The Ocean Lithosphere:
A Fundamental Component of the Earth System

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encapsulating discussions of the
InterRIDGE-IODP "Melting, Magma, Fluids and Life" Workshop [9]

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From its formation at mid-ocean ridges, to its recycling in subduction zones, the oceanic lithosphere serves as the major "process zone" where heat and material is exchanged between Earth's deep interior and the surface. Only within this thermally and hydrologically dynamic region is there direct interplay between mantle, crust, and ocean. The natural variability in thermal conditions associated with differences in accretionary magma supply and tectonics fosters a fascinating variety of hydro-bio-geochemical exchanges in the young (≲ 1 m.y.) lithosphere. Deep sea ecosystems thrive on the seafloor in zones with the highest thermal or chemical gradients, but the nature and extent of microbial life on/within the lower thermal and chemical gradients of aging ocean lithosphere (1-100 m.y.) remain unknown. Although the dominant fluid-rock reactions that occur during hydrothermal alteration of the ocean crust are well established, the magnitude of chemical exchange between the lithosphere and the oceans remains poorly quantified principally because of sparse and unrepresentative sampling. A major change in our understanding has recently occurred with the discovery that crust formed at slow and ultraslow spreading ridges is extremely diverse, ranging from large areas of the oceans floored by altered mantle rock, to regions with a thick layered crust. Such crust and exposed mantle will exchange with the oceans by very different reactions and is likely to play an important and hitherto unaccounted-for role in controlling ocean chemistry. Better quantification of global chemical cycles is crucial to understand the major drivers of climate change. In order to understand the accretion of the ocean crust and to quantify the sources, sinks, and pathways of heat and chemical transfer between the solid Earth, oceans and biosphere, both full penetration across the Moho and shallow targeted drilling, including in situ experiments, are required.

Introduction:

The formation and evolution of the oceanic lithosphere are key components in the Earth System. Many of the concepts and technologies associated with ocean lithosphere research are at the frontiers of human endeavor and knowledge. Implementation of experiments required to solve the science questions posed in this document will provide major inspiration for the next generation of scientists and engineers.

A key outcome of the InterRidge-IODP "Melting, Magma, Fluids and Life" workshop (Southampton, 27-29 July, 2009) was the formulation of integrative scientific questions and implementation approaches that will elucidate the role of ocean lithosphere processes within the broader Earth System. There are three main themes, each comprising geological, hydrological, chemical, and biological processes that are closely interdependent.

- Understanding the accretion of ocean crust. This goal requires (a) full section characterization of minimally-disrupted ocean crust and a sufficient portion of underlying uppermost mantle, and (b) detailed understanding of active processes within the axial zone;
- Understanding lithospheric heterogeneity in slow- and ultraslow spread crust, in particular the impact of serpentinization on global biogeochemical cycles and plate rheology. The latter is likely a controlling factor in regional tectonic behavior;
- Following the maturation process of lithosphere from the axis to the ridge flanks and investigating the hydrological-geochemical-microbiological feedbacks during the aging of the oceanic basement.

Understanding the initial conditions: Formation of ocean crust and interplay with the uppermost mantle *(see also Ildefonse et al.)*

The formation of Penrose-type ocean crust at the mid-ocean ridges is the dominant process that has re-surfaced 60% of our planet over the past <200 million years. This process is the foundation of the plate tectonic cycle and the principal mechanism of heat and material transfer from the mantle, to the crust and oceans. Understanding the magmatic, and inter-related hydrothermal and tectonic processes that occur during the accretion of intact ocean crust provides a reference point against which other styles of accretion at some ocean ridges can be compared.

