Rock and water histories
during sub-oceanic hydrothermal events

C. R. B. Lister
Departments of Geophysics and Oceanography, University of Washington, WB-10, Seattle, Washington 98195, USA.

ABSTRACT
An "active" geothermal system cracks and penetrates hot rock, converting it from an initial hot dry state to a cool altered state. At the same time, hydrothermal fluids evolve from normal oxygen-bearing seawater to acidic reducing solutions containing sulphides. The history of a portion of rock is dependent on whether it starts beneath cool recharge water or beneath a hot convection plume. In the first case, alteration is limited by the short period of time the rock remains bathed in the hot fluid of the convection boundary layer. Conditions change rapidly to that of low-temperature alteration in the presence of oxygen. On the other hand, rock that starts out beneath a hot plume may remain bathed in hot acidic waters for a much longer time, and may even undergo two alteration periods.

The history of a penetrating hydrothermal system can be quite complex even in an idealised situation without geological variations. The "cold finger" growing downward into hot rock may assume a kidney-like planform and migrate laterally due to rock cracking, creep and fatigue. Eventual breakup into separate circulation cells, one above the other, can cause massive sulphide deposition within the oceanic crust and the attainment of amphibolite-facies conditions in the superheated lower cell. Further cooling and re-cracking in later, less vigorous, hydrothermal systems can chill the altered rocks and preserve them for eventual exposure in Ophiolite suites, as well as providing general permeability throughout the oceanic crust.

The physical evidence from heat flow measurements is difficult to reconcile with anything other than a thick and rather pervasive permeable layer. In the "passive" phase of hydrothermal circulation, long after the crustal rocks have been cracked and cooled to form the permeable layer, heat may be transported laterally by several tens of kilometres to hot springs where basement outcrops through sediment cover. Although forced convection of this type is not yet sufficiently understood, the data are hard to reconcile with a purely superficial permeable layer in the 1-2 km of pillow lavas and sheeted dykes.


RÉSUMÉ
L'évolution des roches et des fluides au cours des processus hydrothermaux sous-marins

L'hydrothermalisme « actif » fracture et envahit les roches ignées, les faisant passer d'un stade initial anhydre et chaud à un état refroidi et altéré. Parallèlement, les fluides hydrothermaux constitués au départ d'eau de mer contenant de l'oxygène dissous sont transformés en solutions acides chargées en sulfure. L'évolution de la roche dépend de sa situation par rapport à la cellule convective ; dans les zones de pénétration, de mise en charge de l'eau de mer, l'évolution est différente de celle qui se produit dans les zones de remontée de l'eau chaude. Dans le premier cas, l'altération est limitée par le temps relativement court où la roche reste baignée par les liquides à température élevée du front de convection. Les conditions changent rapidement vers des processus d'altération à basse température en présence d'oxygène. Dans l'autre cas, au-dessus de la branche ascendante de la cellule, la roche reste baignée par des fluides acides et chauds pendant une période beaucoup plus longue. Elle peut même subir deux périodes d'altération. L'histoire géologique d'un système...
INTRODUCTION

