Sources of Geothermal Heat

2

The main purpose of this chapter is to explain how a relatively shallow geothermal resource from which heat is to be extracted relates to the dynamics of the earth. The structure of the interior of the earth is described in general terms. Tectonic plates and events taking place at their boundaries are explained, elaborating on subduction boundaries and discussing the origins of heat sources in the form of intrusive bodies of magma. Examples of these at drillable depths are given. The chapter ends with a brief discussion of geothermal surface discharges.

2.1 The Structure of the Earth

The earth is a sphere 6,400 km in radius which is believed to have formed about 4,500 Ma ago. At present it has a metal core of radius 3,500 km, of either iron or an iron–nickel alloy, which has separated from the surrounding material under the gravitational field. It follows that the core radius must have been increasing over earth's lifetime and the chemical constituents of the surrounding material have been changing. The pressure and temperature at the centre of the core, where the metal is thought to be solid, are estimated to be about 1.4 million bars and 5,000 °C, respectively. The temperature at the outer radius of the core is estimated to be between 3,500 and 4,500 °C. At some radius within the core, the metal is thought to become liquid, although this implies properties like those of common liquids, and "plastic" might be a more appropriate description.

The material surrounding the core is an entirely molten (plastic) layer of oxides of silica and other elements which is referred to as the mantle (literally meaning a cloak or garment) and is 2,900 km thick; the mantle extends essentially to the surface, although not as a homogenous material. It is thought possible that the Moon is made up of mantle material which was separated off at an early stage in earth's development by an asteroid impact. The properties of the mantle have been the subject of considerable research to examine this and other theories about the

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early development of the planet (see, e.g. Ohtani [2009]), and a striking feature is the complexity of the mineral mixture and the need for phase diagrams reaching to pressures of 200,000 bars and 5,000 °C if any quantitative estimates of evolutionary processes are to be made. In broad material terms, the earth is made up only of these two components, the core and the mantle, but it is exposed to low-temperature space through a relatively thin and transparent atmosphere, and as a result the surface temperature is low enough for the material to be solid there—the crust. Being solid and exposed to the atmosphere, it has undergone both chemical and physical changes, making it much more heterogeneous than the plastic mantle on which it floats.

Seismological measurements indicate a change in material at the base of the mantle, 2,900 km below the surface, a change referred to as the Gutenberg discontinuity. Another seismological interface, the Mohorovicic discontinuity, occurs at a depth of about 35 km and divides the mantle from the crust. Accordingly, the crust can be thought of as two layers, a lower solid one of silica- and magnesia-rich material which is described as basalt and an upper one of silica- and alumina-rich material generally described as granite (Whitten and Brookes [1972]). Overlying the crust is a thin layer of sedimentary rocks, the result of the processes taking place at the surface by interaction with the atmosphere. The crust is thinnest beneath the oceans and thickest beneath mountain ranges, and its surface is far from smooth. Taking sea level as the average surface level, the highest mountain is 9 km and the deepest ocean 11 km, and maximum undulations of the surface are within an order of magnitude of the thickness.

The quantity of thermal energy contained in the core cannot be calculated because the material properties are not known; however, that is no detriment here. Humanity has existed for only 2 of the 4,500 Ma since the formation of the earth, so not only is the store of heat of literally astronomical proportions but the state of the interior can be regarded as fixed in human terms. The heat leakage from the surface to the atmosphere is an average of 50 mW/m^2 overall, a very small heat flow rate (flux) compared to the 1.4 kW/m^2 of solar radiation arriving at the outer surface of the atmosphere. The net heat loss from the interior is a negligible proportion of the heat stored. However, very much higher heat fluxes than 50 mW/m^2 escape from the ground surface at some locations, and a figure of 800 mW/m^2 has been estimated by Cole et al. [1995] for the Taupo Volcanic Zone of New Zealand (see also Hochstein and Regenauer-Lieb [1989]).

