Discussion

Gas hydrates: a hazard for the twenty-first century?

1. Distribution and abundance of gas hydrates

The first aspect is the problem of how to gain a better understanding of the distribution and abundance of gas hydrates in continental slope sediments at the present day. Mark Maslin (University College London) and Nick Langhorne (Office of Naval Research, USA) both emphasized that while the potential distribution of hydrates can be defined, based on the pressure and temperature limits of their stability range and the thicknesses of sediments presently located within that stability range, the actual occurrence of hydrates is less well known and so there is a wide range of uncertainty (about an order of magnitude) in estimates of global marine gas hydrate abundance. Furthermore, there is a large uncertainty regarding the amount of gas hydrates in the second major reservoir, the Arctic permafrost, and nothing is known about storage of gas hydrates in Antarctic permafrost. A particular problem for the marine hydrates, noted by Maslin and also Doug Masson (National Oceanographic Center, NOC), is that even where evidence of hydrate occurrence is found, for example in the form of bottom simulating reflectors (BSRs) in seismic profiles, the proportion of sediment pore space actually occupied by hydrate is still undefined. Expanding on this theme, Maslin asked for opinions on whether BSR occurrence was a good proxy for the occurrence of gas hydrates in continental slope sediments. Replying to this, Masson commented that while positive identification of a BSR was a valid indicator of gas hydrates overlying free gas in pore spaces below the BSR, its apparent absence was not a good indicator of the absence of gas hydrates: for example, the hydrate–gas interface might be parallel to bedding and so much less obvious in seismic profiles. Masson also noted that it is not known how much gas hydrate is required to produce a gas-impermeable cap layer within sediments and thus lead to the formation of a BSR as gas accumulates beneath it. Both Maslin and Russell Wynn (NOC) commented that this lack of knowledge reflects a need for in situ investigations and sampling of potentially gas hydrate-bearing sediments to move beyond regions of high gas hydrate abundance (such as the Cascadia–Alaska continental margin) to study other
regions where hydrates may be present but are less obvious. As an example, Wynn noted that few areas of the otherwise well-known European–North Atlantic margin have been subjected to investigations of gas hydrate occurrence and distribution.

2. Variation in gas hydrate geohazards as a function of climate change

Despite the clear need for better quantification of marine gas hydrate distribution and abundance, a rather greater proportion of the discussion was devoted to different aspects of the complex problem of predicting whether catastrophic release of marine gas hydrates might become a major hazard during the twenty-first century as a result of rapid climate change. Particular questions provided foci for discussion.

— Can palaeoclimate data be interpreted unambiguously in terms of marine gas hydrate releases, particularly in rapid climate change events that are used as analogues for predicted twenty-first century climate change?

Pete Talling (NOC) queried whether the excursions of carbon isotope ratios towards light values in marine sediment sequences, commonly interpreted as markers of gas hydrate release, are unambiguous or whether these excursions might also be diagenetic artefacts. Maslin replied that these excursions need to be interpreted on a case-by-case basis: some documented excursions are found in well-preserved planktonic foraminifera from the surface layer of the ocean (as in the well-known Santa Barbara Basin examples) but others are based upon less well-preserved foraminifera and in these cases the possibility of diagenetic artefacts certainly needs to be considered; evaluation of this possibility requires investigation of biomarker molecules in the sediments, which sample algal growth in the surface layer of the ocean, in addition to foraminifera from the same sequences.

— Do these past climate events really provide valid analogues for predicted twenty-first century climate changes in view of the high rate sensitivity of processes involved in raising atmospheric concentrations of short-lived gases such as methane?

Talling noted that one alternative to the study of foraminifera to detect methane releases was the measurement of methane concentration in air trapped in glacier ice cores. Maslin pointed out that these concentrations depend on the release rate of the gas as well as amounts: critically, this means that methane concentrations in palaeoatmosphere samples from past glacial–interglacial cycles may not be good analogues for variations to be expected as a result of more rapid climate change in the twenty-first century. Langhorne noted that this point applies particularly to a critical rate-dependent process in the release of methane from gas hydrates, the escape of released methane from the ocean to the atmosphere before being oxidized in the water. The fraction of methane that escapes in this way and its rate dependence need to be constrained: Langhorne noted that there
Discussion. Gas hydrates

may also be a seasonal effect owing to trapping of released methane beneath seasonal sea ice. Matthew Owen (University College London) proposed that in situ measurements of methane release, for example at pockmark seeps, may be useful, but also noted that seeps in general are likely to be relatively inefficient at releasing methane to the atmosphere, whereas much more of the methane released in catastrophic events such as submarine landslides is likely to reach the atmosphere.

— Do these rate-sensitive processes, particularly in the ocean and atmosphere, vary through geological time and between different climate change episodes?

