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Science 23 April 1999:
Vol. 284. no. 5414, pp. 604 - 605
DOI: 10.1126/science.284.5414.604

PERSPECTIVES

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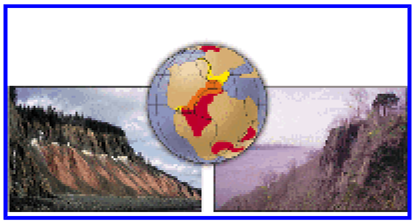
GEOSCIENCE:

Enhanced: Giant Lava Flows, Mass Extinctions, and Mantle Plumes

Paul E. Olsen[*] [HN20]

What are the consequences and origins of the largest volcanic events known on Earth? These include the so-called large igneous provinces [HN1] (or LIPs) that comprise enormous edifices of basaltic lava and associated igneous rocks [HN2] formed over a relatively brief time interval (1). Two of the largest LIPs, the Siberian Traps [HN3] (~2.5 × 10^6 km^3) and Deccan Traps [HN4] (~2.6 × 10^6 km^3), were extruded onto the land surface (2) and are often termed continental flood basalts. Each is also associated with a mass extinction, the Siberian Traps with the extinction at the end of the Permian (250 million years ago) and the Deccan Traps with the extinction at the end of the Cretaceous (65 million years ago). In recent years, a third giant continental LIP associated with a mass extinction has been identified in the long-studied Triassic-Jurassic (~201 million years ago) lavas and igneous intrusions that mark the rifting of the supercontinent of Pangea and the formation of the Atlantic Ocean. As reported by Marzoli *et al.* [HN5] on page 616 of this issue (3), this Central Atlantic Magmatic Province (CAMP) may be the largest LIP of all, at least in area. Before the formation of the Atlantic Ocean, it extended over 7 million km^2, from France to southern Brazil, covering substantial portions of four tectonic plates (see the figure). And yet this igneous activity probably occurred over less than a few million years. The origin of this LIP bears on the mechanisms of mass extinction [HN6], continental breakup, and the motive force behind continental drift itself [HN7].



Big lava. (**Left**) Basalt flow (brown) in the CAMP on top of the Triassic-Jurassic boundary (white) on Triassic rift lake sediments (reddish brown). (**Center**) Pangea during the Late Triassic-Early Jurassic with four terrestrial LIPs (north to south: Siberian Traps, CAMP basalts, Deccan Traps, and Karroo lavas). (**Right**) The Palisades Sill, an intrusive part of the CAMP event, exposed along the shores of the Hudson River, near New York City.

