# Tectonic, Magmatic, Hydrothermal and Biological Segmentation of Mid-Ocean Ridges

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# Tectonic, Magmatic, Hydrothermal and Biological Segmentation of Mid-Ocean Ridges

EDITED BY

C. J. MACLEOD
University of Wales, Cardiff, UK

P. A. TYLER
University of Southampton, UK

and

C. L. WALKER
University of Leeds, UK

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# Preface

Up until the early 1980s it was confidently believed that mid-ocean ridges were simple, linear volcanic features interrupted only by transform faults spaced hundreds or thousands of kilometres apart. It was only when ridge axes were first surveyed with the new, high-resolution multibeam echosounding systems that we discovered that the zone of active volcanism is further sub-divided into discrete spreading segments on a variable, but much smaller, scale. Small lateral offsets or misalignments of these spreading cells occur, and a whole new class of ridge axial discontinuities was recognized: 'overlapping spreading centres', 'non-transform offsets', 'deviations from axial linearity' etc. These findings have given rise to a completely new view of the global mid-ocean ridge system, as a much more complex, dynamic environment, and in turn spawned intensive study of how and why ridges are segmented in this way. We now know that along-axis variations in the morphology of the ridge crest reflect significant differences in the structure of the sub-seafloor magma reservoirs and the extent and nature of upwelling of partially molten mantle beneath the axis. Segments ends are starved of magma relative to segment centres, and plate separation, especially at slow-spreading ridges, may be accommodated by variable degrees of tectonic stretching as well as by magmatic accretion. Seawater penetration into the crust and eventual outflow at black smoker vents depends heavily upon the location of the magmatic heat source and the nature and distribution of permeability in the crust, leading to a relationship between the locus of hydrothermal discharge and the tectonomagmatic segmentation. In turn, the mechanisms of faunal colonization of vent sites and the evolutionary history of the vent organisms are also affected by segmentation of the ridges, depending strongly upon the spatial distribution of vents and the hydrodynamics of dispersal of the vent fluids.

Segmentation, therefore, plays a vital role in all physical, chemical and biological processes at the mid-ocean ridge system. The continuum of processes clearly pays no need to traditional discipline boundaries, yet in order to comprehend any one part of the system it is vital that we understand how they inter-relate. The purpose of this book is to explore the causes and consequences of this ridge segmentation from the tectonic, magmatic, hydrothermal and biological viewpoint. It comprises 15 chapters of recent findings that span and attempt to link the entire spectrum of mid-ocean research. Much of the work presented herein was carried out under the aegis of the British mid-ocean ridge 'BRIDGE' programme, a Thematic Initiative supported by the UK Natural Environment Research Council.

Papers with a predominantly tectonic theme span a variety of scales. **Sempéré *et al.*** examine the segmentation characteristics of the intermediate-spreading rate Southeast Indian Ocean ridge adjacent to the Australian–Antarctic Discordance. Within the Discordance, which is a region of deep seafloor thought to be underlain by anomalously cold mantle, the spreading segments have morphologies akin to those of slow-spreading ridges; to the east of it, the ridge and ridge axial discontinuities are similar in appearance to those at fast-spreading ridges, with rifts propagating towards the Discordance. This shows that mantle temperature rather than spreading rate is the underlying control on segment characteristics. **Allerton *et al.*** and **McAllister & Cann** examine faulting processes and the formation of valley-wall faults at the slow-spreading Mid-Atlantic Ridge between the Kane and Atlantis fracture zones. Both studies use the Southampton Oceanography Centre's deep-towed sidescan sonar system, TOBI. TOBI data are of such high resolution when compared to conventional multibeam bathymetery data that these authors are able to erect detailed models for the processes of initiation, growth and degradation of faults within and between segments. **Blondel** introduces a technique for the automated classification of TOBI data, applying it to a section of the Mid-Atlantic Ridge south of the Azores in order to identify variations in the relationship between volcanism and tectonism along axis.

**Lawson *et al.*** examine the same TOBI images (from two segments immediately north of the Kane fracture zone) as Allerton *et al.*, but with the aim of understanding the volcanic geology on a small scale, and the effects of segmentation on magmatism. The TOBI data they ground-truth using near-bottom photographic traverses and dredges that have been located precisely relative to seabed volcanic features. From this extremely detailed study they obtain new insights into the plumbing system of the neovolcanic zone and, on a larger scale, assess the effects of the transform fault and non-transform discontinuity on magma transport and evolution. **Robinson *et al.*** discuss the geochemistry of dredge samples collected from the ultra-slow-spreading Southwest Indian Ridge. They show that melting is restricted in comparison to other, faster-spreading ridges, consistent with the suggestion that conductive heat loss is a significant factor in these very slow-spreading environments. **Batiza** presents a comprehensive overview of the link between magmatic and tectonic segmentation, based upon a compilation of geochemical studies of lava suites dredged from around the world's mid-ocean ridge system, and ranging from the global scale – from mantle source domains and implications for upwelling and melting processes – to the smallest scale of segmentation yet resolvable: individual volcanic edifices and the products of individual eruptions. **Edwards *et al.*** examine the effects of segmentation-related variations in melting beneath ridges by the complementary approach of studying the mantle peridotite residue from which the lavas were extracted. They compare the petrologies and geochemistries of peridotites recovered by dredging and/or Ocean Drilling Program drilling in the tectonic windows of Hess Deep and Garrett Deep. Both areas expose lithospheric mantle from beneath the East Pacific Rise, but the former is believed to be derived from beneath the centre of a segment, and the latter from the vicinity of a major segment end: the Garrett transform fault. Lower degrees of melting at Garrett Deep are related by the authors to a colder thermal regime adjacent to the axial discontinuity.