The rotation of the earth and the plasticity of its two main component layers results in the circulation of both mantle and core. The mass of mantle fluid in motion, its viscosity and internal heat generation all combine to fracture the crust and cause the pieces—tectonic plates—to move. Heat is generated as a result of gravitational work done in draining the core metal from the mantle, and the decay of radioactive isotopes in the mantle provides an additional source to keep it molten. The induced buoyancy forces and the Coriolis forces due to the rotation lead to it having a complicated flow pattern. The solid crust is subjected to forces causing it to break into large slabs which move slowly in different directions as a result of floating on a liquid. The study of the motion is called plate tectonics, and articles conveying the current scientific thinking are available on the Internet, for example, by the Institute of Geological and Nuclear Sciences, NZ (GNS) [2012], the US Geological Survey [2012] and the British Geological Survey [2012], including animations of the plate motion.

2.2 Processes Taking Place in the Crust

Processes within the crust are controlled by the physical and chemical properties of the material, the temperature distribution and the motion of the plates. The plates move relative to one another at an average speed of typically 3–10 mm/year, although rates several times this have been measured. Heat reaches the surface at some plate boundaries. It is much too simplistic to consider this simply as leakage at the cracks, and the purpose of this section is to give some appreciation of the physics involved. It is clear from maps of earth's surface that volcanism is associated with subduction boundaries in a recognisable pattern, and many geothermal resources occur in volcanic terrain. The Pacific "Ring of Fire" is perhaps the prime example—see US Geological Survey [2012] and Schellart and Rawlinson [2010]. Plate boundary processes attract a great deal of academic research, but progress is inevitably slow given the inaccessibility of the regions of interest, which are well below the surface. What is relevant here is a picture of how a geothermal resource gains its heat and what physical form it takes.

The plates may converge by moving towards each other in a direction normal to the boundary between them, or diverge likewise, or interact with a shear component, and combinations of these occur. At some plate margins, the mode of interaction changes locally from one type to another. Convergent plates are associated with heat release at the surface and hence with geothermal resources, and the dynamics of converging plates has recently been reviewed by Schellart and Rawlinson [2010]. They provide an extensive list of references and define two types of convergent interaction, subduction and collision. Before describing the boundary interactions, more of the physical aspects of the crust must be understood. It may be considered to be in two layers, the rigid outer one called the lithosphere and the inner plastic one called the asthenosphere (the root is Greek, meaning weak). The crust is thicker beneath continents than beneath the oceans, so indications of thickness are not precise; however, the lithosphere may be up to 75 km thick and the asthenosphere from the bottom of the lithosphere to as much as 200 km. What is being described in the latter case is the depth over which the temperature variations induce major physical property variations, particularly viscosity. In discussing the laboratory modelling of subduction boundaries where oceanic crust is overridden by continental crust, Shemenda [1994] suggests that the materials in order of depth are a low-strength brittle upper layer (clearly lithospheric), then a layer showing a gradual transition from brittle to plastic material properties but with elasticity (the ability to carry stress without continuous strain) which renders the material stronger than the first layer and then a decrease in strength beyond depths of "a few tens of kilometres" into high-viscosity fluid behaviour (clearly asthenospheric).

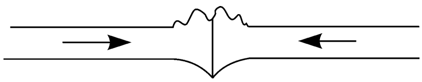

Fig. 2.1 Sketch illustrating a tectonic plate collision boundary

2.2.1 Collision Boundaries

Collision boundaries are defined as those where both plates are continental plates at the colliding margins. The result of the collision is the formation of a mountain range generated by buckling and folding, e.g. the Himalayas, as illustrated by the sketch (Fig. 2.1).

The mechanical forces involved generate internal heat in the same way that the repeated bending of a piece of wire or the cutting of metal in a lathe causes the metal to become hot, by plastic deformation. The location is a plate boundary, but the heat released has only indirect connection to the heat of the mantle, being due to plastic deformation as a result of the motion which is enabled by the earth's internal heat. Hochstein and Regenauer-Lieb [1998] produced a numerical model of the heat generated by plastic deformation in the collision boundary of the Himalayas. There exists a belt of geothermal springs parallel to the inferred plate boundary, and they related the results of their calculations to field measurements of the hot springs. In doing so they estimated that the rate of heat release at the surface was 100 MW/100 km over much of the length of the 3,000 km plate boundary on which the Himalayas are situated and up to 300 MW/100 km towards the eastern end. They concluded that heat generation resulting from plastic deformation was a likely cause of the higher than average heat flux leaving the surface along that particular plate boundary. The quoted heat fluxes of less than 1 W/m^2 are not encouraging for large-scale geothermal power development.