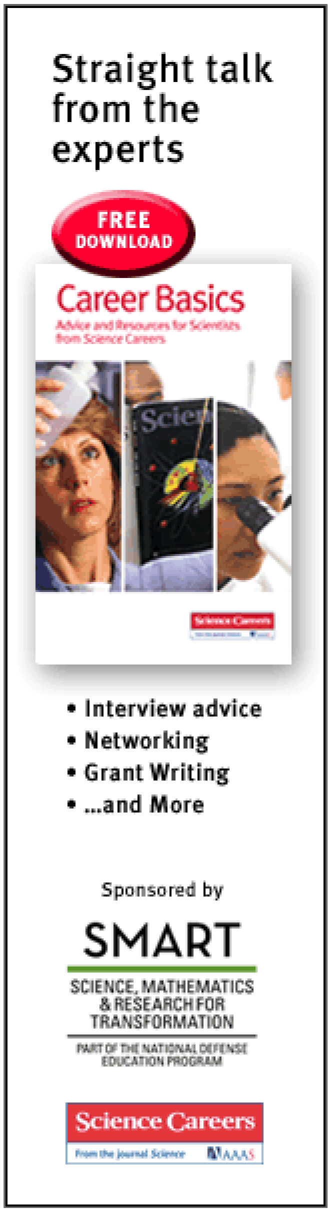
CREDIT : P. E. OLSON

Recognition of this Triassic-Jurassic LIP has been long in coming, perhaps delayed by the fact it was dismembered during formation of the Atlantic Ocean, either deep eroded or deeply buried, and is difficult to precisely date. However, as long ago as 1971, May (4) showed that the numerous linear dikes [HN8] of basaltic composition in eastern North America, Africa, southwestern Europe, and South America made up a giant radiating dike swarm when placed in their predrift positions, their focus being near Florida. This is in fact the largest radiating dike swarm known in the solar system (5). By the 1980s, it was becoming clear that at least some of these dikes fed the voluminous basalt flows and sills [HN9] in the Triassic-Jurassic rift basins [HN10] on the Atlantic Margin (6) and that the age of this dike system is about 201 million years (7). Paleontological data established that the flows were very close in time to the Triassic-Jurassic boundary and hence to its purported mass extinction event and that the flows in fact date the boundary (8). As was true for the events at the end of the Permian and the Cretaceous, the temporal association of the extensive basalt flows and a mass extinction has led to speculation that the eruption of the lavas triggered ecologically catastrophic climate change through massive input of volatiles into the atmosphere [HN11] (9).

As with the other two events, however, the proposed links between the CAMP LIP and mass extinction remain very controversial, with substantial volume, timing, and mechanism problems. Although the preerosional extent of the Deccan and Siberian lavas probably exceeded 2.0 × 10^6 km^3, the present volume of CAMP lavas in the rift basins is more than an order of magnitude smaller. However, all of the exposed rifts are deeply eroded to depths of several kilometers (10). Assuming that the distribution of dikes and other intrusions is a guide to the preerosion extent of the associated lavas, Marzoli *et al.* (3) estimate the original volume of flows at about the same as those of the Deccan or Siberian Traps. There is circumstantial evidence (11) that the recently recognized seaward-dipping reflectors (12) off the eastern United States may also be part of the CAMP, although their age is very poorly constrained. The volume of these basaltic, purportedly terrestrial, flows would raise the total to about 4 million km^3. This excludes the volume of intrusive CAMP rocks, which could add about the same amount again.

So it is plausible that the actual volume of CAMP basalts was as great or greater than that of the Siberian or Deccan Traps. Superficially, however, the timing of the CAMP event has seemed wrong for the extinctions at the end of the Triassic. In recent years, the Triassic-Jurassic boundary, marking the extinction, has been identified with considerable precision, but at all of the places in which the boundary and the lavas have been seen in superposition, from Virginia to Nova Scotia, the boundary always lies below the oldest lavas (8). Although these observations cover only a small part of the CAMP, it is hard to argue causation if the cause occurs after the supposed effect. However, the mostly normal magnetic polarity of the igneous rocks (13) and the statistical properties of polarity stratigraphy [HN12] around the Triassic-Jurassic boundary (13, 14) argue for a brief (less than 2 million years) igneous episode with some magmatic activity preceding the boundary, and half could have occurred before and could have caused the extinctions.

A number of plausible mechanisms linking the mass extinctions at the end of the Triassic with LIPs have been proposed, with strong parallels being drawn with the events at the end of the Permian and the Cretaceous (15). These include massive



emissions of CO_2 or SO_2 aerosols from LIPs (16), rapid sea-level change (17), and a bolide impact (18).

CO_2 input could have produced substantial global warming and SO_2 global cooling if introduced over a sufficiently brief interval. Both should leave a discernible geochemical record in marine and lacustrine sediments, fossil soils (19), and fossil plant anatomy (20). Thus far, the available data from the terrestrial record are consistent with an abrupt and strong disruption of the carbon cycle [HN13], specifically with an increase in CO_2, although explanations of its origin are diverse. There is as yet no evidence of an SO_2-induced cooling.

In the sea-level change scenario, thermal doming associated with the initiation of Pangean rifting followed by collapse during CAMP eruption produced a very rapid regression-transgression couplet that presumably disrupted marine communities, resulting in the observed marine mass extinction (17). Hallam and Wignall (17) have indeed argued that sea-level change was the major cause of all of the major extinctions of the past 500 million years. It is difficult to see how the sea-level change would cause the terrestrial extinctions, however.

