crater collapse, typical of planetary-scale impacts, are not reproduced in the laboratory, and can only be investigated by numerical modeling.**

Ref: Collins, G. S., Melosh, H. J. ,. Marcus, R. A. (2005)

Impact Hazard Modeling and Response Studies …

- **The dynamics of impact cratering events is reasonably well understood and implemented in numerical codes.**
- **The response of materials to shocks is dependent on specific material properties.**
- **Accurate material models are very necessary for realistic simulation of impact cratering, and one of the major problems in numerical modeling of impacts.**

Impact Hazard Modeling and Response Studies …

Predictions of environmental consequences across the United States of hypothetical impact scenarios occurring in Los Angeles.

Some understanding concepts:

1) **seismic shaking** is the most widely spread environmental consequence,
2) **ejecta deposit** thickness and **air-blast pressure** decay much more rapidly with distance than seismic ground vibration,
3) **thermal radiation** causes the most devastating effect close to the impact site.

Impact Hazard Modeling and Response Studies …

- The magnitude of thermal exposure per impact energy in MT, for a hypothetical impact in Los Angeles, with distance as far from San Diego, San Francisco and New York is illustrated by Collins et al (2005), in their Web modeling study.

- Ref:

  Figure 4, p.835, in

  Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth,

  G. S. Collins, H. J. Melosh, R. A. Marcus

  Meteoritics & Planetary Science 40, Nr 6, 817–840 (2005)

Impact Hazard Modeling and Response Studies …

- The effects of an impact events of increasing energy have been discussed in the scientific literature.
- If the impact energy is < ~10 Megaton equivalent of TNT,
  - then a crater may not be formed ,
  - an airburst may destroy/damage the biota and local property.
- The Tunguska explosion of 1908 in Siberia is such an example.

Impact Hazard Modeling and Response Studies …

According to Chapman et al (1994) and Toon et al (1997):

- For energies between 10 Mt and 10^6 Mt,
  - a crater will be formed.
  - the effects of the impact are confined to "**local**" effects,
  - where the effects become more widely manifested with greater energies
- For energies approximately 10^7 Mt
  - the effects of an impact are expected to be **global**,
  - becoming responsible for large-scale biological changes,
  - potentially worldwide extinctions such as the dinosaurs extinction 65 million years ago.

Impact Hazard Modeling and Response Studies …

Cockell (2005) lists the effects of the events:

- Events with global scale consequences are unlikely to be survived by large sections of society.
- Events that form a crater of **~1 km diameter**, and could devastate an area of approximately 8,000 square kilometers, can occur on average about **once every 1,000 years.**
- Events on the scale of **~10^6 Mt** are believed to occur with a frequency of about **once every 100 million years .**
- International response could be possible to the locally-destructive asteroid and comet impacts of energy ~**10^5 Mt and less**.

Impact Hazard Modeling and Response Studies …

Conclusion

- The mapping of asteroid and comet trajectories and the development of countermeasures

  deployed in space to deflect them from Earth may reduce impact hazard.
- Counter measures are not guaranteed 100%

  effectiveness.
- Earth remains vulnerable. prior to such countermeasures,
- Irrespective of planetary protection plans for Earth, human civilization should have procedures in place to respond to an impact event.

Conclusion of the Course

After learning many aspects of terrestrial impact craters, cratering processes, quantifying the impact cratering, economic benefits of impact crater studies, modeling of hazards, responses and so on -

what other aspects remain to be answered?

what else needs to be known in determining the impact parameters accurately?

what are the deficiencies and strengths of current simulation models?

what are geomedical effects of impact craters ?

and … … ….

References For Further Reading

- **Chapman C. R., and Morrison, D.,**

  Impacts on the earth by asteroids, comets: Assessing the hazard,

  Nature 1994, v. 367, p.33–40.

- **Cockell, C.**

  A Scientific Impact Response Team for the aftermath of small asteroid and comet impacts,

  Science and Global Security, 2005, 13, 105–115.

References For Further Reading

- Collins, G. S., Melosh, H. J., Marcus, R. A.,

  Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth

  Meteoritics & Planetary Science 2005, 40, nr. 6, p. 817–840.
- Collins, G. S., and Wünnemann, K.,

  How big was the Chesapeake Bay impact? Insight from numerical modeling,

  Lunar and Planetary Science XXXVI (2005)

  Geology, 2005, v. 33, p. 925 – 928.