The great majority of the magma generated by mantle melting at the ocean ridges is emplaced and crystallizes to form gabbroic rocks in the lower ocean crust. There remains a near complete lack of direct evidence regarding the accretion occurring beneath the volcanic layer of the fast spread crust of the Pacific. The latent and specific heat from cooling and crystallizing magma is the principal driving force for hydrothermal circulation. There is a close inter-dependence between volume, distribution, and timing of magma intrusions and the vigor and geometry of axial hydrothermal circulation. Some accretion models require the penetration of large volumes of hydrothermal fluids deep into the crust but evidence for this is not yet forthcoming. Importantly, we have well-developed, competing, theoretical models that suggest different end-member styles of magmatic accretion, broadly separated into "gabbro-glacier" and "sheeted sill" geometries. These models provide robust predictions (Fig. 1) that could be tested through direct observations if suitable cores and in situ measurements can be recovered from deep drill holes into intact ocean crust or shallow holes in rare tectonic windows into fast spreading ocean crust (e.g., Hess Deep). Recent estimates of hydrothermal fluid circulation passing through the sheeted dikes of fast spread ocean crust are remarkably consistent and appear to be converging on a relatively low, thermally sustainable flux. Quantification of this important end-member can now be used as an anchor point to investigate variations in other processes in major global chemical cycles. Microbial populations seek out high thermal and chemical gradients. Temporal variations in the geometry and nature of hydrothermal recharge and discharge are expected to determine the diversity of ecosystems.

The compositions of mid-ocean ridge basalts are generally interpreted to be the direct result of mantle melting. However, recent evidence indicates that significant reactions occur between melts and lower crustal/mantle cumulates. Understanding the extent to which our knowledge of mantle melting is biased due to unaccounted-for melt-rock interactions can only be assessed through study of genetically related mantle, lower crustal, and extrusive sections. Linked to this, the discontinuity in seismic velocity that marks the transition from mafic to ultramafic compositions is often inferred to be the boundary between the igneous crust and the residual peridotites of the uppermost mantle. The global similarity in depth (~6-7 km) of this Mohorovičić discontinuity (the Moho) in the oceans underlies the premise that magma production rates scale with spreading rate to produce an essentially constant thickness of mafic crust. This premise is key to estimating poorly-constrained physical parameters such as temperature and viscosity in many mantle flow and melting calculations and the validity of this assumption greatly impacts predictions from these models. However, whether some of the ultramafic rocks are igneous cumulates as opposed to residual mantle peridotites remains unknown. The transition from mafic to ultramafic rocks is irregular in many ophiolites and in some regions petrological and geophysical evidence suggest that the Moho is an alteration/serpentinization boundary. These may simply be competing hypotheses, or it may be that the Moho (seismic) discontinuity can be indicative of more than one type of petrologic transition. These hypotheses can only be tested by direct sampling. Samples from *in situ* mantle would lead to major paradigm shifts in planetary chemical models. In addition a suite of hypotheses about the causes of uppermost mantle anisotropy, seismic reflectivity, the relative motions of the crust and the underlying mantle, and magneto-telluric signatures could also be addressed in-situ for the first time.

The formation of heterogeneous crust *(see also Dick et al.)*

One of the major advances in ocean lithosphere science, since the development of the IODP-Initial Science Plan, is the recognition that detachment faulting is a major accretion process at slow- and ultraslow spreading ridges. Newly recognized contrasting styles of crustal architecture range from large areas where the crust is composed of serpentinized mantle, to areas where it is composed of gabbro intrusions in serpentinized mantle with scattered lavas, to areas with a more conventional layer-cake crust of gabbro dikes and basalt. Heterogeneous "crust" makes up at least 25% of slow-spread crust and seafloor exposures suggest that ~70% of such regions are ultramafic rock.

Serpentinization of ultramafic rocks is the dominant reaction that directly results in the occurrence of altered mantle rocks in the newly formed upper lithosphere (e.g., Fig. 2). This alteration has important impacts on crustal rheology by making talc- and serpentine-bearing "weak" lithologies that have low densities and shear strengths, and play a key role in the initiation of detachment faulting.

Serpentinite-hosted hydrothermal vents are another recent major discovery. These sites differ significantly from basalt-hosted systems, with distinct fluid chemistries and microbial communities. Fluid-rock reactions in peridotite-hosted systems also produce hydrogen, and abiotically generated hydrocarbons. These species are likely formed by key "Earth reactions" and peridotite-hosted environments may bear close comparison to those in which early life on Earth developed. Serpentinization is commonly accompanied by carbonation reactions, with a significant potential for carbon sequestration that warrants further investigation. The influence of the alteration of heterogeneous crust on hydrothermal exchange budgets remains poorly quantified, but is likely to be significant for many elements (e.g., B, Li, H, and C). Serpentinization also influences the character and behavior of subducting plates and is a crucial component in the planetary water cycle. Also, in regions of heterogeneous crust, gabbroic rocks are directly subjected to low temperature seawater alteration. These reactions could contribute significantly to global chemical budgets.

