Gas migration in clays

Advances in understanding for environmental applications

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Quantitative information on the mechanisms of gas movement in clays has important applications in environmental engineering, soil mechanics, marine science and petroleum geology. Specific environmental problems which involve gas movement in clay-rich materials include the design of mineral liners and caps for domestic waste landfills, calculation of gas migration fluxes from underground waste repositories, analysis of the movement of gases in the bentonite buffer clays which will enclose certain categories of radioactive waste, and assessment of the environmental impacts of natural subsea hydrocarbon seepages. Gas production is by a diverse range of mechanisms, including biological, chemical and thermal degradation of organic compounds and waste constituents, anoxic corrosion of ferrous metals and the radiolysis of porewater.

Gas migration by the diffusion of gas molecules in porewater is a slow background process in all clays. The diffusion coefficient and the solubility coefficient are two important parameters in the quantitative treatment of diffusion. The diffusion coefficient is essentially a property of the water-saturated medium. If the concentration of gas in water at the source remains constant with time, the magnitude of the steady-state diffusive flux away from the source is regulated solely by the clay. The steady-state diffusive flux of gas can never exceed the upper bound set by the diffusion coefficient and solubility in water.

In many practical situations, the actual gas flux through a clay is determined by the rate of production of the gas and not by the rate at which a particular transport mechanism can accommodate the flux. We can think of the gas flux as being imposed on the material, rather than being determined by it. When the imposed flux exceeds the upper bound for diffusion, the gas must be transported through the clay as a separate gas phase.

The stress at any point in the subsurface can be quantified in terms of three mutually-perpendicular principal stresses. If gas pressure exceeds the minor principal stress, then gas can usually migrate by exploiting existing weaknesses. In many cases these incipient pathways of gas movement are present naturally as crack networks, fissures and faults. When subject to high gas pressure, these pathways can dilate and become gas permeable. If the clay is extremely tight, then it is possible for the gas to make its own pathways by hydrofracturing.

In a series of recent papers and reports, the authors describe the findings of a programme of gas permeability experiments on Boom Clay (Tertiary clay from Belgium) and on pre-compacted Wyoming bentonite. In each experiment, gas pressure rose to a well-defined peak, with no evidence of flow until just before the peak. Gas pressure then fell away spontaneously, indicating that the clay had become gas permeable. The overall pressure-time response during gas injection was similar to hydrofracturing response of a clay soil, suggesting that gas moves through an interconnected network of cracks formed by small-scale rupture of the clay fabric under high applied gas pressure. When gas injection was stopped, the pressure within the flow paths gradually fell away with time to approach some finite limiting value. No gas flow has ever been detected at a pressure less than this critical threshold and the threshold itself can be interpreted in terms of the mechanical and surface tension constraints on gas pathway stability.

Gas entry pressure in clays is found to vary systematically with water content and with plasticity index. Plasticity index

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The Envirotest Module is a vandal-proof and self-contained field testing capability designed by BGS staff to measure the gas transport properties of landfill liner clays. The monitoring instruments are installed in a Lower Lias clay liner at Sidegate Lane Landfill near Kettering. Powered by lead-acid batteries, the unit has been operating continuously for the past 8 months.

Monitoring hazards

is the difference between the liquid and plastic limits (geotechnical index properties). When at similar water contents, high plasticity clays containing significant amounts of smectite or other expansive clay minerals are found to form much better barriers to gas migration than low plasticity clays. This finding has important applications in the design of landfill liners and cut-off trenches. Fully-hydrated bentonite proves to be an extremely good barrier to gas movement.

By examining gas entry mechanisms across the full range of water contents, it has been possible to delineate three modes of behaviour. Mechanism BB, or gas movement in buoyant bubbles, is common to all clays at high to intermediate water contents and leads to fairly modest gas entry pressures (less than 100 kPa). Mechanism TFR, or gas movement in tensile fractures with rapid and complete loss of gas pressure, occurs in clays at low water contents and is associated with high entry pressures. Mechanism TFG is a transitional mechanism characterised by fractures which exhibit slow propagation and a gradual loss in internal gas pressure.

There is little doubt that Mechanism BB is the primary mechanism of vertical gas migration in soft sea bed sediments. Low shear strength is a common characteristic of these sediments. The material can therefore plastically deform and flow around an ascending gas bubble. Pockmark formation provides a good example of gas flow in wet sediments. Pockmarks are crater-like depressions on the sea bed. They are often circular or elliptical in shape and vary in size from some tens to hundreds of metres across. They occur in many offshore locations throughout the world and their presence is usually indicative of underlying hydrocarbon reservoirs. The widely-accepted explanation is that thermogenic gas (largely methane) leaks upwards from the reservoir following distinct migration pathways. When the gas encounters a layer of soft clay-rich sediment close to the sea bed, it becomes trapped beneath this layer. It then accumulates until its pressure is high enough for it to burst through the sediment at some critical overpressure.

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A selection of recent publications and commissioned research reports on gas migration in clays and mudrocks.

Gas release is reported to be a sudden event. The sediments can be lifted upwards into the sea water by the release of gas and then redeposited in the region around the central depression. The fabric of the sea bed sediment is always disturbed by the passage of gas. Examination of gassy sediments reveals that the gas becomes trapped in cavities with dimensions orders of magnitude larger than the normal pores of the sediment.

Many features of gas movement in clay-rich media cannot be explained by invoking ‘textbook models’ of two-phase flow in porous rocks, including the upward motion of large gas bubbles in wet clays, the formation of pockmarks in sea bed sediments, the development of large gas-filled voids, the visual observations of cracking, the lack of evidence for porewater displacement, the conspicuous stress-sensitivity of the gas transport process, the observed relationship between gas entry pressure and swelling pressure in bentonite, the dynamics of the gas transport process and, finally, the absence of any form of experimental confirmation that gas actually flows through the original pores of a fully-hydrated clay. Although specific observations on unlithified clays and muds cannot be interpreted as general proof of difficulties with the conventional theory of two-phase flow when applied to the broad class of argillaceous media (i.e. soils and rocks), the evidence is now sufficiently strong to prompt the development of alternative quantitative theories and models to explain the findings of a growing number of experimentalists and observational geoscientists.

Funding

Research on fluid flow in clays and mudrocks is undertaken using the facilities of the BGS Transport Properties Research Laboratory. Funding sources include: SKB (Stockholm, Sweden); International Mont Terri Project Consortium (coordinated by NAGRA in Switzerland); 3rd and 4th Framework Programmes of the European Union (DG XII); EPSRC/NERC Waste and Pollution Management Programme; JNC (Tokyo, Japan); Nuclear Energy Agency (OECD, Paris, France); GeoPop Consortium (coordinated by Heriott-Watt University). For additional information please contact the authors at s.horseman@bgs.ac.uk or j.harrington @bgs.ac.uk.