due to the reflection of solar radiation back to space and the equally large greenhouse warming due to trapping of upwelling thermal radiation. As seen from space, the net effect of clouds is therefore close to zero, but the heating has been redistributed significantly within the column[10]. Ramanathan and Collins recognize that the cooling effect is felt at the surface, whereas the greenhouse warming occurs within the atmosphere. They claim that this warming is advected away by the atmospheric circulation and does not influence the local SSTs, which experience only the cooling effect. However, modelling studies[10,11] show that the atmospheric warming induces changes in the vertical motion field and thereby influences both the precipitation and circulation fields, which in turn influences the cloud cover at all levels.

Our understanding of the processes that maintain the warmest SSTs on the planet is rudimentary. Compared with the tropical eastern Pacific, the western Pacific is a region where the winds are generally light and the evaporative heat flux is small, where the structure of the ocean mixed layer is complex and the SST is highest and where large-scale east–west and meridional circulation of the atmosphere ensures significant moisture convergence to support the deepest convection, heaviest rainfall and smallest fluxes of solar radiation into the ocean. How these processes intimately link together is not well understood. We have attempted to expose only the simplest aspects of these coupled processes and suggest that the longwave cloud forcing, the precipitation and evaporation as well as dynamical influences on cloud cover must also be assessed to determine whether Ramanathan and Collins's thermostat can function. It is our view that it is impossible to isolate a given feedback unambiguously from other coupled processes using available observations.

Nevertheless, the thermostat and the air-conditioning mechanisms are tantalizing hypotheses which perhaps can only be tested fully by models of the coupled ocean–atmosphere system, once these models have demonstrated sufficient realism. To this end, improved basic understanding of the processes of evaporation, precipitation and radiative transfer and how they couple, together with a better understanding of the influence of large-scale atmospheric and oceanic circulation on these processes, is needed urgently. So it is most timely that a major international experiment will be conducted later this year in the west Pacific; the Tropical Oceans and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE[12]). This will provide some of the sophisticated new observations which are needed to improve our understanding of the processes which maintain the warm sea surface of the equatorial Pacific. ☐

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ORE GEOLOGY

A little rain must fall

Andrew P. Gize

DEEP below the permafrost of northern Alaska, rainwater (meteoric water) which fell perhaps as long ago as 10^5–10^6 years over the Brooks Range mountains in the centre of the State, is carrying heat and minerals through aquifers to the northern coastal plains. In showing this, using detailed borehole studies, Deming *et al.*[1] have confirmed the geochemically and economically important roles that long-range groundwater migrations can have in large sedimentary basins. In addition, their data provide a solid framework against which many geological and geochemical concepts can be evaluated.

The significance of groundwater flow in sedimentary basins is that it provides a fundamental means of transferring heat and mass. The consequences are varied, and include control over the extent of mineral equilibrium or disequilibrium assemblages in the sediments, the force responsible for petroleum secondary migration, and control over the transport and location of some types of metalliferous ore deposits.

Several interpretations have been put forward to describe the sources and driving forces for the water. Some water could be expelled during clay mineral structural transformations or by compaction from overlying sediments[2]. Alternatively, water could be driven by meteoric water precipitated on topographically high regions, providing a hydraulic head[3], or by density gradients resulting from thermal expansion or salinity gradients which then induce free convection[4]. Each of these alternatives has merit in certain circumstances. Nevertheless, a generalized observed pattern has emerged for groundwater flow in basins bordering mountain ranges[1]. In the mountain-range foothills, new meteoric water recharge depresses the geothermal gradient and surface heat flow as it moves downwards. In the basin centre, groundwater flow tends to be horizontal, with little variation in the vertical heat flow. At the far end of the basin, the fluid flow, now rising, is controlled by details in the basin geometry, and localized highs arise in the geothermal gradients and surface heat flow.

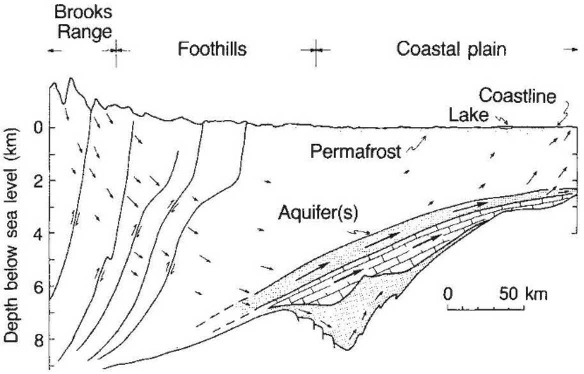

FIG. 1 Conceptual model of regional groundwater flow in the North Slope of Alaska (from ref. 1).

