that should have allowed accumulation. Moreover, it is well known that organic material can strongly interact with clays. Clays have therefore been suggested to have played a significant role in the emergence of life on the Earth. Such a hypothesis makes clay deposits very attractive locations for Mars Science Laboratory and as a future landing site for Exomars.

References

1. Malin, M. C. & Edgett, K. S. *Science* **302,** 1931–1934 (2003).
2. Bibring, J.-P. *et al. Science* **307,** 1576–1581 (2005).
3. Ehlmann, B. L. *et al. Nature Geosci.* **1,** 355–358 (2008).
4. Gendrin, A. *et al. Science* **307,** 1587–1591 (2005).
5. Squyres, S. W. *et al. Science* **306,** 1709–1714 (2004).
6. Poulet, F. *et al. Nature* **481,** 623–627 (2005).
7. Bibring, J. P. *et al. Science* **312,** 400–404 (2006).
8. Chevrier, V., Poulet, F. & Bibring, J. P. *Nature* **448,** 60–63 (2007).
9. Tosca, N. J. *et al. Earth Planet. Sci. Lett.* **240,** 122–148 (2005).

GEOCHEMISTRY

Seeing through tectonic plates

Two overlapping oceanic plates are sinking into the mantle underneath central Japan where they dehydrate, releasing water-rich fluids that enhance mantle melting. Geochemical work helps determine the relative contribution of each plate to the overall fluid budget.

Tatiana Churikova

is in the Laboratory of Petrology and Geochemistry, Institute of Volcanology and Seismology, Far East Division of Russian Academy of Sciences, Peep Avenue 9, Petropavlovsk-Kamchatsky, 683006 Russia.

e-mail: tchurikova@mail.ru

Anyone living near the Pacific coast or on one of its islands such as Japan almost certainly lives in the vicinity of some active volcano. It may be possible to see a volcano spewing steam and — if one is fortunate — even erupting. But the ongoing unrest deep beneath the surface that ultimately leads to volcanism is invisible. Along most of the circum-Pacific region, one oceanic plate is sinking very slowly beneath another continental or oceanic one, releasing fluids in response to the relatively high ambient temperatures. However, near central Japan, two oceanic plates are subducting with some overlap in a setting not unlike two sloppily stacked saucers. On page 380 of this issue, Nakamura and co-authors[1] use geochemical data from volcanic rocks to identify distinct signatures of fluids that originate from each of the subducting plates and find that the upper plate does not appear to inhibit fluid rising up from the underlying one.

In a typical subduction zone (Fig. 1), as a water-saturated oceanic plate subducts beneath either a continental or another oceanic plate, it dehydrates at different depths, releasing water that contains dissolved elements derived from the plate. This subduction fluid changes the chemical composition of the surrounding upper mantle and decreases the mantle's melting temperature. The resultant melts rise to the Earth's surface and often lead to volcanic eruptions[2,3].

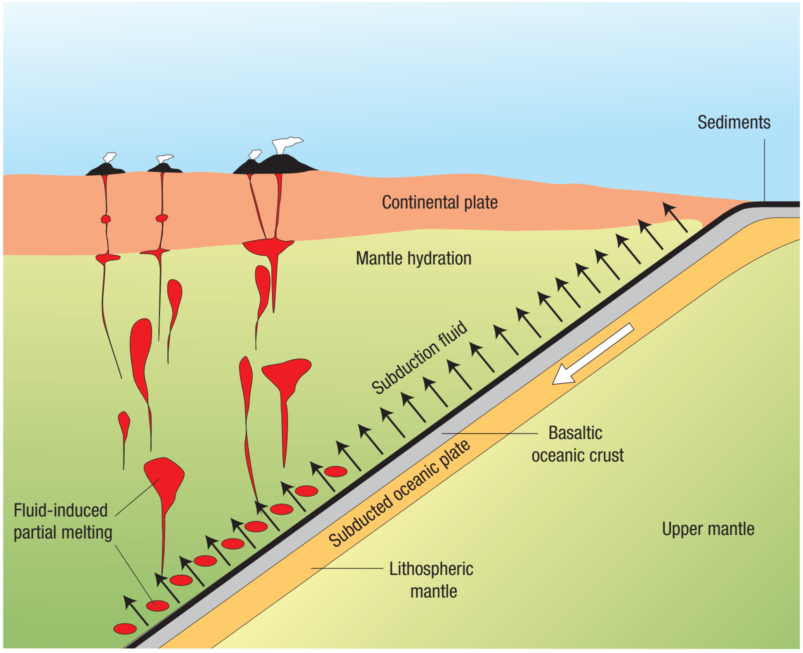

Figure 1 Dehydration and melting in a subduction zone. In subduction zone settings similar to Japan, oceanic plates subduct under continental plates and sink into the upper mantle. At relatively shallow depths, the mantle is too cold to melt. However, as pressure and temperature increase with depth, the altered basaltic oceanic crust and the overlying sediments dehydrate, releasing fluid into the mantle. This process induces partial melting of the mantle. The melts rise to the Earth's surface and can lead to volcanic eruptions. Nakamura and co-authors[1] use the chemical composition of volcanic rocks in central Japan to identify and quantify the respective fluid contributions from the Philippine sea plate and Pacific plate. Using these data they map the extent of the subducting plates beneath central Japan. Modified from ref. 10.

The composition of the subduction fluids can be inferred from the chemical composition of the erupted lavas[4].

However, many subduction zones have a more complicated geometry as three or more plates can be involved[5,6]. Each of these plates can move at its own velocity and in its own direction: the plates may collide, overlap, or break down. Central Japan is one such setting, where the Philippine Sea oceanic plate and the Pacific oceanic plate are subducting below the North American and Eurasian plates, leading to extensive volcanism. At depth, the Philippine Sea plate lies above the Pacific plate, creating overlap and adding to the complexity of this setting.