2.2.2 Subduction Boundaries

At a subduction boundary, one plate rides over the other, which dips (subducts) down into the mantle (Fig. 2.2). Two important surface modifications often occur adjacent to the plate margins, volcanism along a line generally parallel to the overriding plate edge and faulting and surface subsidence some distance behind the overriding plate edge. Schellart and Rawlinson [2010] note that at some subduction boundaries, there is also evidence of the collision process of Sect. 2.2.1 together with the subduction process, referring in particular to the Andes, which is the result of the convergence of the plate forming the bed of the Pacific Ocean moving eastwards and subducting, and the overriding South American continental plate. Buckling and uplift occur adjacent to the subduction boundary.

Shemenda [1994] identifies the difference in density between the lithospheric and asthenospheric materials as a major factor influencing the subduction process. The subducting plate is subject to a drag force from the circulating mantle, a force

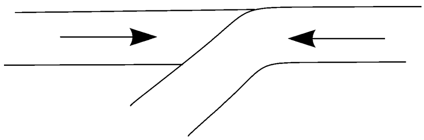

Fig. 2.2 Relative plate movement at a subduction boundary

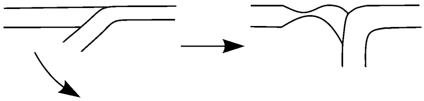

Fig. 2.3 Sketch illustrating the idea of suction force creating back-arc rifting

acting over its entire area and responsible for its movement. If it is denser than the fluid on which it floats, it will sink as it subducts, producing a force supplementing the fluid drag—both forces are acting normal to the plate boundary and pulling the subducting plate towards the overriding one. The weight of the drooping plate will increase because g increases with depth, although this may be insignificant as it appears to be absent from consideration in the geophysical literature. Given these forces, it comes as a surprise that a major deformation of the overriding plate occurs some distance back but close to its edge and, even more surprising, that the deformation takes the form of a localised stretching consistent with a tensile stress rather than the compression expected from Fig. 2.2. One might be justified in anticipating from Fig. 2.2 that although the overriding plate is driven towards the subduction boundary by fluid drag as a result of the mantle convection current, the obstruction caused by the subducting plate would induce compression immediately up-plate from the boundary. However, within about one thickness distance of its edge, the overriding plate accelerates towards the subducting plate. The stretched, brittle lithosphere is subject to faulting and the thinned crust subsides. In some locations where this subsidence occurs, it is referred to as "back-arc rifting". Shemenda [1994] cites references suggesting that there is a suction force that keeps the falling plate attached to the overriding one, and the sketch of Fig. 2.3 illustrates one way in which this might occur as the subducted plate droops (simply to reinforce the picture of events and not as a proposed phenomenon).

He also reviews evidence that the rifting takes place at an already thinned location of the overriding plate, which may involve the other principal feature of the subduction zones mentioned, volcanism. The volcanoes generally occur along a line parallel to the subduction boundary, but there is variation in the distance of the line from the boundary, and Shemenda [1994] suggests that they may occur along a line of weakness. Alternatively, he suggests, the plate may be eroded on its underside as a result of an eddy in the mantle flow within the vertical wedge formed by the two plates (Fig. 2.4).

The vertical wedge between the lower surface of the overriding plate and the upper surface of the subducting one is the source of the magma for volcanism, which is sometimes loosely attributed to rising magma formed by frictional heating of the moving plate surfaces. A proper explanation would call for considerable

