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Thermo-Poromechanics: Applications and Developments

Geomechanics is a well-established area of geotechnique and the geosciences that involves the application of the principles of mathematics, mechanics and physics to describe the response of geomaterials subjected to thermal, mechanical and physical effects. The development of the subject of geomechanics evolved largely through the separate applications of classical theories of continuum mechanics as defined by elasticity, plasticity, fluid flow through porous media and heat conduction to the study of geomaterials that includes soils, rocks and other multiphasic materials. What distinguishes modern developments in geomechanics of multiphasic materials is the consideration of an extensive range of couplings between the dependent variables that characterize the deformation, thermal and flow fields and, on occasions, chemical transport. For example, the consideration of coupling of thermal and elastic behavior forms the basis of the coupled theory of classical thermoelasticity introduced by Duhamel (1837) and further developed in the works of Hopkinson (1879), Neumann (1885), Almansi (1897), Tedone (1906) and Voigt (1910). The classical theory of thermoelasticity developed in these works represents the complete coupling of the deformation and heat conduction processes within the framework of classical continuum mechanics. References to the numerous developments in thermoelasticity are given by Boley and Wiener (1960), Nowacki (1962), Carlson (1972) and Nowinski (1978). In the context of geomechanics, the need to consider coupling effects in geomaterials dates back to the elementary one-dimensional theory of soil consolidation developed by Terzaghi (1925). This has been an important starting point for the multiphasic treatment of fluid-saturated porous media. Karl Terzaghi (1925) is considered to be the main developer of the theory of one-dimensional consolidation, but important contributions by others, particularly Fillunger (1936), should not be overlooked (de Boer, 2000a, b). Terzaghi's one-dimensional theory can explain the processes that occur during soil consolidation, but this cannot be considered

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as a "formal theory". Biot (1941) developed a complete theory of isothermal soil consolidation; this theory is exact in its continuum formulation applicable to a medium with voids and is a generalization of Terzaghi's (1925) one-dimensional theory to three dimensions. Because of the elegance and ease of use, Biot's theory of soil consolidation continues to be used more than seven decades later.

Biot's theory of soil consolidation uses linear elasticity to describe the mechanical behavior of the porous skeleton and Darcy's law to explain the flow of fluid through the accessible pore space. There have been many articles published on both the fundamental aspects of Biot's theory of isothermal poroelasticity and its use in solving problems in geomechanics; these include those by Mandel (1950), de Josselin de Jong (1957), McNamee and Gibson (1960), Cryer (1963), de Wiest (1969), Agbezuge and Deresiewicz (1975), Chiarella and Booker (1975), Rice and Cleary (1976), Gaszynski and Szefer (1978), Booker and Small (1982a,b), Booker and Randolph (1984), Bear and Corapcioglu (1985), Whitaker (1986a,b,c), Kassir and Xu (1988), de Boer and Ehlers (1990), Atkinson and Craster (1991), Ehlers (1991), Detournay and Cheng (1993), Selvadurai and Yue (1994), Yue and Selvadurai (1995a,b), Lan and Selvadurai (1996), Jupp and Schultz (2004), Oyen (2008) and Galli and Oyen (2009). More recent developments in the application of Biot's theory are detailed in the volumes and articles by Coussy (1995), Selvadurai (1996a, 2007, 2015a), Cheng et al. (1998), Drew and Passman (1998), Lewis and Schrefler (1998), Thimus et al. (1998), de Boer (2000a,b), Wang (2000) and Verruijt (2014). These references, and the reviews and compilations by Scheidegger (1960), Paria (1963), Schiffman (1984), Cowin (2001) and Cheng (2016), *inter alia*, give a considerable number of references to other applications of Biot's classical three-dimensional theory of poroelasticity, covering problems in environmental geosciences, geomechanics, biomechanics, materials science and materials engineering. Biot's classical theory of isothermal poroelasticity is now firmly established (Altay and Dokmeçi, 1998). A number of alternative approaches have been put forward for developing the governing equations using the continuum theory of mixtures (e.g., Crochet and Naghdi, 1966; Green and Steel, 1966; Green and Naghdi, 1970; Mills and Steel, 1970; Crochet, 1971; Atkin and Craine, 1976; Bowen, 1976, 1980; Bedford and Drumheller, 1978, 1983; Hassanizadeh and Gray, 1979a,b, 1980; Dell'Isola and Romano, 1987; Coussy, 1995; Murad et al., 1995; Rajagopal and Tao, 1995; Bennethum and Cushman, 1996; Drumheller, 2000; Ichikawa et al., 2001, 2010; Gajo, 2010). However, there appears to be no significant advantage to using these approaches for the solution of the initial boundary value problems for *linearized theories of poromechanical behavior*. The mixture theory-based formulations do