A viable alternative for a CAMP-induced extinction at the end of the Triassic is a bolide impact [HN14]. The overall extinction pattern and associated floral effects at the Triassic-Jurassic boundary [HN15] do parallel those associated with the Cretaceous-Tertiary Chicxulub impact [HN16] (21). Evidence includes the presence of a massive increase of spores at the Triassic-Jurassic boundary (8), which has been attributed, as in the case of the very similar "fern spike" at the Cretaceous-Tertiary boundary, to impact-induced massive ecological disruption (22). In addition, shocked quartz [HN17] has been reported from two marine boundary sections (23), although both are disputed (17). However, concerted efforts to find shocked quartz in continental sections at the Triassic-Jurassic boundary have yet to be carried out.

Conventional theories of the origin of LIPs involve mantle dynamics, in particular, mantle plumes and hot spots [HN18] (1). In these models, the deep mantle generates a hot, upwelling plume of relatively low-density material that rises and eventually ponds at the base of the lithosphere, generating melt. Rifting in the region of the CAMP was occurring for at least 30 million years before the magmatic episode, so the crust was thinning in advance. According to Marzoli *et al.* (3), their new age and geochemical data are consistent with a plume head separated from its tail and spread over an extremely large area. Structural data from rift basins in the southeastern United States suggest that they ceased subsidence [HN19] and underwent tectonic inversion (under compression in the same direction in which they were previously under extension) close to the focus of the CAMP before or at the time of its emplacement (11). Simultaneously, rift basins farther north actually accelerated in subsidence. Sequentially, over the next 145 million years, the pattern of initial sea floor and seaward-dipping reflector formation and concomitant rift basin inversion seems to have proceeded north and probably south from the locus of CAMP igneous activity (11). All this suggests strong, if poorly understood, links behind the CAMP, core-mantle processes, and plate motions.

Presently, virtually all aspects of the CAMP LIP are controversial. Major problems that need to be addressed in the near term include (i) establishing the precise age range of the igneous event by direct dating of CAMP dikes in eastern North America by multiple methods; (ii) determining the magnetic polarity of a large suite of dikes, sills, and flows over a major portion of the CAMP; (iii) establishing the relative stratigraphic position, age, and magnetic polarity of the basalt flows in the southeastern United States; (iv) direct sampling and dating of the deeply buried, seaward-dipping reflectors offshore of the southeastern United States; and (v) searching for biological, geochemical, and mineralogical proxies of events related to the CAMP event, impacts, and the Triassic-Jurassic boundary.

As has long been noted, the implications of bolide impacts and massive volcanism can be very similar (24). The Cretaceous-Tertiary Chicxulub bolide, for example, struck marine limestone and sulfate, so a massive input of both CO_2 and SO_2 has been proposed as a major cause of the extinctions and ecosystem disruption (25), the same cause proposed for the effects of terrestrial LIPs. Indeed, an impact origin for both the Triassic-Jurassic and Cretaceous-Tertiary LIPs has been hypothesized (26), although plausible linkages with the specific events seem hard to come by. Nonetheless, the coincidence of the three largest Phanerozoic mass extinctions with the three largest continental LIPs--two possibly with giant bolide impacts--does demand very close scrutiny.