The island of Iceland has long been recognised as a part of the Mid-Atlantic Ridge, and as a type area for the geyser style of geothermal activity. Speculations that hydrothermal circulation could be important also on the deeply submerged portions of the mid-ocean ridge system have tended to originate from thoughts about this coincidence (Palmason, 1967). The earliest oceanic measurements to be interpreted as direct evidence of such circulation were the relatively high concentrations of certain heavy metals in the surface sediments near mid-ocean spreading centers (Bostrom, Peterson, 1969; Bender et al., 1971; Corliss, 1971; Dasch et al., 1973; Piper, 1973). Soon after, the large discrepancy between the measured and expected heat flow over young oceanic crust led first to suggestions that some of the missing heat may be liberated at hot springs, and then confirmation that the patterns of observed heat flow were consistent with widespread circulation of fluids (Talwani et al., 1971; Lister, 1972; Hyndman, Rankin, 1972; Williams et al., 1974). That the unusual metal concentrations at the surface are derived from the fresh crustal rocks emplaced at sites of plate divergence, is a concept now consolidated by studies of alteration in Ophiolite suites, well established as subaerially exposed sections of former oceanic crust (Gass, 1968; Coleman, 1971; Dewey, Bird, 1971; Muehlenbachs, Clayton, 1972; Hart, 1973; Robertson, Hudson, 1973; Spooner, Fyfe, 1973; Hart et al., 1974; Spooner et al., 1974). Similarly, the physical concept of heat transfer by circulation of fluids in cracks or a porous layer has received some attention, though most work has been directed at the understanding of land geothermal areas and only a small proportion concerns the ocean floor directly (Bodvarsson, Lowell, 1972; Hartline, 1978). However, an important idea appears in the first of the references just cited, that a small amount of thermal contraction can produce the cracks needed to make hard rocks permeable. When the concept of a cracking front, a sharp boundary between the cold, permeable and hot impermeable regions, is added, a theory of water penetration into hot rock can be developed (Lister, 1974; 1981). Though in a very primitive state, the qualitative results of this theory can be applied to the general ridge crest problem: how a mass of basaltic magma is converted to a thick, cold, quasi-layered and partly altered oceanic crust.

GENERATION AND HISTORY OF THE PERMEABILITY

Although most people would accept the idea that thermal contraction can produce the cracks needed for fluid flow, the question of the spacing of these cracks is not trivial. The concept of a well-defined cracking front, separating the convectively cooled region from essentially untouched hot rock, leads inexorably to a moderately fine crack spacing of the order of a meter. This is because the conductive boundary layer ahead of the cracks in thin when crack advance is rapid, and crack advance must be rapid when the cracked region is permeable enough to convect vigorously (Lister, 1974; 1981). Fortunately, the geochemical evidence strongly supports this: the rate of diffusion of metal ions through hydrated silicates is far lower than the rate of diffusion of heat. Significant chemical interaction between the circulating fluid and the rock can occur only if the crack spacing is small, because the lifetime of a hot-fluid geothermal area is relatively short. The existence of metal rich superheated brines (e.g. Corliss et al., 1979) confirms that the chemical exchange occurs simultaneously with the heating of the water, and the flow rates are such as to preclude "steaming" of the rocks for thousands of years. When cracks penetrate into hot rock, the heat stored in that rock is liberated into the hydrothermal system at a rate dependent only on the rate of advance of the cracks and the temperature difference between the rock and the circulating fluid. If the cracked region is highly permeable, the convection can extract a high heat flux from a small area of cracks, so that the high output of a major geothermal system can be supplied, for a short time, by a relatively small volume of
hot rock. The traditional idea (Elder, 1965) that geothermal heat is gathered from a small conductive heat flux over a wide area is belied by the close spacing of geothermal areas in New Zealand, along a line of most recent magma intrusion, and the close proximity of all ocean floor hot springs, found so far, to the axis of rifting. The circumstantial evidence is thus in agreement with an important qualitative conclusion of the water penetration theory: that the penetration of the cracks occurs at a speed of several meters per year, and therefore that the existence of hydrothermal systems is an intermittent, local phenomenon. I have coined the term “active” geothermal area, to distinguish the vigorous circulation over a volume of hot rock being penetrated by cracks, from the much gentler circulation that should continue in the permeable zone, when the cracks have ceased to advance. This “passive” circulation is driven by heat conducted to the base of the permeable region from hot lithosphere below, and may continue until either the permeability is reduced by clogging of the cracks, or the heat flux drops below the critical level needed to drive convection (Lister, 1981).

The gross history of ocean crustal permeability can be summed up as rapid formation of cracks while the rock is still very near the zone of new emplacement, followed by a long period of slow alteration and decay as the crust ages. Paradoxically, clay-rich deep-sea sediments have permeabilities much lower than those of cracked rocks, and so a substantial sediment cover can seal off interchange between the circulating fluids and the ocean. The evidence from heat flow measurements is that differences between the means for completely sealed ocean floor, and ocean floor only partially covered by sediments, persist out to great ages (Schluter et al., 1976). This is consistent with the slow pace of rock alteration predicted by the “active”/“passive” concept: the ambient temperature in a highly permeable layer supplied by a normal oceanic heat flux is only a few degrees above that of the deep ocean water (Lister, 1981). Only where sediment cover is both thick and complete can the rock temperatures rise enough to permit more rapid alteration.