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have advantages when dealing with nonlinear theories of material behavior, for example when modeling living tissue where the porous skeleton can experience large strains or large-strain nonlinear viscoelastic and viscoplastic phenomena that can influence fluid transport. Extensive references to recent applications in this area are given by Selvadurai and Suvorov (2016).

The consideration of thermal actions on the movements of fluids is a topic that has applications in a number of areas in the engineering and mathematical sciences, including areas related to geophysical fluid dynamics, atmospheric sciences, environmental fluid flows, fire-induced movement of air masses and biological fluid dynamics. The pioneering works in this area are attributed to Oberbeck (1879), Boussinesq (1903), Rayleigh (1915) and Benard (1900a,b). Studies in this area are numerous, and informative accounts of the subject area are given by Joseph (1976), Nield and Bejan (2013) and Vafai (2015). The important observation is that many of these formulations involve couplings that can be classified as weak. For example, in classical thermoelasticity, it is invariably assumed that the deformations of the solid do not contribute to heat generation or a change in the heat conduction law. Similarly, in classical poroelasticity, it is implicitly assumed that Darcy's law governing flow through the porous medium is uninfluenced by the deformations of the porous skeleton. In classical treatments of thermally driven flows, if heat transfer occurs by conduction, then the basic heat conduction process is assumed to be of a Fourier type. The consideration of reduced forms of couplings of dependent variables (i.e., heat conduction and deformation in thermoelasticity, fluid flow and deformations in poroelasticity, and fluid flow and heat conduction in thermally driven flows) makes the modeling of complex problems mathematically and computationally tractable. Furthermore, as the range of couplings increases, the material parameters and material functions required to describe such theories also increase, and the experimental techniques needed to determine the parameters are neither straightforward nor routine. This is particularly important in the context of naturally occurring geomaterials, where sample recovery, influences of scale, the influence of *in situ* stress states in both the porous fabric and the pore fluids, and temperature play a significant role in developing experimental arrangements for conducting multiphysics experiments. In the development and application of multiphysics theories to geomechanics, the geosciences and environmental geomechanics, the approach adopted has been to limit the range of couplings so that solutions to problems of practical interest can be obtained in a meaningful manner, with specified limits of applicability.

In this chapter, we introduce certain areas of interest to thermo-poromechanics that have led the way to incorporating multiphysics in geomechanics, geosciences and environmental geomechanics. The list of references

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related to each application is not meant to be exhaustive; key articles cited can be consulted for further references.