Rate-dependent processes also affect the climatic consequences of methane release once the escaped methane reaches the atmosphere. Peter Ward (Teton Tectonics) commented that the oxidizing capacity of the atmosphere (potentially affected by release rates of other gases, such as SO2 from volcanic sources) will affect the lifetime of methane in the atmosphere before it is oxidized to much less infrared-absorbent CO2. Another area of research in which assessment of rate-dependent processes is critical is the interpretation of the Palaeocene–Eocene thermal maximum and whether it forms a useful analogue for the twenty-first century (Tom Dunkley Jones, University College London).

— Can particular palaeoclimatic isotope excursions be related to specific geological events, such as continental slope landslides, or are they related to other processes that occur within the biosphere–ocean–atmosphere system, such as methane release from anoxic decomposition in wetlands?

Talling noted that demonstration of the landslide–gas hydrate link requires correlation of dated landslides with carbon isotope excursions in well-preserved pelagic foraminifera sequences, in which the possibility of diagenetic artefacts can be excluded. In some cases, such diagenetic effects can be excluded (such as the Santa Barbara Basin records noted above); in others, preservation of the foraminifera is much less good and diagenetic effects are plausible. Maslin agreed with Talling that the glacial-period isotope excursions within Amazon Fan sequences may be one example where diagenetic alteration affects the isotope records. Dansgaard–Oeschger (D–O) events were discussed: Ward asked whether these could be linked to gas hydrate methane releases, but Maslin cited the work of A. Ridgwell (Bristol University) that implicates flooding of coastal wetlands and consequent release of methane from waterlogged vegetation in the excursions associated with D–O events. Andrew Russell (Newcastle University) agreed with this point, noting that jökulhlaups from unstable ice sheets (evidenced by the glacigenic sediment layers associated with the D–O events in deep sea records) may be responsible for the rapid, transient sea-level rises that can produce wetland flooding-related excursions.

— Conversely, should changes in gas hydrate stability be seen as preconditioning factors rather than triggers for geological events such as continental slope landslides?
The distinction between climate changes, both past and future, as direct triggers of geohazard phenomena and as accelerators or preconditioners that make such phenomena more likely, was a wider theme of the colloquium. Several instances of the latter type of connection between climate change and geohazards were raised in the discussion of gas hydrate-related hazards. Masson cited a study by J. Cartwright (Cardiff University) and others of a landslide on the Norwegian margin where reaction of fresh water released by hydrate decomposition with clay-rich marine sediment led to the development of liquefied ‘quick clays’ and consequent catastrophic slope failure. Maslin, David Tappin and Talling all noted that gas hydrate decomposition on high-latitude continental margins could be seen as a preconditioning factor leading to catastrophic failures triggered by other processes such as deglacial rebound-related seismicity, or to a transition from progressive to catastrophic failure.

A common theme of much of the discussion was the relative magnitudes of hazards associated with marine gas hydrates when compared with the gas hydrates in permafrost. While the abundance of the latter is also poorly constrained, a number of contributors to the discussion emphasized that permafrost hydrates are likely to be much more vulnerable to destabilization during the twenty-first century, particularly in view of the very large (up to 16°C) temperature increases in high-latitude continental regions now being predicted by Hadley Centre model simulations presented at the colloquium by Richard Betts; and also in view of the potential for thermal shocking of permafrost in low-lying areas as they are flooded by rising sea levels. Owen, Maslin, Nissen and Masson all raised different aspects of the problems associated with estimating the potential for catastrophic release of methane from Arctic permafrost areas in the twenty-first century, both as a direct result of permafrost melting and as a consequence of subsequent organic material decomposition in the swamps that will replace the permafrost. Even the total amount of hydrate in the permafrost regions, as well as its distribution, is very poorly constrained. Furthermore, almost nothing is known about the amount and distribution of hydrate in Antarctic permafrost, let alone its sensitivity to climate change in the twenty-first century.

Overall the discussion emphasized the need for the following.

— More research on the amount of gas hydrate stored in marine sediments worldwide and in permafrost regions at both poles.
— A clearer understanding of mechanisms involved in triggering of the release of large volumes of methane from gas hydrates and from sub-hydrate layer-trapped gas layers, both through investigations of the physical processes involved and through more detailed investigation and dating of past isotope excursions that have been linked to hydrate decomposition.
— With regard to climate effects in the twenty-first century, increased knowledge about whether these will trigger hydrate release immediately, or whether they will precondition hydrate reservoirs to instability and lead to gas release on longer time scales.
— A more robust appreciation of the overall fate of released methane, in order to understand whether past events provide close analogues to potential future releases in the rapidly changing climate of the twenty-first century and beyond.

Phil. Trans. R. Soc. A (2010)
— Improved understanding of the fate of released methane, and the proportion that reaches the atmosphere, especially from deep water releases where much of the gas may be oxidized while passing up through the water column.

S. J. Day\textsuperscript{1} and M. Maslin\textsuperscript{2,*}

\textsuperscript{1}Aon Benfield UCL Hazard Research Centre, Department of Earth Sciences, and
\textsuperscript{2}Department of Geography, University College London, Gower Street, London WC1E 6BT, UK

\textit{E-mail address:} mmaslin@geog.ucl.ac.uk

\textsuperscript{*}Author for correspondence.