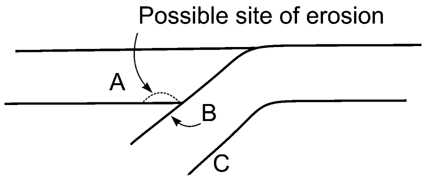

Fig. 2.4 Identification of regions near a subduction zone wedge

analysis, but material properties are poorly known. In Fig. 2.4, the plate lower surface shown at A marks the depth at which the crust changes from solid to plastic—in reality the change is gradual but a simple two-layer picture is sufficient here. Beneath A the mantle material is hot, plastic and in motion. Surface C is similar to A, but surface B is cold, water-saturated crust which will cool the plastic material in the wedge. In Sect. 4.5 it will be shown that the timescale for a slab of thickness L to reach a uniform temperature when one side is suddenly exposed to a heat source is of order L^2/κ where κ is the thermal diffusivity, and knowing the subducting plate speed would allow the time required for melting of the subducted plate to be estimated. If the mantle material beneath A was able to rise towards the surface and intrude or erupt simply as a result of its temperature, then it should have been capable of doing so at any time, regardless of its proximity to the subducting plate. Suction forces, a line of weakness and local erosion are all suggestions as to the mechanism of deformation of the overriding plate. A further suggestion is that release of the water carried down within the subducting plate changes the composition of the asthenospheric material so that it tends to rise by melting its way through the crust. Manning [2004] outlines the relevant chemistry and Gerya and Yuen [2003] illustrate the physics. The wedge material can thus be cooled, intuitively expected to make it solidify, but chemical changes result in it becoming a viscous liquid which rises towards the surface and may reach it and erupt.

The general picture which emerges is of the periodic occurrence of a body of magma sufficiently hot and fluid to rise from within the wedge between the subsiding and overriding plates and penetrate the latter, thinned and weakened as it may be. The periodicity of events is evidently long in human terms but the occurrences are not sparsely distributed, as can be seen from the maps of the "Pacific Ring of Fire" referred to in the introduction to Sect. 2.2. If the penetration is complete, the result is a volcano, and if partial, the body is referred to as a pluton or intrusion. The geological description is unimportant—to bring a large enough quantity of heat into the near-surface crust to create a geothermal resource, the magma body must have a large volume.

Much of the literature on this topic is not written in the language of the mathematical sciences, but focuses on the chemical changes, and the problem is often poorly described in physical–mathematical terms, but there is no point in attempting mathematical analysis before the processes have been adequately described. In what might be viewed as a preliminary skirmish, Norton and Knight [1977] modelled the cooling of a discrete mass of magma as it rose towards the surface by setting out the equations governing heat transfer and fluid flow and solving them for various boundary conditions. The fluid circulating in the permeable rocks around and above the magma body was assumed to have the properties of pure water, and they presented temperature and fluid circulation contours.

The immediate question raised by the above discussion is whether there is any evidence from drilling that magma bodies occur as described.

2.2.3 Evidence of Magma Bodies at Drillable Depths

Drillable depths are far less than the depths involved in the processes discussed above; the limits are set by the temperature encountered and by economics. The result is that wells in most liquid-dominated geothermal resources are less than 4 km deep. Magma bodies have been encountered in several.

Stimac et al. [2008] provide a cross section of the Awibengkok geothermal resource (also known as Salak) in western Java, Indonesia (Fig. 2.5). The data comes from 81 wells, of which several have intersected a geological formation at about 2,000 m below the surface which is interpreted as the top of a large intrusion (of magma). Figure 2.6 is a simplified version of the geological cross section of the Kakkonda resource, Northern Honshu, Japan, produced by Doi et al. [1998]. The figure shows the tracks of six wells which were drilled into the magma body.

Further examples are given by Christenson et al. [1997] at Ngatamariki, New Zealand, although in this case the intrusion is cool because of its age, which they estimate as 0.7 Ma. A magma body referred to as the Geysers felsite has been identified beneath the Geysers geothermal resource in California, USA (Hulen and Nielson [1996]), and a further example occurs in the Tongonan resource in Leyte in the Philippines (Reyes [1990]). In the Tongonan case, it is considered that the outer surface zone of the magma body has increased permeability, perhaps due to fracturing under thermal stresses while cooling, which provides enhanced convection as a plume towards the surface, shown diagrammatically in Fig. 2.7.

The Taupo Volcanic Zone (TVZ), New Zealand, is notable for having many separate geothermal resources close together, that is, separate convective plumes. The usual method of delineating the region permeated by geothermal fluid, where a plume is deflected by the presence of ground surface, for example, is by measuring electrical resistivity. The electrical resistivity of the ground is reduced as a result of chemical alteration and minerals deposition by the convecting geothermal fluid. Individual plumes can be identified by resistivity boundaries and also characterised by the detailed chemical composition of the deep fluid.