Importantly, major progress in understanding the development of detachment faulting, the estimation of the extent of seafloor exposure of ultra-mafic rocks through the calibration of geophysical observations, quantifying hydrothermal exchange fluxes in heterogeneous ocean crust, and in situ experiments to assess serpentinization and carbonation reactions and rates as well as microbial sensitivities could be achieved with a tangible number of shallow to moderate (~100 to 500 m) depth drill holes.

Maturation of the Ocean Crust. *(see also Harris et al.)*

Hydrothermal chemical exchange between the crust and oceans is a fundamental component of global geochemical cycles, affecting the composition of the crust, the oceans and, through subduction, the mantle and arc magmas. These chemical and thermal exchanges occur at the mid-ocean ridge axes and continue across the vast reservoir of the ocean ridge flanks. Although recent studies of slow spreading ocean ridges have recognized significant departures from the standard Penrose ocean crust stratigraphy, the oceanic lithosphere reservoir is young (<200 Ma), and *relatively* monotonous in composition compared to the continents, which are old, highly heterogeneous and isotopically radiogenic. This gives some confidence in the proposition that, if we can quantify hydrothermal exchanges with the ocean lithosphere, this will provide a rigorous benchmark against which variations in other major Earth system processes contributing to global chemical cycles can be compared. Previous ocean basement drilling efforts have been made in young (<20 Ma) and ancient (> 110 Ma) crust. No hole penetrates deeper than 50 m in 45-80 Ma basement. This is a critical time frame as it is in this interval that the crust becomes "sealed" to circulating fluids. However, the “sealing” concept relates to global averages of conductive heat flow measurements and their coincidence with plate cooling model heat flow predictions. It is likely that hydrothermal circulation can occur in crust of all ages wherever hydrological gradients can be established. The transport of heat may also subtly disconnect from the movement of chemicals needed for mineral growth or microbial habitats. Hence, thermal, chemical exchange and microbial processes could all be occurring at different times and in different locations on the ridge flanks. Although there is mounting molecular evidence for microbial activity within ocean crust, we are as yet unable to quantify the impact of microbial colonization on ocean-crust exchange budgets. Direct connection to the oceans will also influence hydrothermal alteration, and ventilation of the oceanic basement via seamounts that penetrate sedimentary cover may influence very large regions of the ocean crust.

Drilling of intermediate age upper crust, preferably along a crustal flow line, would provide essential information on how the crust ages as well as better age resolution for investigations of past seawater chemistry based on crustal alteration.

Technology:

The ocean lithosphere community has a strong record of science-driven technology development (e.g., CORKS). The fundamental and challenging science questions outlined here are a major incentive for continued technological development and innovation. The full suite of available and next-generation technological capabilities needs to be employed to optimize scientific return in ocean lithosphere drilling efforts. This includes, for example, *D/V Chikyu*, seabed rock drills, CORKS, the capacity to drill fractured basalts, the monitoring of and fluid/gas sampling in boreholes in high-temperature environments, borehole experiments (e.g., cross-hole experiments, VSP), borehole-hosted laboratories and instruments (e.g., microbe culturing), improved wireline tools, mud logging (cuttings analysis, fluid/gas monitoring), and sidewall coring. The need to drill and core a full intact section of ocean crust to the Moho and into the upper mantle continues to be enthusiastically supported by the ocean lithosphere community. They strongly endorse development and continuation of efforts to assess and design coring and borehole characterization capability that enable coring, measurement and sampling at high temperatures, in very deep holes and in great water depths.