References and Notes

1. M. F. Coffin and O. Eldholm, *Rev. Geophys.* **32**, 1 (1994).
2. I. H. Campbell, G. K. Czamanske, V. A. Fedorenko, R. I. Hill, V. Stepanov, *Science* **258**, 1760 (1992) **[GEOREF]**.
3. A. Marzoli *et al.*, *ibid.* **284**, **616** (1999).
4. P. R. May, *Geol. Soc. Am. Bull*. **82**, 1285 (1971) **[GEOREF]**.
5. Based on comparisons of figures in R. E. Ernst *et al.*, *Earth Sci. Rev.* **39**, 1 (1995).
6. A. R. Philpotts and A. Martello, *Am. J. Sci.* **286**, 105 (1986) **[GEOREF]**; N. M. Ratcliffe, *U.S. Geol. Surv. Bull.* **1776**, 113 (1988).
7. J. F. Sutter, *U.S. Geol. Surv. Bull.* **1776**, 194 (1988); P. Hodych and G. R. Dunning, *Geology* **20**, 51 (1992) **[GEOREF]**.
8. S. J. Fowell *et al.*, *Geol. Soc. Am. Spec. Pap.* **288**, 197 (1994).
9. P. R. Renne, Z. Zichao, M. A. Richards, M. T. Blank, A. R. Basu, *Science* **269**, 1413 (1995) **[GEOREF]**; D. M. McClean, *Cretaceous Res.* **6**, 235 (1985) **[GEOREF]**; M. R. Rampino and R. B. Stothers, *Science* **241**, 663 (1988) **[GEOREF]**; V. Courtillot *et al.*, *Lunar Planet. Inst. Contrib*. **825**, 27 (1994); J. G. McHone, *Geology* **24**, 319 (1996) **[GEOREF]**.
10. K. Roden and D. S. Miller, *Schweiz. Min. Petrogr. Mitt.* **71**, 187 (1991); M. S. Steckler *et al.*, *Geology* **21**, 735 (1993) **[GEOREF]**; M. A. Malinconico, *Geol. Soc. Am. Abstr. Program* **31**, A31 (1999).
11. M. O. Withjack *et al.*, *Am. Assoc. Pet. Geol. Bull.* **82**, 817 (1998).
12. W. S. Holbrook and P. B. Kelemen, *Nature* **364**, 433 (1993) **[GEOREF]**.
13. W. A. Smith, *Tectonophysics* **136**, 137 (1987) **[GEOREF]**.
14. D. V. Kent *et al.*, *J. Geophys. Res.* **100**, 14965 (1995).
15. K. G. Caldeira and M. R. Rampino, *Geol. Soc. Am. Bull.* **247**, 117 (1990).
16. J. M. McHone and J. H. Puffer, in *Aspects of Triasssic-Jurassic Geoscience*, P. M. LeTourneau and P. E. Olsen, Eds. (Columbia Univ. Press, New York, in press).
17. A. Hallam and P. B. Wignall, *Mass Extinctions and Their Aftermath* (Oxford Univ. Press, Oxford, 1997) **[publisher's information]**.
18. P. E. Olsen, F. J. Fowell, B. Cornet, *Geol. Soc. Am. Spec. Pap*. **247**, 585 (1990).
19. C. J. Yapp and H. Poths, *Earth Planet. Sci. Lett.* **137**, 1 (1996) **[GEOREF]**.
20. J. C. McElwain and W. G. Chaloner, *Palaios* **11**, 376 (1996).
21. P. E. Olsen, N. H. Shubin, M. E. Anders, *Science* **237**, 1025 (1987) **[GEOREF]**.
22. R. H. Tschudy, C. L. Pillmore, C. J. Orth, J. S. Gilmore, J. D. Knight, *Science* **225**, 1030 (1984) **[GEOREF]**.
23. D. M. Bice, C. R. Newton, S. McCauley, P. W. Reiners, C. A. McRoberts, *ibid.* **255**, 443 (1992) **[GEOREF]**.
24. W. Glen, *The Mass Extinction Debates: How Science Works in a Crisis* (Stanford Univ. Press, Stanford, CA, 1994).
25. K. O. Pope *et al.*, *Earth Planet. Sci. Lett.* **128**, 719 (1994) **[GEOREF]**; J. D.

O'Keefe and T. J. Ahrens, *Nature* **338**, 247 (1989) **[GEOREF]**.

26. R. S. Dietz, *Lunar Planet. Inst. Contrib*. **600**, 1 (1986); R. Nason, *Eos* **74** (Fall Meet. Suppl.), 556 (1993); M. B. Boslough *et al.*, *Geol. Soc. Am. Spec. Pap.* **307**, 541 (1996).
27. This is Lamont Doherty Earth Observatory contribution 5923.

