# Continental Breakup and Sedimentary Basin Formation

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Earth history is punctuated by continents breaking apart and births of oceans, phenomena occurring today in places such as the high Arctic, East Africa/Red Sea, the Gulf of California, and the western Pacific near Papua New Guinea.

The tectonic, magmatic, geodynamic, and sedimentary processes associated with continental rifting and breakup interact to produce a variety of margin styles of rifting and breakup, ranging from narrow to hyperextended margins, from weakly to strongly magmatic margins, and from sediment-starved to thickly sedimented margins. The wide variety of styles has puzzled and inspired Earth scientists for generations, who have employed an increasingly diverse and sophisticated set of observational tools to investigate, and conceptual models to explain, continental rifting and breakup.

A trio of Integrated Ocean Drilling Program (IODP) platforms and associated technologies available beginning in late 2007 or early 2008 will provide researchers worldwide with enhanced capabilities for sampling, logging, and monitoring the Earth's crust and uppermost mantle beneath the sea. Opportunities offered via the proposal-driven IODP by the new Japanese riser (controlled drilling fluid circulation and blowout prevention) drill ship *Chikyu*, the converted to-be-named U.S. riserless (sea-water as the drilling fluid) drilling vessel, and shallow-water and Arctic mission-specific platforms provided by the European Consortium for Ocean Research Drilling (ECORD) essentially lay bare the entire Earth beneath the sea for investigation.

Fifty-one scientists from six continents met in Pontresina, Switzerland, in mid-September to discuss strategies for advancing understanding of continental rifting and breakup using the new drilling platforms and associated technologies. Over four days of plenary and breakout group meetings, including a one-day field trip, observational scientists and modelers educated one another about the world's continental margins, discussed the outstanding problems related to margin initiation and development, and outlined a global mission to address these problems via drilling and monitoring, in conjunction with complementary geophysical and geological studies.

### Setting the Stage

Rifted continental margins globally span a continuum from highly magmatic to magma-poor, or hyperextended, although they are typically characterized as volcanic or nonvolcanic end-members, respectively. To set the stage for intensive discussions, workshop participants heard global overviews of volcanic (Sverre Planke, Volcanic Basin Petroleum Research, Norway) and nonvolcanic (Timothy Reston, University of Birmingham, U.K.) rifted margins, keynote presentations that illuminated both magmatic and tectonic aspects, respectively, of continental rifting and breakup. Focusing on the two most studied conjugate margin end-members, Norway–East Greenland and Iberia-Newfoundland, respectively, Planke and Reston summarized current knowledge, hypotheses, and outstanding problems. The next keynote presentation (Anthony Watts, University of Oxford, U.K.) homed in on the role of the IODP in addressing key themes in continental rifting and breakup.

Critical outstanding problems highlighted in the three keynote addresses included (1) determining the geochemistry, ages, volumes, fluxes, and emplacement processes of magmatism during rifting and breakup, important for understanding both geodynamic processes and potential paleoenvironmental impacts; and (2) overall rifting history (including pressure-temperature-time paths), symmetry/asymmetry of extension and breakup, timing and geometry of detachment faulting, vertical crustal movement and strain rate histories, the extent of mantle unroofing, the role of preexisting crust (e.g., in rift localization and segmentation), and evolution of the continental lithosphere during rifting.

The fourth and final keynote presentation (Greg Myers, IODP Management International) introduced and compared capabilities of the three IODP platforms (riser, nonriser, and mission-specific), summarized drilling and coring techniques and tools, and detailed downhole logging and observatory opportunities for researchers.

### Margins Around the Globe

The depth and breadth of expertise among workshop participants enabled sharing of continental rifting and breakup knowledge from around the globe. Active rifting in the Gulf of California, Woodlark Basin (western Pacific), Lena Trough (Arctic), and East Africa/Red Sea is literally 'where the action is,' offering contemporary examples for investigations into the tectonic processes controlling and accompanying rifting and breakup. However, it appears that no highly magmatic margins are forming today, so ancient examples such as the conjugate East Greenland–Norwegian (global type example), conjugate Kerguelen/Naturaliste–East Antarctic/Bruce Bank, conjugate South Atlantic, and the conjugate-less West Australian margins constitute areas for investigation of magmatic processes associated with rifting and breakup.