The results of Deming *et al.* are the culmination of a 10-year collaborative programme of the US Geological Survey and the National Petroleum Reserve Alaska, covering an area of approximately 300 × 500 km^2 between the Brooks Range mountains and Prudhoe Bay on the northern coast. The borehole data were obtained between 1977 and 1984, and were used to confirm the generalized heat flow model for the basin[5]: in the Brooks Range foothills the vertical geothermal gradients are less than 22 °C km^{-1} whereas on the coastal plain they are as high as 53 °C km^{-1}. Although it was suggested then that the measured geothermal gradient variations could be due to vertical advection, effects from variable sedimentary thermal conductivities were acknowledged to be a potential factor. Now, with thermal conductivity measurements completed, and potential effects from variations in sediment conductivity clearly eliminated, Deming *et al.* show that for the North Slope of Alaska, the only viable interpretation for groundwater movement is forced convection by a topographically driven system (Fig. 1). It is this clear elimination of all other possible mechanisms for the fundamental circulation which allows constraints to be imposed on a wide spectrum of other sedimentary-basin processes.

The significance of basinal groundwater flow in providing a driving force behind the secondary migration of petroleum is discussed by the authors, with the suggestion that the North Slope groundwater flow was involved in petroleum accumulation in Prudhoe Bay. There remain other critical problems in sedimentary basins, several of which can be exemplified by the economically important Mississippi Valley type (MVT) lead–zinc sulphide deposits. In spite of appearing, from their mineralogy, geology and geochemistry, to be among the simplest types of metalliferous deposits, aspects of their genesis from such large-scale basinal groundwater flows remain a source of contention[6].

A consequence of topographic recharge is that the water input will fluctuate with climatic cycles. The question is how far into the basin these fluctuations are observable before being dampened out. An indication of the fluid flow complexities which are evident at the far end of the basin, and which need to be incorporated into any basin flow model, are indicated by the delicate micrometre-scale banding observed in some MVT sphalerites (such as the Upper Mississippi Valley District, Fig. 2). This banding can be correlated between individual ore bodies on the kilometre scale, indicating large-scale spatial and temporal fluid fluctuations[7].

Using time-series analyses, some but not all of the banding has been shown to occur at periodicities comparable to known climatic cycles (such as the Milankovitch cycles), and has been attributed to reduced basinal fluids interacting with cyclic, oxidized, near-surface waters[8]. Similar banding in petroleum reservoir silicates cannot be related to interaction with shallower waters, and reflects either fluctuations in the recharge area or structural processes in the basin[9,10]. Clearly the interpretation presented by Deming *et al.* will be far more complex in reality with fluid flow fluctuations arising at several points. One intriguing question is how far along the flow path can these fluctuations be observed, and what are their relative contributions at the end of basin flow?

Deming *et al.* relate heat flow and borehole temperatures with basement structure. Lower heat flow and geothermal gradients are correlated with thick sedimentary sequences over the basin, whereas high geothermal gradients depend on thinner sedimentary cover with a strong influence by available aquifers. Variations in the duration and temperature of fluid flow should affect the extent of mineral equilibration in the aquifers, with evidence for more complete re-equilibration over basement highs. This kinetic implication may be one reason why MVT mineralization is absent from dolomitized Palaeozoic carbonates in northwest Scotland, but present in the equivalent carbonates of Newfoundland. The Scottish carbonates are separated from the basement by a thick sequence of quartzo-feldspathic arenites whereas in Newfoundland there are no such underlying sediments. According to the new results, the geothermal gradient will have been locally higher in Newfoundland, which (coupled with fewer aquifers) enabled development of a coarse dolomite with pore space to host mineralization. In spite of extensive dolomitization in northwest Scotland, there is no such coarse crystalline dolomite.

A second aspect of heat transfer touched on by Deming *et al.* concerns the extent to which heat is transferred along the length of the fluid flow path. MVT deposits formed at the end of the fluid flow path have typical precipitation temperatures in the range 200–100 °C, raising questions on the heat budget of the fluid migration. In the North Slope system, the fluids are heated early in the deeper parts of the basin, and maintain their temperature of 200–100 °C for most of the fluid path. This observation removes superficial questions about the extent to which heat is transferred in the basin, but not about the underlying heat budget.

Finally Deming *et al.* provide a severe test of our current understanding of solution chemistry. In the North Slope, the average groundwater velocity is estimated to be 10 cm yr^{-1} and, excepting climatic factors, there are no obvious reasons why these flow rates should not be applied elsewhere. Taking the Upper Mississippi Valley District as an example, it has been estimated by several independent techniques that a major ore body (10^6 tonnes ZnS) takes 10^5–10^6 years to form[11]. A simplistic calculation at the temperatures and acidities inferred from the North Slope and other aquifers suggests the ore solution has to carry between 1–10 parts per million metals to form an ore body. This estimate is in agreement with other workers, and reinforces the opinion that metal chloride and bisulphide complexing alone are insufficient by approximately two orders of magnitude to account for the required solubility. The North Slope data imply that other metal complexes are required, perhaps organic ligands[12] which were derived during petroleum formation. ☐

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FIG. 2 Thin section of sphalerite (ZnS) from Shullsburg ore body, Wisconsin. Variations in colours are due to variations in iron content over timescales of 10^5–10^6 years. The height of the section is 70 mm. (Photograph by S. Maher.)

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