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HyperNotes

Related Resources on the World Wide Web

GENERAL HYPERNOTES

West's Geology Directory, maintained by I. West, School of Ocean and Earth Science, Southampton University, UK, is an annotated collection of links to geological Web resources arranged by topic.

The Department of Geology and Paleontology, University of Geneva, Switzerland, provides links to Earth sciences resources on the Web.

The Geoscience Information Center at the Scripps Institution of Oceanography offers a searchable database of Web resources in geoscience.

Yahoo! provides links to Internet geology and geophysics resources.

The Department of Geology and Geophysics, University of Alaska, Fairbanks, presents a geologic time scale. A guide to geologic time divisions is provided by the University of California Museum of Paleontology.

Global Earth History, presented by R. Blakey, Department of Geology, Northern Arizona University, Flagstaff, is a series of plate tectonic reconstructions that show the broad patterns of Earth history.

The Geology Department of Iowa State University provides the Illustrated Glossary of Geologic Terms.

J. Rial, Geology Department, University of North Carolina, Chapel Hill, offers a hypertext introduction to geodynamics.

The March-April 1995 issue of *American Scientist* featured an article by M. Wysession titled "The inner workings of the Earth."

T. Lay and R. Anderson, Department of Earth Sciences, University of California, Santa Cruz, provide lecture notes for a course on Earth catastrophes.

R. Phinney and A. Rubin, Department of Geosciences, Princeton University, offer lecture notes for a course on earthquakes, volcanoes, and other hazards. A glossary is provided.

The Department of Geology and Planetary Sciences, University of Pittsburgh, offers V. Schmidt and W. Harbert's hypermedia course Planet Earth and the New Geosciences, which includes a unit on plate tectonics.

Georgia Geosciences Online presents a Web-based course by P. Gore on physical geology; links to Internet resources are provided for each topic.

The Volcanic Homepage of J. Dehn, Geological Survey of Japan, has an extensive collection of Web resources on volcanism.

The Volcanic Hazards Program of the U.S. Geological Survey (USGS) presents a

Photoglossary of Volcanic Terms.

VolcanoWorld, funded by NASA at the University of North Dakota, is an educational site with extensive information about volcanoes and volcanism; an index of topics covered is provided.

The Global Volcanism Program of the U.S. National Museum of Natural History provides links to Internet resources on volcanology.

The 1999 Spring meeting (Boston, June 1-4) of the American Geophysical Union will include a session on the earliest magmatism of the Circum-Atlantic Large Igneous Province.

NUMBERED HYPERNOTES

1. The **Institute for Geophysics**, University of Texas, Austin, provides a page about **large igneous provinces** in their summaries of **research projects**. The **Natural Resources Development Centre**, Trinity College, Dublin, provides an introduction to **large igneous provinces**. The **Whyfiles: Science Behind the News** from the University of Wisconsin has a section about **flood basalts** in the **Volcano Lovers** presentation. The **USGS Cascades Volcano Observatory** provides an **introduction** to lava plateaus and flood basalts. P. Asher, Department of Geology, Pomona College, Claremont, CA, summarizes information about **continental flood basalts** as supplemental material for teaching about **petrology and plate tectonics**.

2. The USGS **Photoglossary of Volcanic Terms** has entries for **basalt**, **magma**, and **lava**. J. Revenaugh, **Department of Earth Sciences,** University of California, Santa Cruz, presents lecture notes on **igneous rocks and volcanism** for a **course** in geologic principles. L. McKenna, Department of Geology, University of Kansas, provides lecture notes on **igneous rocks** for a **course** on the history of the Earth. S. Nelson, Department of Geology, Tulane University, discusses the formation of magmas and igneous rocks in **lecture notes** for a **petrology course**.