1.1 Nuclear Waste Management

The development of safe technologies for the deep geological disposal of heat-emitting nuclear fuel waste has been a topic of major importance to environmental geomechanics (Holister et al., 1981; Laughton et al., 1986; Hancox, 1986; Chapman and McKinley, 1987; Tsang, 1987; OECD, 1988; Pusch, 1990; Arnould et al., 1993; Gray, 1993; Gnirk, 1993; Johnson et al., 1994a,b; Simmons and Baumgartner, 1994; Glasser and Atkins, 1994; Grauer, 1994; Hueckel and Peano, 1996; Selvadurai, 1997, 2002; Selvadurai and Nguyen, 1996, 1999; Huertas et al., 2000; NAP, 2001, 2003, 2006; Alonso and Gens, 2002; Chijimatsu et al., 2003; Alonso et al., 2005; Schweitzer and Sharber, 2005; Pusch et al., 2011; Taniguichi and Hiyama, 2014). Interest in this area will continue if nuclear energy is looked upon as a means for energy production to reduce the burden on fossil fuels that contribute to greenhouse gas emissions. Worldwide consensus favors deep geologic disposal of nuclear waste in a manageable, monitored and retrievable form, and the development of such methodologies becomes even more critical as the reactors themselves reach the end of their functional life and cannot be regarded as suitable sites for even temporary storage of the highly radioactive spent fuel. The incidents at Chernobyl in 1986 and Fukushima in 2011 clearly underscore the need to develop safe technologies for management of hazardous nuclear fuel wastes.

Current deep disposal concepts identify several important components that are intended to serve as both the engineered and natural geological barriers for mitigating the long-term radionuclide migration from the storage area to the biosphere. The vault system itself is constructed to a specific shape in a rock mass with known physical, mechanical, chemical, hydrogeological and tectonic characteristics; the rock mass serves as the primary natural geological barrier for radionuclide migration. The primary engineered barrier is the sealed cylindrical container that houses the heat-emitting radioactive waste (Fig. 1.1).

The primary engineered geological barrier that will be in direct contact with the heat-emitting waste is a mixture of highly compacted bentonitic clay and crushed quartz sand (Lopez, 1987; Graham et al., 1990; Selvadurai and Cheung, 1991; Selvadurai, 1990, 1996a,b). This engineered clay barrier, which is also referred to as a "buffer", is either compacted *in situ* in emplacement boreholes that are drilled into the base of the galleries of the waste disposal vault system

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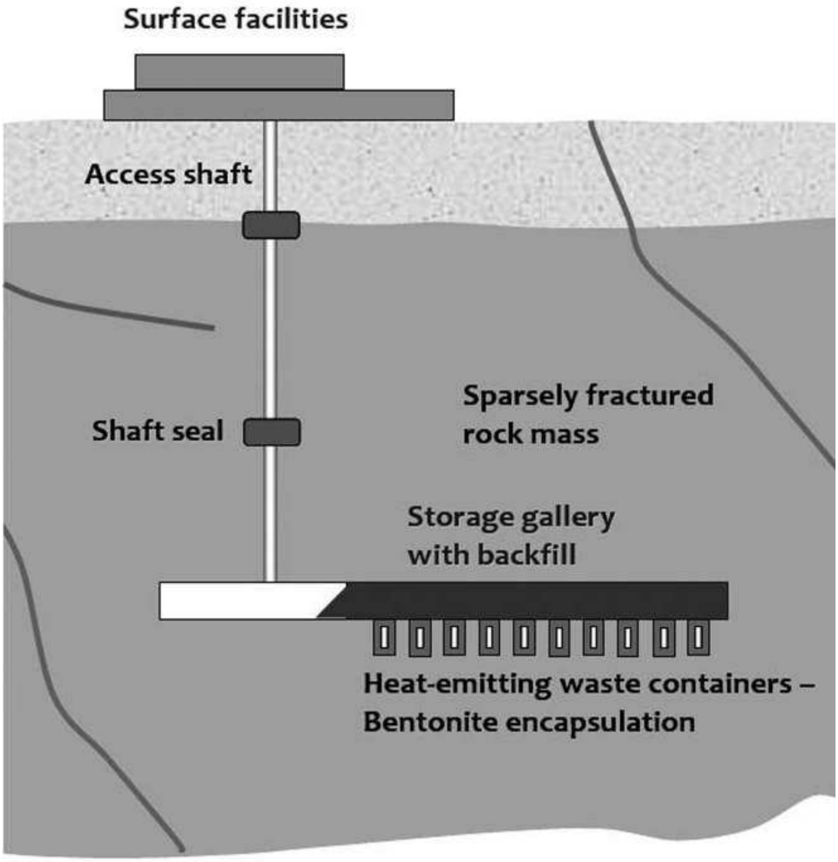