Despite the completely separate approaches adopted in those papers in this volume concerned with hydrothermal processes, a concensus is emerging as to the relative influence of both magmatism and tectonism upon hydrothermal circulation. **Haymon** updates conceptual models for ridge-crest hydrothermal systems in the light of new observations from the East Pacific Rise made from submersibles and remotely-operated vehicles. Venting appears to be associated either with 'magma-rich' or 'magma-poor' settings: in the former case discharge is magmatically controlled, associated spatially and temporally with a volcanic eruption or dyking episode; in the latter, the heat source is at greater depth, and venting is related to the spatial distribution of tectonically-induced faulting and fissuring. **MacLeod & Manning** investigate the latter, documenting the cooling history and development of permeability in high-level gabbros from the East Pacific Rise drilled in Hess Deep. They demonstrate that tectonically-induced fracturing at segment ends is an important means of allowing seawater deep into the lower crust at or near the ridge axis. **German *et al.*** come to a similar conclusion, but based upon evidence from seafloor and water-column data for abundant hydrothermal venting in spatial association with segment terminations on the Mid-Atlantic Ridge south of the Azores hotspot. This tectonic setting contrasts markedly with those of the other known vent sites elsewhere in the Atlantic, for example Broken Spur, which are situated in segment centres and fall in Haymon's 'magma-rich' category. With its abundant venting the Azores area also differs from the Reykjanes Ridge, which occupies a similar setting south of the Iceland hotspot, but along which hydrothermal activity is near-absent. On a slightly different theme, **Zaykov *et al.*** describe the setting and occurrence of fossil hydrothermal deposits in the Urals palaeo-ocean basin/island arc complex. Mineralization was apparently located close to the centres of the original oceanic segments, and in the more central parts of the palaeo-ocean.

Although the distribution of vents and their fauna is driven by physical and chemical processes, the fauna at vents is also a function of the regional plate tectonic history and segmentation pattern. **Tunnicliffe *et al.*** examine the distribution of present-day faunas with respect to the global configuration of the plates and, in particular, the spatial location of ridge axes. We often think of the mid-ocean ridge as a single, long, interconnected chain, but there are a number of places such as the Juan de Fuca Ridge where the spreading axis has been isolated long enough for a fauna to evolve that is related to, but distinctly different from, that of the East Pacific Rise and Galapagos Rift. Understanding the differences between the faunas of the mid-ocean ridge systems of the Pacific and Atlantic represents a future challenge. **Southward *et al.*** address the possible mechanisms for speciation at separate vent sites. Initially it was believed that two species of *Ridgeia* exist on the Juan de Fuca Ridge; however, the authors show, using molecular methods, that they are one, and therefore that the transform faults represent a minimal obstacle to genetic exchange. The last paper in the volume, by **Nisbet & Fowler**, presents some thought-provoking ideas on the origin of life at vents and particularly how bacteria have been central to this concept.

We would like to thank Lindsay Parson, who convened the original, highly successful meeting of the same name at Burlington House, London; his encouragement has been much appreciated. We are indebted, too, to Angharad Hills of the Geological Society Publishing House, for her calmness, patience and promptness during the preparation of this volume, especially at those times when we showed none of these qualities. Finally, we would like to thank the following individuals for refereeing the manuscripts submitted for publication in this volume; without their help we could not have maintained the high scientific standards for which we have striven: S. Allerton, R. Batiza, A. Briais, P. Browning, J. Cann, D. Christie, J. Cope, P. Cowie, G. Foulger, M. Fowler,

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The cover image, kindly provided by Roger Searle, shows the bathymetry of a spreading segment on the Mid-Atlantic Ridge between 28°40′ and 29°30′N. Warmer colours represent shallower regions. The blue region striking NNE through the centre of the image is the axial valley, containing the active plate boundary and site of most recent volcanism. The axial valley deepens towards the ends of the segment (as shown by the purple tones), and the plate boundary is offset right-laterally by approximately 20 km at each end. The image uses Sea Beam data collected by G. M. Purdy *et al.* (*Marine Geophysical Researches*, **12**, 247–252, 1990), illuminated for the NW and gridded at approximately 170 m intervals.

C. J. MacLeod
P. A. Tyler
C. L. Walker