List of Participants in the MMFL Workshop

Natsue Abe, Louise M. Anderson, Shoji Arai, John Armitage, Ryosuke Azuma, Wolfgang Bach, Neil Banerjee, Keir Becker, Michael Bickle, Donna Blackman, Jon Bull, J. Pablo Canales, Mathilde Cannat, Teddy Castelain, Mike Cheadle, Gail Christeson, Mike Coffin, Rosalind Coggon, Alice Colman, Jenny Collier, Laurence Coogan, Henry Dick, Katrina Edwards, Emanuele Fontana, Kathy Gillis, Nicholas Harmon, Michelle Harris, Robert Harris, Eric Hellebrand, Timothy Henstock, Susan Humphris, Benoît Ildefonse, Fumio Inagaki, Jenny Inwood, Barbara John, Peter Kelemen, Shuichi Kodaira, Shin'ichi Kuramoto, Sabrina Lissandrelli, Johan Lissenberg, Andrew McCaig, Jay Miller, Rachel Mills, Timothy Minshull, Sumio Miyashita, Sally Morgan, Tomoaki Morishita, Antony Morris, Bramley Murton, Greg Myers, Toshio Nozaka, Nicola Pressling, Julie Prytulak, Stephen Roberts, Jennifer Rutter, Nobukazu Seama, Roger Searle, Maria Seton, Donna Shillington, John Sinton, Christopher Smith-Duque, Yoshiyuki Tatsumi, Damon Teagle, Maya Tolstoy, Masako Tominaga, Douglas Toomey, Maria-Nefeli Tsaloglou, Susumu Umino, Heinrich Villinger, Flurin Vils, Alexander Webber, Masaoki Yamao, Ting Yang, and Huaiyang Zhou.

Selected Relevant White Papers:

Dick, H.J.B., and colleagues **“Ocean Drilling and Exploring a Heterogeneous Ocean Crust”**

Harris, R.N., Coggon, R.M., Fisher, A.T., Becker, K., Edwards, K.J., and Teagle, D.A.H., “**Evolution of Hydrothermal Circulation**”

Ildefonse , B., N. Abe, P.B. Kelemen, H. Kumagai, D.A.H. Teagle, D.S. Wilson, G. Acton, J.C. Alt, W. Bach, N.R. Banerjee, M. Cannat, R.L. Carlson, D.M. Christie, R.M. Coggon, L. Coogan, R. Detrick, H.J.B. Dick, J.S. Gee, K. Gillis, A. Harding, J.A. Karson, S. Kodaira, J. Koepke, J. McLennan, J. Maeda, C.J. MacLeod, J. Miller, S. Miyashita, J.H. Natland, T. Nozaka, M. Nedimovic, Y. Ohara, K. Okino, P. Pezard, E. Takazawa, T. Tsuji, S. Umino “**Drilling deep through the ocean crust into the upper mantle”**