Figure 1.1. Schematic view of a deep geological disposal concept and the components of the multi-barrier scheme.

or placed around the waste containers in pre-compacted units. The use of bentonitic clays as engineered geological barriers is advocated in many concepts put forward for the deep disposal of heat-emitting radioactive wastes (Come et al., 1985; Chapman and McKinley, 1987; Tsang; 1987; Lopez, 1987; Ishikawa et al., 1989; Cheung, 1990; Pusch, 1990; Gray, 1993; Johnson et al., 1994a,b; Jing et al., 1995; Hueckel and Peano, 1996; Fujita et al., 1997; Selvadurai, 1997; Gens et al., 1998; Stephansson et al., 1996, 2004; Hoteit et al., 2002; Gens, 2010; Mancuso et al., 2012; Mancuso and Jommi, 2013; Charlier et al., 2013). The potential for the bentonitic clays to act as geochemical filters for the sorption of radionuclides is an important factor in their choice as an engineered geological barrier. It is anticipated that radionuclide migration

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cannot be prevented indefinitely, and will eventually occur as a result of the natural disintegration of the waste containers. The composition of the engineered clay barrier and the chemical characteristics of its constituents must be chosen so that the conflicting constraints relating to heat conduction, swelling during moisture migration or shrinkage during heat-induced moisture depletion, radionuclide migration, strength, creep, etc., can be satisfied simultaneously. Investigations conducted on the candidate buffer material for the determination of the heat conduction, moisture transport, radionuclide migration, creep and other mechanical interactions in the clay–sand buffer mixtures are discussed by Cheung and Chan (1983), Cheung et al. (1983), Radhakrishna (1985), Radhakrishna et al. (1990), Yong et al. (1985, 1986, 1990, 1997), Selvadurai (1990), Selvadurai and Onofrei (1993) and Ichikawa et al. (2001). References to further works are also given in the articles cited previously. In earlier treatments of the modeling of the engineered bentonitic barrier, attention was largely restricted to the coupled heat and moisture movement in the barrier, which was considered to be non-deforming (Philip and de Vries, 1957; Thomas et al., 1980; Thomas, 1985, 1987; Geraminegad and Saxena, 1986; Yong et al., 1990; Mohamed et al., 1990; Radhakrishna et al., 1990; Jiang and Rajapakse, 1994; Selvadurai, 1996b,c; Frydrychowicz and Selvadurai, 1996; Basha and Selvadurai, 1998). In recent research, the scope of the treatment has been extended to include thermo-poroplasticity effects that can materialize as a result of thermal deformations and pore pressure changes in the pore fluids and unsaturated phenomena resulting from heating effects (Schiffman, 1971; Lewis et al., 1989; Hueckel and Borsetto, 1990; Giraud et al., 1998; Pariseau, 1999; Cui et al., 2000; Delage et al., 2000; Laloui and Cekerevac, 2003, 2008; Laloui et al., 2005; Sanchez et al., 2008; Hueckel et al., 2009; Gens, 2010; Silvestri and Abou-Samra, 2011; Mašín and Khalili, 2012; Charlier et al., 2013). Even with the development of sound theories to account for the inelastic skeletal behavior (Desai and Siriwardane, 1984; Darve, 1990; Davis and Selvadurai, 2002; Pietruszczak, 2010), the corresponding advances that account for the influence of inelastic behavior on flow and transport properties of the unsaturated and saturated regions of a thermo-poro-elastoplastic medium still remain a challenging problem in both constitutive modeling and experimentation. The secondary engineered geological barrier in most deep geological disposal concepts is the backfill material that occupies the major part of the waste disposal vault system. In addition, other engineered barriers, such as the backfilling of the access shafts and boreholes, the use of bulkheads for shaft and borehole sealing, etc., form the complete system of engineered barriers intended to minimize the migration of radionuclides from the repository to the biosphere throughout the harmful life of the stored waste.