The conjugate Iberia-Newfoundland margins, although inactive, constitute the global type example of hyperextended rifting and breakup, offering an array of opportunities for tectonic hypothesis-testing using drill cores and downhole logs as ground truth. Dense industry data coverage of the South Atlantic margins north of the Sao Paulo Plateau (South America) and Walvis Ridge (Africa) provides complementary prospects for understanding another hyperextended conjugate margin pair. Tectonic understanding may also be advanced at relatively young conjugate rifted margins such as those flanking the Gulf of Aden, the Adare Trough (East Antarctica), as well as at the margins of the marginal or back-arc basins of the western Pacific (e.g., South China Sea, East Sea/Sea of Japan, Shikoku Basin, Parece Vela Basin), the Aegean Sea, and the Black Sea.

### Alpine Ground Truth

Northern Italy and the Engadin region of southeastern Switzerland feature well-exposed remains of continental rifting and breakup. Workshop participants devoted a day to viewing, examining, and discussing remnants of hyperextended ancient Tethyan continental margins, led by Engadiner Gianreto Manatschal (Université Louis Pasteur, Strasbourg, France).

The first locality, Livigno/Il Motto in Italy, preserves structures of the proximal Adriatic margin and was viewed from a distance. The second locality, the Tasna ocean-continent transition above Scuol in the Lower Engadin of Switzerland, afforded participants the opportunity to walk from the continent to the ocean side of the transition and examine changing rock types and deformational styles. Both locales are analogs for the hyperextended conjugate Iberia-Newfoundland margins.

### Nuts and Bolts of IODP Proposals and Drill Site Characterization

Practical matters necessary for scientific ocean drilling were the subject of two presentations, (1) the IODP proposal process, including preparation, submission, nurturing, evaluation, ranking, and scheduling via the IODP Science Advisory Structure, IODP Management International, and the implementing organizations (Mike Coffin, University of Tokyo, Japan), and (2) drill site characterization, primarily on the basis of geophysical (seismic reflection) data, but also including geological data, and electronic submission of digital site characterization data to the IODP Site Survey Data Bank (Dale Sawyer, Rice University, Houston, Tex.). Workshop participants learned that a proposal benefits from a team of coproponents whose expertise encompasses all aspects of the proposal, including drill site characterization. Following drilling expeditions, both operational and scientific reviews are conducted.

During the workshop, participants presented and examined many site characterization data, especially seismic reflection and refraction, and highlighted the importance of linking such data with drilling much more closely. They endorsed the principle of integrated site characterization and drilling within the IODP, and unanimously recommended that the IODP provide financial support for site characterization as well as drilling in addressing high-priority scientific themes and initiatives of the IODP.

### *Key Themes*

Salient problems involving continental rifting and breakup discussed at the workshop fall into six themes: (1) rift initiation, (2) tectonic and dynamic aspects of rift evolution, (3) magmatic aspects of rift evolution, (4) sedimentary, paleoenvironmental, and oceanographic aspects of rift evolution, (5) initiation of seafloor spreading, and (6) consequences and impact.

Rift initiation objectives include understanding rift dynamics, inherited lithospheric conditions, and early magmatism. With respect to tectonic and dynamic aspects of rift evolution, goals are to elucidate both strain distribution and variations in dynamics in space and time. Key targets in magmatic aspects of rift evolution are increased knowledge of melting, magmatic flux, magma transport, and emplacement, discussion participants agreed.

For sedimentary, paleoenvironmental, and oceanographic aspects of rift evolution, meeting attendees believed that the aim is to increase comprehension of paleogeography, paleoenvironments, and the development of depositional systems in space and time. The purpose of investigating the initiation of seafloor spreading is to glean information on seafloor spreading ridge evolution as well as the tectonic and magmatic response on the preferably conjugate margins.