3. The 18 September 1995 issue of *Time* magazine had an **article** about P. Renne's research that links the Siberian volcanic eruption with the Permian extinction. A 12 July 1991 **press release** from the University of Rochester titled "Massive volcanic eruptions in Siberia linked to largest extinction" described the research of P. Renne and A. Basu; a 22 July 1998 **press release** about research on the Siberian flood basalt was titled "Magma's makeup yields new clues to catastrophic eruptions." The 15 May 1998 issue of *Science* included a **Research News article** by Richard Kerr titled "Biggest extinction looks catastrophic" about research that indicates the sudden Permian extinction may be related to the Siberian Traps volcanism. R. Cowen, Department of Geology, University of California, Davis, presents an **essay** on the Permo-Triassic extinction and the Siberian Traps.

4. **VolcanoWorld** presents a brief introduction to the **Deccan Traps**. **D. McLean**, Department of Geological Sciences, Virginia Polytechnic Institute, Blacksburg, offers an **introduction** to Deccan Traps mantle plume volcanism.

5. A. Marzoli is in the **Départment de Minéralogie**, University of Geneva, Switzerland. **P. Renne** is at the **Berkeley Geochronology Laboratory** and the **Department of Geology and Geophysics**, University of California, Berkeley. E. Piccirillo and A. de Min are in the **Dipartimento di Scienze della Terra**, Universita di Trieste, Italy. **M. Ernesto** is in the **Departamento de Geofísica**, **Instituto Astronômico e Geofísico**, Universidade de São Paulo, Brazil. G. Bellieni is in the **Dipartimento di Mineralogia e Petrologia**, Universita di Padova, Italy.

6. **Mass Extinctions of the Phanerozoic** is a presentation of the **Hooper Virtual Paleontological Museum**, a project of the Ottawa-Carleton

Geoscience Centre and the Department of Earth Sciences, Carleton University, Ottawa, Canada. T. Sherry, Department of Ecology, Evolution, and Organismal Biology, Tulane University, New Orleans, discusses the **causes of mass extinctions** in lecture notes for a **course** on the processes of evolution. **S. Leslie**, Department of Earth Sciences, University of Arkansas, Little Rock, provides an overview of **extinction** in **lecture notes** for a **paleontology course**. T. Lay and R. Anderson, Department of Earth Sciences, University of California, Santa Cruz, provide **lecture notes on extinction** for an Earth sciences **course** on catastrophes. The **University of California Museum of Paleontology** provides information about the **dinosaur extinction** and the theories of its cause.

7. The **University of California Museum of Paleontology** provides an introduction to **plate tectonics** that provides animations of continental drift and a discussion of the **mechanism** involved. The **Hartebeesthoek Radio Astronomy Observatory**, South Africa, presents an introduction to **plate tectonics and continental drift**. C. Ammon, Department of Earth and Atmospheric Sciences, St. Louis University, provides an illustrated **introduction to plate tectonics** in **lecture notes** for a **course** on earthquakes. ***This Dynamic Earth: The Story of Plate Tectonics*** is available on the Web from the USGS.

8. The USGS **Photoglossary of Volcanic Terms** defines **dike**.

9. **Sill** is defined in the **Illustrated Glossary of Geologic Terms**.

10. **Rift** is defined in the **glossary** for a course on earthquakes, volcanoes, and other hazards at Princeton University. An introduction to the structural geology and stratigraphy of **rift basins** is provided by the **Extensional Tectonics Working Group** at the Department of Geological Sciences, Rutgers University. The **Newark Basin Coring Project** of the Lamont-Doherty Earth Observatory was a rift basin drilling project to document the record of ancient continental climate cycles and to produce a **Late Triassic magnetic polarity time scale** and a detailed record of the evolution of a continental rift basin.

11. The **Volcanic Information Center**, maintained by R. Fisher, Department of Geological Sciences, University of California, Santa Barbara, provides an introduction to the **effects of volcanic gases**. The **USGS Volcanic Hazards Program** provides information about **volcanic gases**. The **USGS Cascades Volcano Observatory** has a **project** on volcanic emissions and climate change and provides a **fact sheet on volcanic gases**. VolcanoWorld offers a presentation on **volcanic gases**, which includes a section titled **"Dead dinosaurs and gases."** D. McLean, Department of Geological Sciences, Virginia Polytechnic Institute, Blacksburg, offers a **presentation** titled "Dinosaur extinction: The volcano-greenhouse theory."