Alcaraz et al. [2012] present a model of the TVZ, from the basement upwards, from which Fig. 2.8 is taken. New Zealand is situated along a plate boundary which is only partly a subduction zone—the mode of interaction changes southwest of the TVZ, and to further complicate matters, there is a relative rotational component between the plates where they are subducting. The zone has a high heat output—Hochstein and Regenauer-Lieb [1989] estimated it as 5,000 MW. Various ideas have been proposed for the detailed subduction process resulting in the TVZ, and

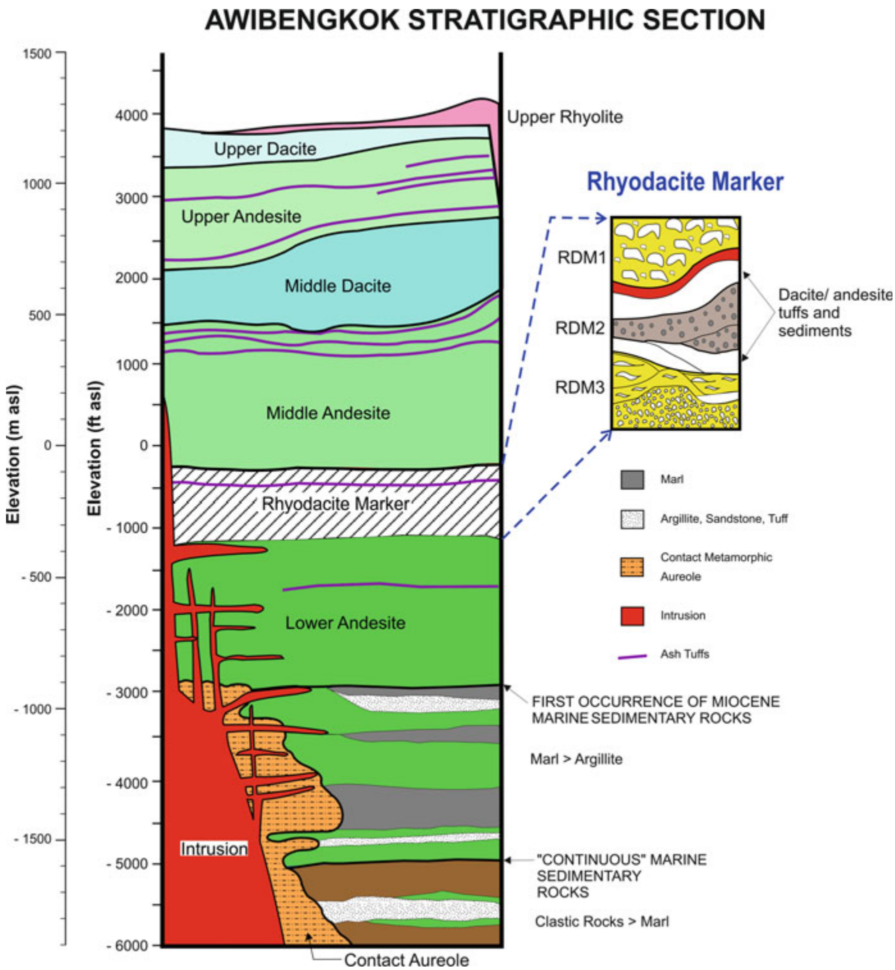

Fig. 2.5 Cross section showing an igneous intrusion at Awibengkok, Indonesia, from Stimac et al. [2008] (*figure provided by J. Stimac and reproduced by permission of Elsevier*)

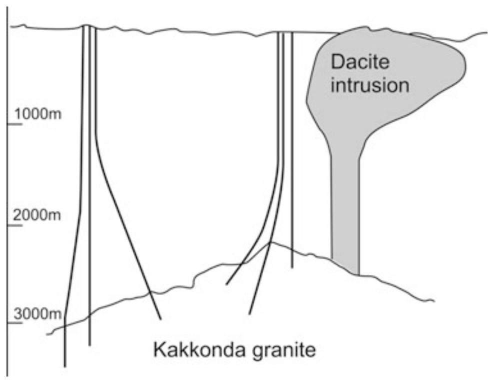

Fig. 2.6 Sketch of the Kakkonda granite body showing the intersection by wells. Based on a cross section from Doi et al. [1998] (*original cross section provided by N. Doi and reproduced by permission of Elsevier*)