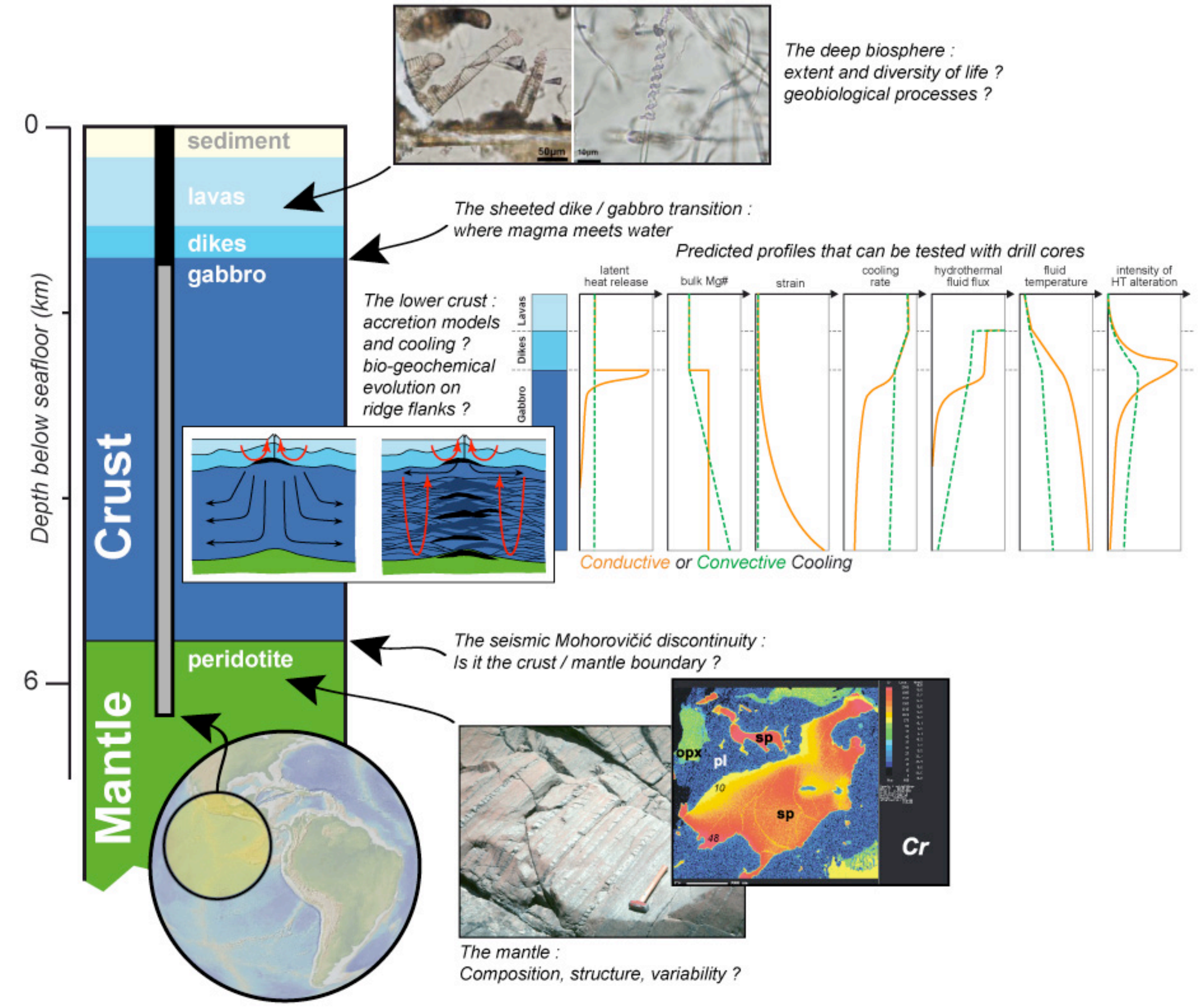

Figure 1: Schematic cross-section of fast-spread crust with anticipated MoHole penetration. The thicknesses of sediment, lavas and sheeted dike complex are taken from ODP/IODP Hole 1256D (Teagle et al., 2006). Top photographs: microbial ichnofossils in basalts from the Troodos ophiolite (McLoughlin et al., 2009). Predicted physical/chemical profiles in the crust: original figure from Rosalind Coggon; lower crust accretion models: after Korenaga and Kelemen (1998). Bottom photograph : layered harzburgites from the Oman ophiolite (photo Benoît Ildefonse). The chromium content map of impregnated abyssal peridotite shows extreme disequilibrium between melt and residue at infra-millimeter scale (Von der Handt et al., in revision). Figure by Benoît Ildefonse.

