can arise in part from the interpretation of different geochemical proxies used to reconstruct redox conditions, from genuine physiographic separations between different ocean basins around the globe, or as the result of secondary alteration of the original geochemical signals[8].

One way to wring order from this chaos is to use several adjacent locations to reconstruct a three-dimensional framework of redox variability over time. Recently, this approach was applied to the Ediacaran-aged Nanhua Basin in China, which led to suggestions that Ediacaran oceans may have been doubly redox-stratified, with a wedge of sulphidic waters separating deep ferruginous waters from oxic surface waters[7].

Poulton and colleagues[4] have used a similar approach to investigate redox conditions more than one billion years earlier, examining several stratigraphic sections in the 1.8 billion-year-old Animikie basin of North America to look for spatial variation associated with the transition to sulphidic conditions. The distribution of redox-sensitive phases of iron clearly indicates a stratified redox structure, with a near-shore wedge of sulphidic waters intruding between overlying oxic surface waters and deeper ferruginous waters. These results imply the coexistence of ferruginous and sulphidic conditions in spatially distinct zones, similar to those found in the Ediacaran oceans (Fig. 1).

In both cases, it remains unclear exactly what physical (and biological) conditions are necessary to support these redox gradients in the water column, and how long such stratified conditions are likely to remain stable. For this we can look to modern ocean settings such as the Cariaco Basin[9] off the coast of Venezuela, where circulation with the open ocean is restricted by physical barriers, resulting in localized reducing conditions at depth. Spatial redox variability can also arise in the open ocean in the form of oxygen minimum zones[10]. There, bursts of biological productivity in the upper ocean lead to localized depletion of oxygen at intermediate depths, as the sinking biomass is eventually degraded and respired. Oxygen minimum zones often occur where nutrient-rich waters from the deep ocean upwell to the surface, such as off the western coast of Chile.

Thus there are modern physical mechanisms that could plausibly be invoked to generate spatial gradients in redox conditions in the ancient ocean, in addition to any conditions perhaps unique to such ancient biogeochemical cycling[4,8]. However, the expected duration of these oceanic redox gradients remains an open question. Presumably the conditions would have needed to persist for millions of years to be preserved in the Animikie sediments, but transient conditions lasting for short periods cannot necessarily be ruled out.

The apparent spatial variability found in redox signals at such critical biogeochemical junctures in Earth history may put many ill at ease. It is difficult to tell whether these reports reflect spatially varying conditions in the ancient ocean itself or from some other means, such as chemical alteration of the signal during or after deposition[7]. A note of caution comes from the analysis of many of our most trusted redox proxies (iron speciation, sulphur isotopes and carbon/sulphur ratios) in samples from the mobile mud belts of the Amazon River delta[11]. Taken at face value, the geochemical redox indicators of these sediments suggest deposition under an anoxic, sulphate-poor system[11], but we know they were deposited in well-oxygenated, sulphate-rich marine waters. In this instance, the proxies instead reflect the continued reworking of these sediments as they migrate along the coast of South America. As this example demonstrates, a detailed understanding of the depositional context is essential for building robust interpretations of geochemical data.

Poulton and colleagues[4] have provided intriguing evidence for early spatial variability in redox structure, which will undoubtedly spur renewed efforts to model early ocean chemistry. However, much work integrating geochemical and stratigraphic data sets remains ahead of us before we can have a true sense of the three-dimensional redox structure in the oceans, and how this has varied through time. ❐

David Fike is in the Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri 63130, USA.
e-mail: dfike@levee.wustl.edu

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STRUCTURAL GEOLOGY

To fault or not to fault

Most of the oceanic crust has a simple layered structure. The discovery that slow-spreading ridges exhibit a comparatively complex crustal structure and some of the largest extensional faults on Earth is leading to the recognition of a new mode of seafloor spreading.