DISCONTINUOUS HYDROTHERMAL “EVENTS” NEAR A SPREADING CENTER

Both the results of one-dimensional water penetration theory, and the circumstantial evidence from the size and spatial disposition of hot-fluid geothermal areas, agree that water penetration into hot rock is a rapid process. Since the penetration rates are about two orders of magnitude faster than the rate of sea-floor spreading, it follows that high-temperature geothermal activity is not a steady-state phenomenon, but must occur episodically in localized areas. That, in turn, means that the water-penetration process is a three-dimensional phenomenon, where the water somehow attacks a cooled-magma body of relatively small size. The incompatibility of thermal contraction cracking and a liquid magma intrusion, capable of convecting actively within itself, has already been discussed by Lister (1977). The physics of a cracked permeable region with vertical boundaries, as well as a base, is considerably more complex than the one-dimensional cracking model considered so far (Lister, 1974; 1981). The qualitative aspects have been developed by Lister (1975), and the one-dimensional pressure difference between the permeable interior of the cracked region and the hot rock outside. By definition, a hydrothermal system has a water connection from the surface to its base, so that the pressure within the cracks is always just the hydrostatic pressure pgh. The rock outside must bear the full weight of overlying strata, and will do so hydrostatically if it is thick enough to be plastic. Hence there is a difference pressure \( p_h - p_g \) that must be taken up by extra stresses in the walls of the permeable zone if the cracks are to remain open, a difference that increases about 150 bars/km with increasing depth.

The “pressure-case” concept for a three-dimensional penetrating convection cell was advanced by Lister (1975), but in fact the system considered was really only two-dimensional because of implied cylindrical symmetry. While it would not be impossible to start a symmetrical system, with a hot plume in the middle and cold descending fluid near the walls, such symmetry is unlikely in nature, and would probably be unstable to finite perturbations. The search for a suitable stable asymmetric convection and cracking arrangement must be guided by a few qualitative physical principles. The first is, that the colder the rock is, the higher the stresses it can support at a small rate of creep, but there is a brittle fracture limit to the deviatoric compressive stress. The second is that the conductively cooled boundary layer has a 1/e thickness inversely proportional to the speed of advance of the cracks, \( u \). The third is that the speed \( u \) is proportional to the thermal gradient in the fluid boundary layer, itself a complex function of the flow rate, \( T^* \), and the temperature at which the rock can crack and the flow length along the heated boundary. The fourth is that there are no momentum or momentum-transfer effects between fluid parcels in porous-medium flow: the local flow rate is a function only of the local pressure gradient in the fluid.

An immediate corollary of the fourth is that, where cold fluid is descending along a hot boundary to the permeable zone, the warmer fluid near the crack tips will tend to stagnate due to its local buoyancy, and thus reduce the thermal gradient in the boundary layer. This is necessary because the thickness of stressed rock cannot be thicker than the conductively cooled boundary layer ahead of the cracked rock, which would be much too thin at the rapid cracking rate implied by cold water near the boundary. The corollary of the first principle is that the cracking, where the rock has supported all necessary compressive loads and can finally go into tension, drops if the effective stresses are large, according to a complex (and largely unknown) relationship outlined in Lister (1974), Table 2. The numerical values in that table would imply a great deal of creep and very low cracking temperatures where the stresses are large, but they are for “wet” (or “wet” lherzolite, and the pristine oceanic rocks are largely, though not totally, dry. It is not clear whether partially dry rocks follow the activation energy law for wet rocks at a correspondingly lower strain rate, or whether there are creep sites where hydrogen ions cannot penetrate and higher activation energies apply. However, a drop in relative creep rate of two orders of magnitude from that of fully wet rock would bring the numerical values into line (see Lister, 1981, Appendix I, Table 1). The details of the numerical calculations, to such accuracy as is possible at present, are messy and too large a digression for this short paper.