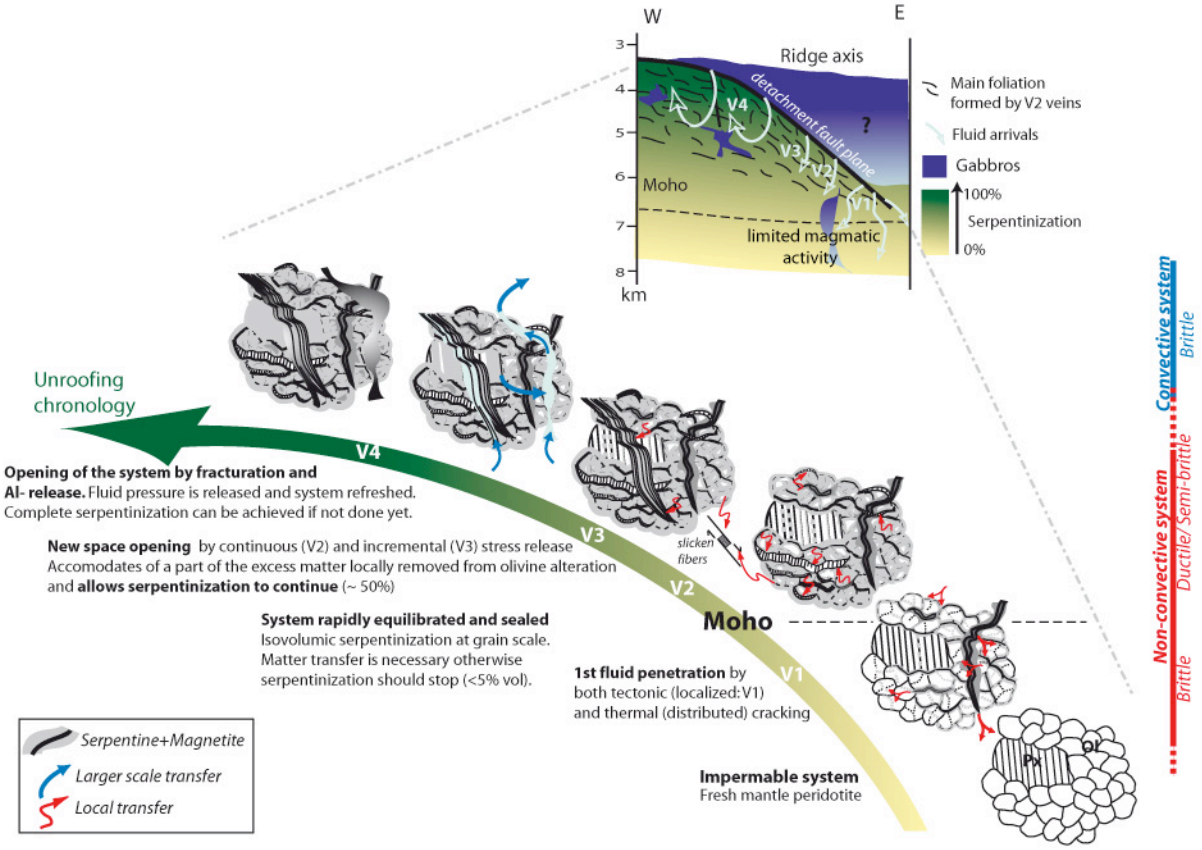

Figure 2: Serpentinization and detachment faults. Proposed model of serpentine vein formation and hydrothermal circulation during the progressive unroofing of peridotites exposed in the MARK area (from Andreani et al., 2007).