Michael Cheadle and Craig Grimes

Mid-ocean ridges are the locations where the Earth's crust is renewed. Here, the tectonic plates that form the sea floor spread apart and new oceanic crust is generated from upwelling magma. Studies of ancient oceanic crust have led to the idea that it forms in simple layers[1]. However, in 1983, large faults that expose rocks from deep below the mid-ocean ridge were discovered at the Mid-Atlantic Ridge[2]. These structures have since been identified in most ocean basins. At the American Geophysical Union Chapman Conference[3] on 'Detachments in oceanic lithosphere' in May 2010, geoscientists and biologists concluded these oceanic fault systems should be recognized as a fundamentally distinct mode of seafloor spreading.

Conventionally, oceanic crust is thought to have a relatively constant thickness of 6–7 km and a simple layered structure. The basal layer of the oceanic crust forms as minerals crystallize within a deep magma chamber. Above this layer, melt is injected vertically into the overlying crust, supplying pillow lavas that are erupted onto the sea floor, forming a third layer. As the tectonic plates move apart, new crust is added in the same configuration, creating a laterally continuous, layered structure. This model explains much of what we see in the Pacific Ocean where new crust is formed at a mid-ocean ridge, spreading at fast rates of more than 7 cm yr^{-1}. However, it has long been recognized[4,5] that slower-spreading ridges, such as the Mid-Atlantic and the Southwest Indian ridges, do not entirely fit this simple model. In places, the crust does not consist of layers of igneous material, as expected. Instead, heterogeneous mixtures of mantle peridotite and crystallized magma are found on the sea floor, exposed by movement on large detachment faults with significant displacement. These faults run parallel to the mid-ocean ridge and open up in a direction perpendicular to the ridge. Typically, the detachment faults can accommodate 30–40 km of plate extension. However, in exceptional cases they can accommodate extension on the scale of up to 125 km, making them some of the largest known extensional faults on Earth. The displacement on these faults can also generate extremely high topography that forms up to 6 km of mountainous relief.

Much of the variability in the structure of the oceanic crust, ranging from a simple layered crust to faulted and heterogeneous crust, can be explained by variations in the rates of plate spreading and magma supply. At fast-spreading ridges, the rate of magma injection balances the rate at which the plates separate and new ocean crust is formed by shallow magma injection. In contrast, at slow-spreading ridges, the lithosphere has a more variable thickness. Where the lithosphere is thick, the magma is prevented from reaching the Earth's surface and the magma supply is insufficient to accommodate the full amount of seafloor spreading. The classic rift valley found at slow-spreading ridges has faults that can only account for 10–15% of plate separation[6], the remaining 85–90% is accommodated by magma injection. It now seems that in areas of reduced magma supply, these extensional faults continue to slip, forming faults with large offset that can accommodate up to 100% of the plate separation.

At the Chapman conference[3], oceanic detachment faults were formally defined as low-angle extensional faults with large displacements (Fig. 1). These faults account for significantly more than the classic 10–15% of plate separation. Detachment faults represent a mechanism of mid-ocean ridge extension that is distinct from the classic mode of seafloor spreading whereby extension is accommodated by the injection of magma.