Finally, studies of consequences and impact are needed, meeting participants agreed. Such studies will target paleoenvironmental changes related to rifting and rift magmatism, and the prospects for eventual subduction or obduction.

### *An IODP Mission*

The IODP is poised to solicit and consider a new type of proposal, one for missions. A mission is an intellectually integrated and coordinated drilling strategy originating from the scientific community that (1) addresses a significant aspect of an IODP Science Plan theme on a global basis over an extended period of IODP, and (2) merits urgent promotion to achieve overall IODP program goals.

Workshop participants reached consensus to develop a mission proposal addressing continental rifting and breakup globally that provisionally will target active rifting and breakup in the Gulf of California and Woodlark Basin, highly magmatic margins (e.g., conjugate Norwegian–East Greenland and conjugate-less Western Australian), and the hyperextended conjugate margins of Iberia-Newfoundland and the South Atlantic. Spearheaded by John Hopper (Texas A&M University, College Station), the mission proposal will be developed between now and an anticipated 1 April 2007 submission by a team of observational and modeling specialists working on mission component themes.

Importantly, however, the mission proposal will not exclude individual proposals on any aspect of continental rifting and breakup from being developed and submitted to the IODP by interested proponent groups.

The Investigating Continental Breakup and Sedimentary Basin Formation workshop, presented by IODP Management International and InterMARGINS, was held 15–18 September 2006 in Pontresina, Graubünden, Switzerland. A scientific white paper on continental breakup and sedimentary basin formation is in preparation for publication in *Scientific Drilling*, and the full workshop report is scheduled to be available in late 2006 at http://www.iodp.org, which is also the source of comprehensive information about the IODP.

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# FORUM

## On "Earth Sciences and Public Schools"

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Earlier this year, Robert Kitchen (*Eos, 87*(24), 235, 2006) drew attention to declining interest in Earth science education in public schools. The reason for a lack of interest in teaching Earth sciences in public schools may involve more than just the attitudes of parents who may wish for their children a better preparation for advanced placement courses later on. Part of the problem may lie with our present mind-set that technology can solve all the world's problems, from poverty, to better health, and to prosperity.

Underlying this mindset is an implicit belief in the primacy of the physical sciences. A corollary is that Earth sciences do not have an independent existence within human knowledge, but exist merely as an adjunct to physical-mathematical sciences. Given sufficient time, and bigger computers, it is believed, science can and will know everything there is to know about the Earth. This perception probably has an influence on school administrators who feel that students need a demanding curriculum, comprising rigorous training in the physical sciences.

It is true that imparting instructions in mathematics and physics is demanding. It is also necessary, though, to recognize that training the mind to 'read' rocks, the landscape, the animals, and the plants can be equally demanding and fascinating. For example, the remarkable contributions of James Hutton (who surmised that the Earth must be so old as to be timeless), Charles Darwin (who estimated that the Earth must be as old as 300 million years), Thomas Chamberlain (who suspected that there must be some source of heat within the Earth, perhaps tied up with the atoms), and Alfred Wegener (who argued persuasively for continental drift) stemmed from intrinsic curiosity about the Earth, rather than from the processes responsible for shaping it. Our ability to solve well-defined problems and the gift for connecting seemingly disparate ideas both are part of our astonishing human psyche. The challenge of precollege education is to strike a balance between the two. One part of the training consists of providing students with a critical quantum of information, tools, and methods. Another part consists of nourishing their ability to think, make sense, and figure out the world around them.

Human knowledge includes physical sciences and Earth sciences as parts of a larger whole. This is the spirit of a liberal education. Over the past few decades, we have learned enough to conclude that the Earth is a very complex system with myriad intricately linked components. We are also learning that we face a greater challenge of adapting to the constraints of a finite Earth than of developing new technologies to control it. Important social decisions of the future likely will test our ability as citizens to make difficult judgments on matters that defy quantification but are subject to 'values.'

It seems reasonable to conclude that the future of Earth science education in our public schools will depend upon whether we consider our Earth and environment to be deserving of comprehension in their own right, or whether we believe that technology, combined with market forces, renders Earth science education dispensable.

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