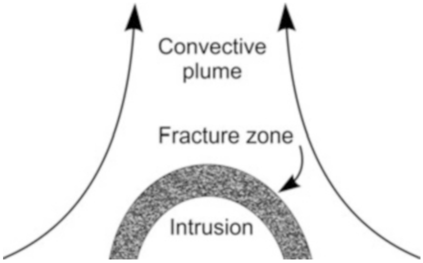

Fig. 2.7 Sketch of a convective plume over a magma body

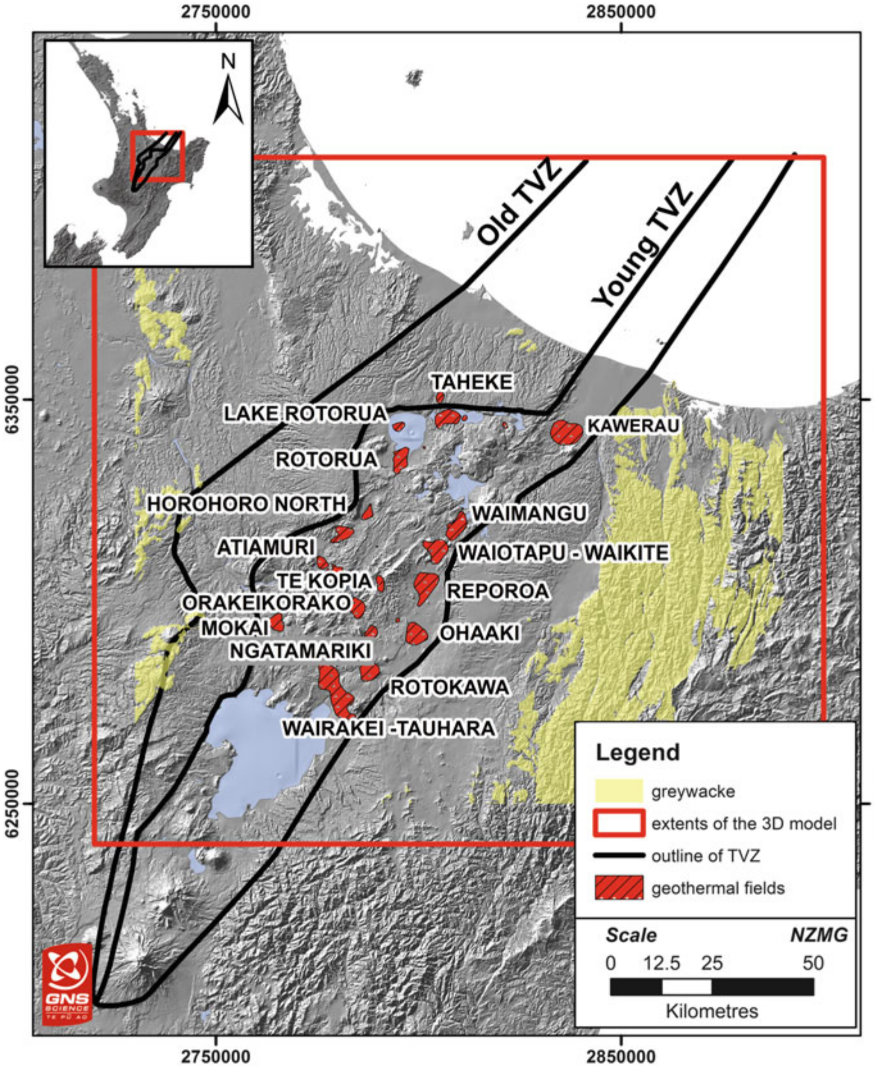

Fig. 2.8 Map of the Taupo Volcanic Zone (TVZ), New Zealand, showing individual geothermal resources as identified by their resistivity boundaries, from Alcaraz et al. [2012] (*figure provided by S. Alcaraz and reproduced by permission of GNS*; *all rights reserved*)

the question appears unresolved at present. McNabb [1992] proposed that the base of the TVZ was in effect a “hot plate”, a thin crust heated directly from the mantle beneath. He drew analogy with Benard cellular convection, a laboratory arrangement of a horizontal flat plate held at constant temperature and forming the base of a vessel containing a shallow layer of viscous liquid, which exhibits a pattern of hexagonal natural convection cells known as Benard cells. In fact, Benard cells form in a layer of fluid with a free surface and involve surface tension, but cellular convection in confined layers can occur—see Zarrouk et al. [1999]. Hochstein and Regenauer-Lieb [1989] questioned whether the TVZ is a back-arc rift basin, but Cole et al. [1995] describe it as such, giving the average heat flux in the area as 800 mW/m^2. They note that volcanism in the TVZ has taken place over the last 2 Ma. Dempsey et al. [2012] have produced a model illustrating how a repetitive process of sealing of the upper levels of the convective plume and then faulting could be responsible for the maintenance of the separate geothermal resources observed. The debate continues.