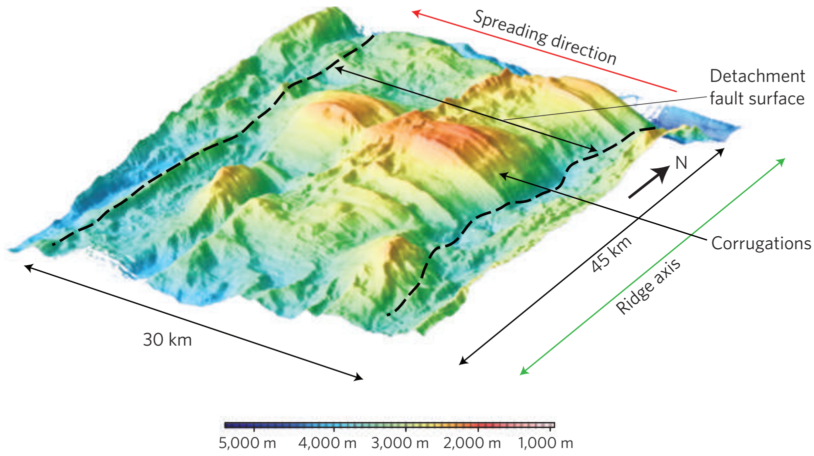

Figure 1 | A three-dimensional view of the Kane segment of the Mid-Atlantic Ridge at 23° N. At the Chapman conference[3], detachment faults were defined as low-angle extensional faults that generate large displacements as they slip. The faults uplift blocks of heterogeneous crust that is composed of mantle peridotite and crystallized magma. The dome-shaped uplifted blocks form oceanic core complexes. Here, the Kane oceanic core complex shows topography with a vertical extent exceeding 3 km. The exposed detachment-fault surface extends between the black dashed lines.

The lithosphere at mid-ocean ridges is hot and weak. As a detachment fault slips, it lifts up blocks of lithosphere, and mantle peridotite and crystallized magma are accreted at the base of the blocks. The faults are not strong enough to maintain a high angle of slip. They flatten over time, dipping at low, almost horizontal angles at the sea floor. The lithospheric blocks uplifted by the detachment faults form relatively smooth, sometimes dome-shaped sea floor, with small ridges or corrugations that run parallel to the direction of plate spreading. At slow-spreading mid-ocean ridges, these structures may form up to 60% of the sea floor[7]. The underlying mantle peridotite and crystallized magma are uplifted and exposed by the detachment faults, in topographic features that are called oceanic core complexes.

Traditional rock mechanics suggests that faults in the brittle crust should form and slip at high angles, yet detachment faults are observed to slip at unusually low angles. This implies that the fault is weak. Detachment faults probably originate as high-angle faults, extending to depths of 5–8 km in the brittle crust, but are later weakened. The ingress of sea water into the detachment faults to depths of several kilometres can lead to the formation of weak, highly altered and metamorphosed rocks (M. Cannat, Institut de Physique du Globe de Paris; G. Fruh-Green, ETH Zurich). Because of their weakness, these altered rocks may localize deformation and facilitate gradual slip at low angles as the faults roll over (A. Morris, University of Plymouth; B. John, University of Wyoming). Thus, water plays a key role in allowing detachment faults in the brittle crust to slip at low angles. At depth, slip is probably accommodated by ductile flow and indeed rocks that exhibit ductile deformation are found on the surfaces of these faults (M. Cheadle, University of Wyoming).

Importantly, intense hydrothermal activity seems to be strongly correlated with detachment faulting. Some of the largest known hydrothermal systems, such as the Trans-Atlantic Geotraverse hydrothermal field, are associated with oceanic core complexes[8] (A. McCaig, University of Leeds; R. Sohn, Woods Hole Oceanographic Institute). Fluids circulating along these fault systems extract and mobilize metals, such as copper, lead and zinc, from the surrounding rock and concentrate them as ore minerals near the sea floor. These hydrothermal systems are also uniquely rich in hydrogen and methane, suggesting that these systems could host abundant and unique deep-sea life. Yet the diversity of the deep sea and subsurface biosphere here has only just begun to be recognized (D. Kelley, University of Washington; A-L. Reysenbach, Portland State University; M. Perner, University of Hamburg).

We do not know why a detachment fault might continue to slip for up to four million years without breaking up[9]. Plate separation could more easily be accommodated by several smaller, successive faults, whose combined displacement equals that of the slip on one larger fault. It seems that for large detachment faults to slip, a particular set of thermal conditions and volume of magma input may be required[10]. Those areas with very low magma injection rates form smaller detachment faults, similar to those observed at the slow-spreading Gakkel Ridge in the northern Atlantic and the far eastern Southwest Indian Ridge. In contrast, large detachment faults are formed at spreading ridges with moderate magma supply, such as the structures seen at the Mid-Atlantic Ridge (M. Cannat, Institut de Physique du Globe de Paris).