The result of all these qualitative physical considerations is the growing convective system sketched in Figure 1. It is fully asymmetric, with the recharge water flowing down one side of the permeable region, and the hot plume returning up the other. The side bathed by superheated fluid is too hot to withstand the external lithostatic pressure by forming a stressed layer, and must therefore be convex toward the
permeable zone. The extra pressure is taken up by lateral stress in the cracked matrix, implying a radial distribution of the major cracks, and an anisotropic permeability. This consideration essentially forces the permeable region to be kidney shaped, with the only isotropic permeability in the region of the tips of the kidney, where the wall radius is small and the external pressure can be taken up by the conductively cooled boundary layer. On the large-radius cold side, most of the external pressure is balanced by the radial horizontal stress in the cracked region, but the difference in length between the hot and cold sides means that some stress must be taken up in the cold layer just outside the crack tips.

The base of the convective system grows fastest because the least stresses need to be built up in the cooling rock to permit cracks to propagate, and because the radial orientation of the boundary thermal gradient induces the highest heat transfer rate. At very high overall Rayleigh numbers, the boundary layers can become unstable to subsidiary convection that enhances the heat transfer rate and makes the plume of hot fluid thicker and more uniform. A combination of creep and static fatigue should cause the hot vertical wall of the permeable region to migrate inward, while the cold vertical wall advances outward at a much slower rate than the base of the system grows downward. The aspect ratio of the kidney-shaped "cold finger" should remain roughly constant until something happens to disturb the system. One possibility is the collision of the expanding cold boundary with the edge of the hot pluron, coming into contact with cooler rock that is not cracked as easily by thermal contraction. Another is the lateral migration of the whole circulation system, bringing it away from direct access to paths for the recharge and venting of the fluids. Either of these or simple elongation, could cause a fundamental instability in the circulation, with breakup into two separate convection cells one above the other. Such a system is sketched in Figure 2A, where it should be noted that the lack of momentum transfer within the fluid in a permeable medium makes it immaterial whether the flows on either side of the intermediate boundary are in the same or opposite directions.

Once the circulation has split, the chemical reactions within the system ensure a permanent separation. The hot fluid in the lower cell is largely isolated from fresh seawater, so it is fully reduced and acid, and the lower convection cell becomes a sulphide still. The massive sulphide deposit at the intermediate boundary seals off the cracks and the permeability, while the high thermal conductivity of metal sulphides maintains a moderate thermal transfer rate between the cells. The temperature of the lower convection cell is now much higher than in the open system, so creep and alteration processes are more rapid relative to the penetration rates for the cracks. It is probable that the lateral thickness begins to decline due to the more rapid failure of the hot side than growth of the cold side, leading to a limited life for this phase of the hydrothermal circulation, and a limited total penetration of the system in the vertical direction. A late stage is sketched in Figure 2B.

ROCK AND WATER HISTORIES DURING A GEOTHERMAL EVENT

The preceding section has developed a possible scenario for the birth, growth, and death of an "active" geothermal system. The picture is idealised, since it starts with a...
ROCK AND WATER HISTORIES AND HYDROTHERMALISM

uniform body of hot rock that is opened to hydrothermal penetration at a convenient point. Near a real ridge crest, geological inhomogeneities will intrude on the process, but mechanisms are present to permit the basic steps to occur. An impermeable boundary can be formed between a magma chamber and surface circulation (Lister, 1977), permitting the formation of a hot cumulate body. Once the magma has crystallised, water can gain access either through generally falling temperatures, and thermal cracking, or through tectonic action. The "active" geothermal system then starts and processes until penetrative cracking ceases to occur. The rapid drop in temperatures then "freezes" much of the alteration states of the rock, leaving only very slow low-temperature alteration as a post-print over the young active phase.