References For Further Reading

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

  Traces of the marine Mjølnir impact event,

  Palaeogeography, Palaeoclimatology, Palaeoecology, 2006, v. 241, p. 621–636.

- **Edwards L. E. and Powars, D.,**

  Impact Damage to Dinocysts from the Late Eocene Chesapeake Bay Event,

  PALAIOS, 2003, v. 18, p. 275–285.

References For Further Reading

- **Gault, D. E. and Sonett, C. P., 1982,**

  Laboratory simulation of pelagic asteroidal impact: Atmospheric injection, benthic topography, and the surface wave radiation field, in Silver, L. T., and Schultz, P. H., Eds., Geological implications of impacts of large asteroids and comets on the Earth: Geological Society of America Special Paper 190, p. 69-92.

References For Further Reading

- Gohn, G.S., Sanford, W.E., Powars, D.S., Horton, J.W., Jr., Edwards, L.E., Morin, R.H., and Self-Trail, J.M., 2007,

  Site report for USGS test holes drilled at Cape Charles, Northampton County, Virginia, in 2004: U.S. Geological Survey Open-File Report 2007-1094 22 p.
- Grieve, R.A.F. and Masaitis, V.L.,

  The economic potential of terrestrial impact craters,

  Internatl. Geol. Rev., 1994, v. 36, 105-151.

References For Further Reading

- **Gudlaugsson, S. T.,**
  Large impact crater in the Barents sea,
  Geology, 1993, v. 21, p. 291-294.

- **Masaitis, V. L., 1989,**
  The economic geology of impact craters,
  Internat. Geol. Rev., 31, 922-933.

- **Mazur, M. J., Stewart, R. R., and Hildebrand, A. R. ,**
  The seismic signature of meteorite impact craters,
  Canadian Society of Exploration Geophysicists (CSEG)
  CSEG Recorder, June 2000, p.10-16.

References For Further Reading

- **Melosh, H. J.,**

  Impact Cratering: A geologic process

  New York, Oxford University Press, 245 p., 1989.

  ISBN 019504284 0

- **Naldrett, A. J.,**

  From Impact to Riches: Evolution of Geological Understanding as Seen at Sudbury, Canada

  GSA Today, February 2003, v. 13, Issue 2, Article: pp. 4–9.

References For Further Reading

- Powars, D.S., and Bruce, T.S., 1999, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of the lower York-James Peninsula, Virginia: U.S. Geological Survey Professional Paper 1612, 82 p.
- Powars, D.S., 2000, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of southeastern Virginia, south of the James River: U.S. Geological Survey Professional Paper

  1622, 53 p.

References For Further Reading

- **Self-Trail, J. M.**

  Shock-wave–induced fracturing of calcareous nano fossils from the Chesapeake Bay impact crater,

  Geology, August 2003, v. 31, nr. 8, p. 697–700.

- **Toon, O. B., Zahnle, K. , Morrison, D. , Turco, R. P. ,and Covey, C.,**

  Environmental perturbations caused by the impacts of asteroids and comets.

  Reviews of Geophysics 1997, v. 35, 41–78.

References For Further Reading

- Tsikalas, F., Gudlaugsson, S. T., Faleide J.I , Eldholm, O.,

Mojlnir Structure, in Barents Sea: A marine impact crater laboratory pp. 193-204, in Large Meteorite Impacts: Planetary Evolution II, (Special Papers (Geological Society of America), 339.)

International Conference on Large Meteorite Impacts and Planetary Evolution (1992): Sudbury, ON, Canada,

Eds. B. O. Dressler, V. L. Sharpton

Geological Society of America 2002,

ISBN: 9780813723396.

References For Further Reading

- **Tsikalas, F., Gudlaugsson, S.T., Faleide, J.I.,**

  The anatomy of a buried complex impact structure: the Mjølnir Structure, Barents Sea,

  Journal of Geophysical Research, 1998,

  v. 103, p. 30,469- 30, 484.

- **Westbroek H., -H., and Stewart, R. R.,**

  The formation, morphology, and economic potential of meteorite impact craters

  CREWES Research Report — 1996, v. 8, 34-1 to 34-26.

CREWES:

Consortium for Research in Elastic Wave Exploration Seismology

Session 5 End

Course End