The dehydration of a slab is not a simple process. Fluid formation results from the breakdown of several different water-rich minerals, which become unstable and begin to decompose at specific depths. The resultant fluid composition therefore varies with depth[7,8]. Moreover, the upper part of an oceanic subducted slab is composed of an upper sedimentary layer underlain by basaltic oceanic crust. Both of these layers dehydrate in their own ways producing fluids of different compositions.

One way of tracing the fate of subduction fluids is the use of lead isotopes: lead is preferentially incorporated into the fluids, rather than being left behind in the residues of dehydration, and it is more abundant in subducted plates than in the surrounding mantle. More importantly, lead isotope ratios of the mantle, oceanic crust and sediments are distinct. The source of fluids derived from these various reservoirs can therefore be inferred from lead-isotopic compositions of volcanic rocks. The sensitivity of lead isotopes is such that even a small addition of fluid from subducted sediments to the mantle shifts the lead-isotopic composition of the mantle considerably.

Nakamura and co-authors identify the composition of the fluids released by the two subducting plates, primarily using lead isotopes measured from young volcanic rocks and the concentrations of trace elements. They provide quantitative calculations identifying the subduction fluids that are produced beneath central Japan through the multiple stages of dehydration at different depths and by a variety of physical and chemical processes.

This information enables the authors to unveil complex subduction-related processes. Interestingly, the Philippine Sea plate does not shut off fluid flux from the underlying Pacific plate. Subducted plates could thus be permeable to fluids. If so, there is no reason to assume that fluid permeability should be restricted to subduction fluids. Other types of fluids in the mantle, such as those produced during melting in a mantle plume region or fluids rising from the deep mantle could also permeate through subducted slabs. However, the overlying Philippine Sea plate is relatively small and is surrounded by the large Pacific plate, which makes the permeability of the former hard to determine unequivocally. Permeability of a subducted slab has not been reported before and would have to be verified by geochemical data from other regions with similar geology.

The geometry and extent of subducting plates is normally determined by the distribution of earthquake locations, which can be traced to depths of up to 650 km in subduction zones[9]. However, seismic research and hence seismic data acquisition goes back to only about a century ago. If a slab happens to have been inactive during this period, or if a slab subducts aseismically, it is not possible to map its extent using earthquake data. By contrast, the method used by Nakamura and co-authors is not bound by these restrictions. The geochemical signatures of fluid from the Philippine Sea plate were found in volcanic rocks located more than 100 km away from its edge at depth, which was reconstructed from seismic observations. Whether this fluid is derived from the aseismic continuation of the Philippine Sea plate or from upper mantle convection is yet to be determined and merits further research.

Nakamura and co-authors find that the two overlapping subducting plates produce more fluid than subduction zones involving only one subducting plate. This may increase volcanic activity and hence the associated volcanic and seismic hazards. To generate forecasts for the most volcanically and seismically dangerous regions, it is extremely important to be able to look inside the Earth and to know the spatial extent of the subducting plates.

References

1. Nakamura, H., Iwamori, H. & Kimura, J. I. *Nature Geosci.* **1,** 380–384 (2008).
2. Anderson, R. N., Delong, S. E. & Schwarz W. M. *J. Geol.* **86,** 731–739 (1978).
3. Hawkesworth, C. J., Gallagher, K., Hergt, J. M. & McDermott, F. *Lithos* **33,** 169–188 (1994).
4. Cervantes, P. & Wallace, P. J. *Geology* **31,** 235–238 (2003).
5. Yogodzinski, G. M. *et al. Nature* **409,** 500–504 (2001).
6. Alexeiev, D. V., Gaedicke, C., Tsukanov, N. V. & Freitag, R. *Int. J. Earth Sci.* **95,** 977–993 (2006).
7. Ishikawa, T., Tera, F. & Nakazawa, T. *Geochim. Cosmochim. Acta* **65,** 4523–4537 (2001).
8. Chan, L. H., Leeman, W. P. & You, C. F. *Chem. Geol.* **160,** 255–280 (1999).
9. Lander, A. V. & Shapiro, M. N. *AGU Monograph Series* **172,** 57–64 (2008).
10. Dorendorf, F., Wiechert, U. & Wőrner, G. *Earth Planet. Sci. Lett.* **175,** 69–86 (2000).

PALAEOCLIMATE

Marinoan meltdown

The termination of the Marinoan glaciation 635 million years ago is one of the most spectacular climate change events ever recorded. Methane release from equatorial permafrost might have triggered this global meltdown.

Graham Anthony Shields

is in the Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK.

e-mail: gshields@uni-muenster.de

Imagine that the planet Earth fell into a seemingly perpetual deep freeze. As thick ice caps formed, sea levels would drop by hundreds of metres, turning huge tracts of previously submerged continental shelf into Arctic wasteland. Imagine now, after millions of years, how such an icescape might begin to thaw. This is exactly what geologists have been trying to do for decades, as they have been struggling to piece together the puzzle of what happened at the end of a glaciation that may have covered the entire planet in ice. Several hypotheses have sprung up, one of which suggests that a massive expulsion of methane from previously frozen ground set in motion runaway global warming and sea-level rise due to the melting of glaciers. In their article in *Nature*, Kennedy *et al.*[1] mount support for this 'methane release hypothesis' by identifying evidence for a mix of methane and glacial meltwater directly below the recognized global marker for the end of this glaciation.

Over the past decade, evidence has been building to suggest that the Earth experienced up to 100 million years