The Chapman conference[3] raised as many questions as answers. Whatever the details surrounding the origin and development of detachment faults, they do not fit our textbook model of crustal formation at mid-ocean ridges. A consensus emerged at the meeting that oceanic detachment faults and oceanic core complexes should be considered a distinct and fundamental mode of seafloor spreading. ❐

Michael Cheadle is in the Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071-3006, USA. Craig Grimes is in the Department of Geosciences, Mississippi State University, Mississippi State, Mississippi 39762-5448, USA.
e-mail: Cheadle@uwyo.edu

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Acknowledgements

Citations relating to the Chapman conference indicate those speakers who were invited to give overview talks. The ideas discussed here therefore represent a summary of ideas from various workers.

ECONOMIC GEOLOGY

Volatile destruction

Direct evidence for the role of volatiles in magmatic ore formation has been elusive. Magma degassing at Merapi volcano in Indonesia is found to be directly linked to the selective leaching of metals from sulphide melts that ultimately form ore deposits.

Bruno Scaillet

Sulphur carried by magmas plays a pivotal role in many geological processes. A great chemical affinity exists between sulphur and metals that is important for ore formation. Thus many ore deposits of economic interest are intimately associated with magmatic activity. The sulphur and metals merge together at the magmatic stage to yield immiscible sulphide melts. At some stage during magma evolution, the ore-forming elements are removed or concentrated, but the reasons for this, particularly in subduction-zone settings, remain obscure. The volatile content of the magma has long been thought to play an important role in the separation process[1], but direct evidence has been lacking. Writing in *Nature Geoscience*, Nadeau *et al.*[2] report observations from Merapi volcano, Indonesia, that indicate that present-day arc magmas, produced during the subduction of water-rich oceanic crust, owe their ore potential to the abundance of volatiles associated with this tectonic setting.

After water and carbon dioxide, sulphur is the third most abundant dissolved volatile in magmas. Concentrations of sulphur range from a few hundred to a few thousand parts per million[3,4]. When placed in the upper crust, the majority of magmas soon saturate with an immiscible sulphide melt that hosts numerous economically interesting elements, such as copper, nickel, gold and the platinum-group elements[5]. According to the classic mechanism of magmatic sulphide ore formation[6], sulphide melts readily settle out of the main molten body of magma because they are much denser than the surrounding silicate melt. They accumulate at the base of the magma chamber or intrusion (Fig. 1a). This mechanism works well for dry iron- or magnesium-rich (mafic) magma, which is typical for magmatic activity at intraplate or extensional rift-related settings. These tectonic settings are associated with many metallic deposits of huge economic interest, such as at Norilsk in Siberia[7]. There, some 250 million years ago profuse intraplate volcanism created the largest nickle–copper–palladium deposits in the world.

The abundance of water in arc magmas, however, adds an intriguing complexity to this scenario. As far as we know, water does not significantly affect the solubility of sulphur in silicate melts[8,9], at low pressures at least. Therefore, hydrous magmas, such as those formed in arc settings, should follow the same pattern of sulphide removal as that of dry magmas. In fact, water should lower the density of silicate liquids, amplifying the density difference and accelerating the settling out of sulphides. Yet, hydrous magmas are not observed to produce layers of accumulated sulphides. Instead, field evidence shows that sulphur-bearing rocks related to arc magmas accumulate above the main silicate–magma intrusion, and not in it, forming the so-called hydrothermal ore deposits. One of the reasons for this observation lies in the degassing processes at work in such settings, in particular the loss of water by the magma. During their ascent to the surface, magmas lose their volatiles continuously because water solubility in silicate melts decreases with decreasing pressure[1]. The escaping gas rises towards the upper reaches of the magma plumbing system. As the volatiles percolate through the magma they scavenge elements and essentially destroy the sulphide melt (Fig. 1b). The volatiles thus provide a mechanism for the removal and transport of metal elements, depositing them either above the main magma intrusion or carrying them into the atmosphere as a gaseous emission.

Nadeau *et al.*[2] present detailed petrological analyses of rocks ejected during an explosive event at Merapi volcano in 2006. They provide a comparison between some preserved sulphide melt, the main