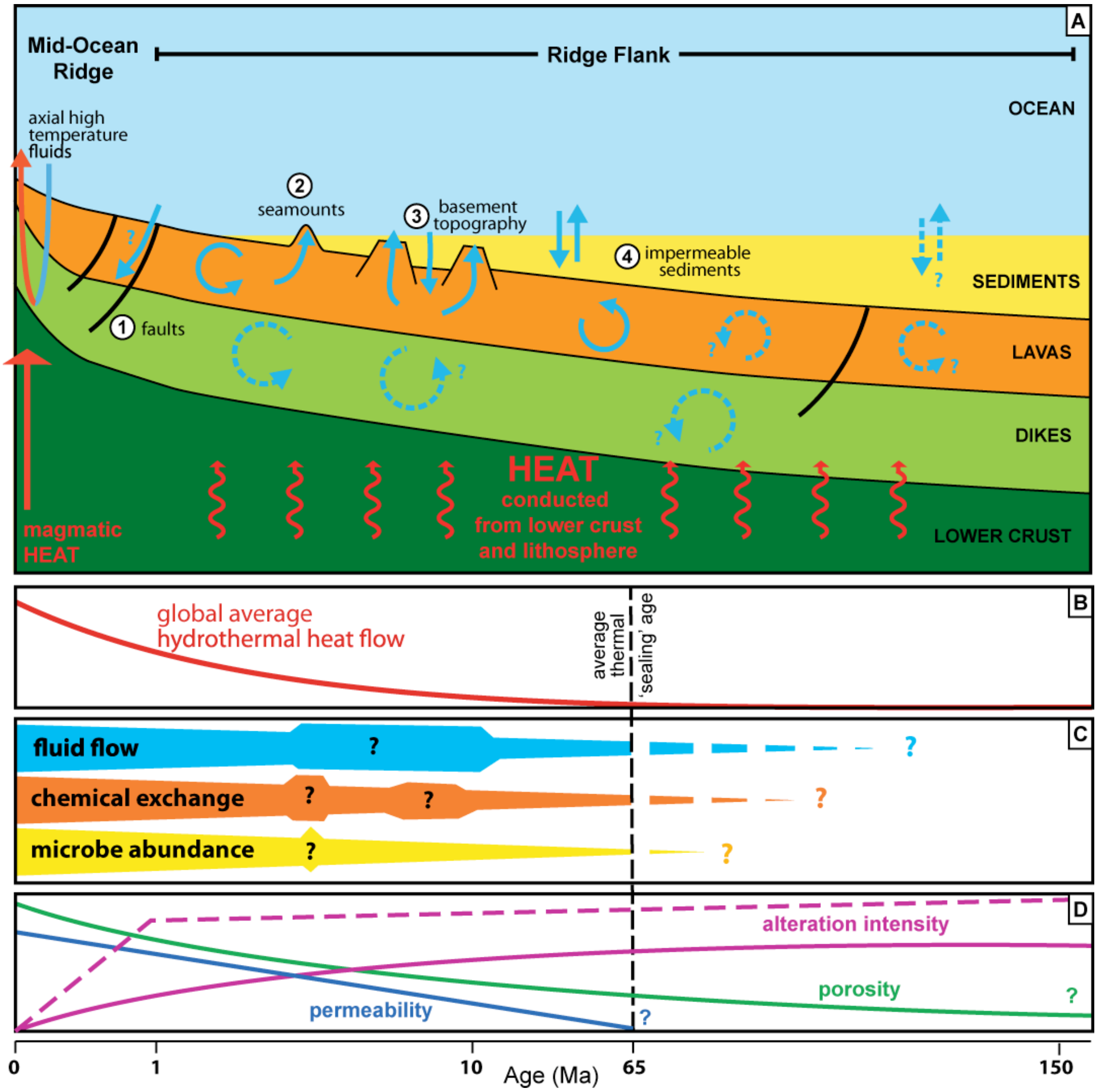

Figure 3: Maturation of the ocean crust. A cartoon showing the schematic architecture of a mid-ocean ridge flank (**A**; not to scale), illustrating parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks, such as (1) faults, which may channel fluids, (2) seamounts, which can act as permeable 'short-circuits' between the crust and ocean, (3) basement topography, which can produce sufficient differential fluid pressure to drive fluid flow, and (4) impermeable sediments, which isolate the crust from the oceans. Arrows indicate heat (red) and fluid (blue) flow. The calculated global hydrothermal heat flow (**B**; the difference between the average measured conductive heat flow and that predicted from conductive cooling plate models) decreases to zero, on average, by 65 Ma. At this age the crust is typically assumed to be 'sealed' to hydrothermal circulation. However, global averaging removes much of the heat flow signal from local effects (e.g., basement topography) and fluid flow, chemical exchange and microbial activity may persist in ridge flanks of all ages. **C**; The effects of parameters such as basement topography and sediment thickness on their intensity and relative cessations remain undetermined. The hydrological, physical, chemical and biological evolution of hydrothermal circulation through the ridge flank could be investigated by an integrated research program comprising surveys (mapping, seismic surveys, and heat flow studies), drilling, and subsequent borehole testing, sampling, in situ experiments and monitoring, across a ridge flank. **D;** The controls on the intensity and style of hydrothermal circulation could be investigated by the measurement of multiple parameters such as porosity, permeability, and alteration mineralogy. Figure by Rosalind Coggon.