Turning to heat sources in the form of granites within the lithosphere, the decay of radioactive isotopes provides a heat source, particularly thorium and uranium but mainly the latter according to Forster and Forster [2000] who quote heat generation rates of 4–10 μW/m^3 at maximum. The heat generated within a solid body results in a temperature increase at the location farthest away from the boundary, thus establishing a temperature gradient down which heat conducts. The maximum temperature reached depends on the boundary condition at the surface, the dimensions of the body and its thermal conductivity, as explained later in Sect. 4.5. Enhanced geothermal systems (EGS) are comprised of large bodies of unfractured rock with internal heat generation, the centre temperature of which has risen to well above atmospheric surface temperature. The thermal conductivity of granite is approximately 2 W/mK, and with an outside temperature of 25 °C, a cylindrical body would have a radius of 10 km if the centre temperature was to reach 100 °C by means of the heat generation rate quoted above, neglecting axial variations. The technology proposed to extract the heat is to fracture the rock and circulate water, or as examined by Stacey et al. [2010], carbon dioxide. The capture of carbon dioxide from coal fired power stations is being developed, and trials to store it in stable formations are in progress, so synergy between the two technologies is being examined.

2.3 Geothermal Surface Discharges

The natural discharge of heat at the surface has no doubt always attracted human attention. The discharge produces effects that are rare over most of the globe, ranging from geysers and fumaroles to warm, coloured ground and warm streams growing unusual vegetation. The rising plume of geothermal fluid illustrated by Fig. 2.7 is directed horizontally by the presence of the ground surface, which also adds meteoric water and provides cooling, leading to the wide range of effects mentioned.

Surface geothermal activity is of direct interest to earth scientists, since it provides clues to understanding the nature of the resource and the physical and chemical processes taking place—see, for example, the extensive review and categorisation of the surface discharges from resources with volcanic heat sources (i.e. of the type described in this chapter) by Hochstein and Browne [2000]. Studying it represents a significant part of the role of earth scientists in geothermal development. In contrast, surface activity provides almost no assistance to the problems confronting geothermal engineers. It may create civil engineering problems, if, for example, locations with heat and water or steam discharge have to support buildings or be crossed by pipelines, but these are relatively minor engineering issues. Shallow fluid flow is not amenable to the usual types of engineering analysis, analytic or numerical, primarily because of the random nature of the material through which the heat and fluids flow and the wide variability of material properties that control the resistance to flow. Geysers, a very distinct and infrequent occurrence, are perhaps the sole exception. They arise from flow in natural subsurface tunnels and cavities, as opposed to permeable rock, and exhibit a type of fluid flow that sometimes occurs in wells. They have attracted the attention of engineers and physicists, both experimental and analytical; see, for example, the review by Rinehart [1980] and the work of Lu et al. [2006]. To play their proper role in multidisciplinary activity of resource exploration and development, geothermal engineers must understand surface geothermal activity and its origins, but that information does not form part of the study of geothermal engineering per se.

There is, however, an aspect of the investigation of surface discharges which calls for the direct involvement of engineers, whose duty might be regarded as helping to meet the national demand for electricity as well as helping to develop any particular resource. In a list of the potential effects of geothermal resource use on the natural environment, the effect on geothermal surface features figures prominently. The surface discharges that attract and inform earth scientists of the presence of a usable resource also often have value as tourist attractions and are likely to rank highly as features to be preserved on aesthetic grounds. Despite the conflict between resource development and the preservation of geothermal surface features having first arisen, at least in New Zealand, more than 70 years ago, very little scientific effort has been applied to the problem. Sufficient is understood about the natural discharges to recognise and explain the effects of development by examining changes over a decade or more, but only after capital has been invested to enable the resource use, which is too late, as examples in Chap. 14 will demonstrate. What is required is research directed to achieving the earliest possible identification of effects, which may allow methods of prediction or testing to be developed; a start in this direction was made by Leaver et al. [2000].

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