12. **J. Kappelman**, Department of Anthropology and Department of Geological Science, University of Texas, Austin, provides a brief introduction to **paleomagnetism**. Bill Chaisson, Department of Earth and Environmental Sciences, University of Rochester, provides lecture notes on **geomagnetics** for a **course** on the evolution of Earth. R. Maddocks, Department of Geosciences, University of Houston, discusses **paleomagnetism** and **polarity reversals and sea-floor spreading** in **lecture notes** on early tectonic theories for an **introductory oceanography course**. The **American Geophysical Union** provides an **article** by G. Acton and K. Petronotis titled "Studying oceanic plate motions with magnetic data" and an **article** by K. Hoffman titled "How are geomagnetic reversals related to field intensity?"

13. An introduction to the **global carbon cycle** is provided by the

Woods Hole Research Center.

14. The **Chesapeake Bay Bolide** Web page provided by the **USGS Woods Hole Field Center**, offers an **introduction to bolides**. An **article** by R. Cygan titled "Shock therapy: How Earth responds to impacts from outer space" is available from the **AGU Science for Everyone** Web page. **Nine Planets** includes a presentation on **meteors, meteorites, and impacts**. The January-February 1997 issue of ***American Scientist*** had a **column** by L. Penvenne titled "The bolide and the biosphere." P. Olsen, Lamont-Doherty Earth Observatory of Columbia University, provides lecture notes on the **impact theory of mass extinction** for a **course** on dinosaurs and the history of life.

15. The 16 May 1998 issue of ***Science News*** had an **article** by R. Monastersky titled "Target Earth: Geologists link a chain of craters" about the possible link between impact craters and Triassic extinctions. P. Olsen discusses the **Late Triassic mass extinction** in **lecture notes** for a **course** on dinosaurs and the history of life.

16. The **Chicxulub Seismic Experiment** Web site of the **Geophysics Research Group**, Imperial College London, provides background information on the impact and the crater. The **Meteorite and Impacts Advisory Committee** to the Canadian Space Agency offers a **presentation** about the Chicxulub crater and the Cretaceous-Tertiary boundary. The American Geophysical Union provides an **article** by V. Sharpton titled "Chicxulub impact crater provides clues to Earth's history." In his **contribution** to the ***U.S. National Report to IUGG, 1991-1994***, P. Claeys included a **section** titled "Chicxulub crater and impact products at the KT boundary in the Gulf of Mexico region."

17. In **lecture notes** for a **course**, P. Smith, Department of Earth and Ocean Sciences, University of British Columbia, provides a definition of **shocked quartz**.

18. The Illustrated Glossary of Geologic Terms defines **hot spot** and **mantle plume**. T. Lay presents **lecture notes** on rifts, hot spots, and volcanic products. A. Rubin provides **lectures notes** on volcanism in the oceans for a **course** on earthquakes, volcanoes, and other hazards. ***This Dynamic Earth***, available on the Web from the USGS, includes a **chapter** titled "'Hotspots': Mantle thermal plumes." VolcanoWorld presents a **lesson** on hot spots and mantle plumes from the **book** titled *A Teacher's Guide to the Geology of Hawaii Volcanoes National Park*. **A. Basu**, Thermal Ionization Mass Spectrometry Laboratory, University of Rochester, provides an illustrated overview of his research projects on **deep mantle plumes**.

19. **Subsidence** is defined in the **Dictionary of Mining, Mineral, and Related Terms**.

20. **P. E. Olsen** is in the **Triassic-Jurassic Working Group** at the **Lamont-Doherty Earth Observatory** of Columbia University. His **homepage** provides additional information.

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Science. ISSN 0036-8075 (print), 1095-9203 (online)