As can be seen from examination of Figures 1 and 2, rocks in different parts of the system have very different time, temperature and fluid chemistry histories. Near the cold recharge waters, rock is cooled to essentially seawater temperature in a time equal to the boundary layer thickness divided by the crack advance rate. The figures in Lister (1981) suggest a mere 2 years for the one-dimensional calculation: conservatively, only a few years. With crack spacings of the order of a meter, this implies minimal alteration. By contrast, rock that happens to end up in the hot plume can be immersed in acid 400°C water for a time comparable to the life of the whole active phase, more like 1,000 years, and should show substantial alteration with minor sulphide deposition. In the separated deep convection cell, rock behind the failing hot boundary could even reach conditions where Amphiboles can be formed, while the top of this cell is a zone of massive sulphide deposition (these exist in Ophiolites: Barriga, pers. comm.).

Water histories are essentially complementary to the rock histories. During the open circulation phase, where the hot fluids are discharged directly onto the ocean floor through chimneys made of mineral deposits, the water residence times are extremely short — of the order of a few hours to tens of hours in the hot plume. Recharge fluid descends rapidly to the hot cracking boundary at the base of the system and is heated to 200-400°C in contact with freshly exposed rock surfaces. It becomes deoxygenated, acid and loaded with sulphides. In this form it tends to seal itself into channels by mineral deposition, and discharges at the surface without much cooling or chemical alteration, unless special circumstances permit mixing.

When the hydrothermal system has split into two cells, the upper circulation is still open, contacts very little freshly exposed rock, and therefore remains oxygenated and relatively cool. Some mixing with hot fluid leaking from below may occur if tectonic faulting opens up the leaks. The semi-sealed lower cell becomes a nearly closed chemical system, where the fluid comes close to equilibrium with freshly exposed hot-rock surfaces. Its composition should be similar to the hot plume of the open system, but probably even more acid and with a sulphide content that fluctuates with temperature. This type of convection, driven vigorously by the continual exposure of fresh hot rock, can form an extremely efficient mineral still, and may well be responsible for many kinds of ore deposit, on the continents as well as on the ocean floor.

When alteration, creep and static fatigue have finally caused the collapse of the permeability in the hot cell, the high-temperature phase of hydrothermal circulation is over for this particular system. This does not necessarily prevent new systems opening up in any residual hot rock nearby: conductive cooling is slow enough not to affect rock more than 300 m away from the permeable zone in the ~ 1,000 year life of the system. And, as long as there is rock significantly above seawater temperature within reach of the water, cooler cracking can still occur, and cool penetrative systems can develop to chill even highly altered rock. Thus the state of the crust at the end of all active hydrothermal circulation is completely cold and somewhat permeable everywhere. Mineralisation residues of our active system might appear as in Figure 2 C, with large volumes of very little alteration, but traces of the hot plume mineralisation, massive sulphide deposits and zones of amphibole-facies alteration. More than one generation of cracks are likely, especially in the altered rock, but the picture should be frozen into the crust at this point unless the ocean floor is covered by thick sediment deposits while the heat flow from below is still high, leading again to higher temperatures.

CONCLUSIONS

In this paper I have tried to point out how the basic physical principles of penetrative hydrothermal convection can be applied to developing histories of water/rock interaction in young oceanic crust. The actual physical properties are not well known even for representative rock types, so that only order-of-magnitude estimates can be made of numerical values. This means that the qualitative picture, expressed in the cartoons of Figures 1 and 2, is as far as it is reasonable to go. The quantitative data are simply not reliable enough to warrant running accurate numerical models on a computer. One important result of prior work on the one-dimensional penetration theory (Lister, 1974; 1981) is the relative stability of the results to wide fluctuations in the physical relationships. This gives some confidence that the results are significant in the qualitative sense in spite of the admitted limitations of the theory. Some of the possible geological complexities have been touched upon in this paper, though most progress on developing the details of geothermal histories is now likely to come from careful field work on good Ophiolite exposures.

Acknowledgements

This work was supported by National Science Foundation grant OCE 77-17870 via subcontract from the Massachusetts Institute of Technology. I am particularly grateful to Fernando Barriga for sharing with me an early draft of a review paper on oceanic geothermal effects that provided several useful ideas and some key data.

REFERENCES