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The objective of a deep geological repository setting is to take advantage of the rock mass to act as a barrier against the migration of radionuclides from the repository to the biosphere. In a deep geological repository setting, thermo-poroelastic effects can materialize in the host rock as radiogenic heating takes place. The application of thermo-poroelastic modeling is perhaps best justified in situations where the rock mass is either intact or sparsely fractured. Extensive studies have been completed by researchers from several countries that are developing strategies for deep geologic repositories to store nuclear waste. A comprehensive review of work in this area, however, will not be attempted within the framework of this chapter, and only salient articles that also make an effort to provide comprehensive references to developments will be briefly summarized. Early applications of thermo-hydro-mechanical (THM) modeling to geomechanics problems are given by Morland (1978), Derski and Kowalski (1979), Bear and Corapcioglu (1981), Palciauskas and Domenico (1982), Borsetto et al. (1984), Aboustit et al. (1985), Booker and Savvidou (1985), McTigue (1986), Schrefler and Simoni (1987), Bear et al. (1993), Smith and Booker (1993, 1996), Bai and Roegiers (1994), Seneviratne et al. (1994), Selvadurai and Nguyen (1995), Kodashima and Kurasighe (1996, 1997), Bai and Abousleiman (1997), Baggio et al. (1997), Zhou et al. (1998, 1999), Nguyen and Selvadurai (1995, 1998), Wang and Papamichos (1999), Rutqvist et al. (2001a,b, 2005), Yow and Hunt (2002), Bart et al. (2004), Sulem et al. (2004), Nguyen et al. (2005), Sonnenthal et al. (2005) and Suvorov and Selvadurai (2010, 2011). Applications and references to further developments are also given by Belotserkovets and Prevost (2011), Wu et al. (2012), Selvadurai and Suvorov (2012, 2014), Abousleiman et al. (2014), Selvadurai (2015a) and in the ensuing chapters.

The several reports and publications resulting from the international DECOVALEX initiative (Jing et al., 1995; Stephansson et al., 1996, 2004; Chan et al., 2001; Rutqvist et al., 2001a,b, 2008; Hudson et al., 2001, 2005; Alonso et al., 2005; Tsang et al., 2005; Birkholzer et al., 2008; Nguyen and Jing, 2008; Rejeb et al., 2008) have contributed significantly to research and developments in the area of thermo-poroelasticity. Other advances in this area can be found in the volumes and articles by Selvadurai (1996a), Thimus et al. (1998), Auriault et al. (2002), Abousleiman et al. (2005), Ling et al. (2009), Ichikawa and Selvadurai (2012) and Hellmich et al. (2013). In the application of THM modeling to intact geological media, the behavior of the rock mass is generally modeled by Hookean elastic behavior, fluid flow through the intact material by Darcy's law, and the heat transfer in the medium by Fourier's law of heat conduction. Furthermore, it is assumed that the heat conduction process is uncoupled, in the sense that neither the deformations of the medium nor the fluid flow through

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the porous skeleton contribute to heat generation. This is an approximation that not only makes the solution of THM problems tractable but is also borne out by experiments where the heat conduction process stabilizes well in advance of pore fluid transport through the pore space.

It is also recognized that the construction of a repository can alter the stress state in the vicinity of the repository, which can contribute to the development of an excavation damage zone (EDZ) consisting of a highly fractured zone with significant alterations to both the deformability and fluid transport characteristics. Also, the substantial increase in the fluid transport behavior in damaged zones, in comparison to fluid transport in intact rocks, implies that the THM processes can exhibit heat transfer that includes both conduction and convective processes. In such situations, the application of theories of thermo-poroelasticity is justifiable if the fractured rock mass can be accurately characterized in terms of its deformability response and fluid transport and heat transfer characteristics. While approaches involving double porosity modeling (Bai and Roegiers, 1994; Loret and Rizzi, 1999; Callari and Federico, 2000; Masters et al., 2000; Pao and Lewis, 2002; Khalili and Selvadurai, 2003; Selvadurai and Ghiabi, 2008), damage mechanics formulations (Selvadurai and Mahyari, 1997; Mahyari and Selvadurai, 1998; Souley et al., 2001; Mitaim and Detournay, 2004; Martino and Chandler, 2004; Selvadurai, 2004, 2015b; Selvadurai and Shirazi, 2004, 2005; Pellet et al., 2005, 2009; Pellet, 2009; Sterpi and Gioda, 2009; Massart and Selvadurai, 2012, 2014; Delage, 2013; Nguyen and Le, 2015) and contact mechanics of geomaterial interfaces (Selvadurai and Au, 1987; Aliabadi and Brebbia, 1993; Selvadurai and Boulon, 1995; Selvadurai and Atluri, 2010) have been developed in the literature to describe both hydro-mechanical and thermo-hydro-mechanical processes in geologic media, the development of experimental techniques for determining the relevant material parameters governing such models remains a challenge. There are extensive studies that deal with the purely flow problem related to fractured media (NRC, 1996; NAP, 2015a); however, from the point of view of geomechanical applications, the influence of the stress state is a key factor in the study of fractured media, where the fluid flow characteristics will evolve as the stress state changes. From the brief overview presented here, it is clear that there is extensive application of the classical theory of thermo-poroelasticity to the topic of deep geologic disposal of heat-emitting wastes. There are also extensive developments in the area of large-scale laboratory experiments and field tests conducted in underground research laboratories that provide opportunities for the refinement of the theoretical and computational developments.

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1.2 Geologic Sequestration of Greenhouse Gases

The sequestration of CO_2 in supercritical form in deep geologic settings that are conducive to the development of stable plumes of the injected fluids is one of the strategies for mitigating the effects of anthropogenic carbon that has contributed to global warming (see, e.g., Holloway, 2001; Bachu and Adams, 2003; Maldal and Tappell, 2004; Wilson and Gerard, 2007; Oelkers and Cole, 2008; Lal, 2008; Benson and Cole, 2008; Chadwick et al., 2009; McPherson and Sundqvist, 2009; Eiken et al., 2011; Hosa et al., 2011; He et al., 2011; Malo and Bedard, 2012; Hou et al., 2012; Vargas et al., 2012; Pijaudier-Cabot and Pereira, 2013; Bandyopadhyay, 2014; NAP, 2015b). The literature covering these topics is vast, and no attempt will be made to provide an extensive compendium of relevant articles dealing with the topic. Although the contributions in this area are plethoric, there is an urgent need to identify the contributions that truly represent seminal articles that can advance the role of geomechanics in the geologic sequestration process.

A competent caprock formation and a storage reservoir that can accommodate and trap injected fluids are regarded as essential requirements for successful implementation of carbon capture and secure storage (CCSS). Stable plumes can enhance the activation of other trapping mechanisms, which require time scales substantially longer than the injection period. For example, if CO_2 injection lasts 50 years, primary trapping mechanisms such as adsorption, structural and stratigraphic trap filling and hydrodynamic trapping are expected to commence immediately and last up to a million years; secondary trapping mechanisms such as residual CO_2 trapping can peak at around 10 000 years and continue thereafter; dissolution can peak around a thousand years and last up to a million years; while mineralization can continue beyond a million years. To effectively activate all trapping mechanisms, it is essential that the injected CO_2 remains in a storage formation in a hydrodynamically stable condition. There are a number of processes and conditions that can potentially result in the development of adverse conditions, which could compromise the secure storage potential of a geological formation (Fig. 1.2). Geologic sequestration of CO_2 becomes feasible when stratigraphic configurations can promote the development of stable plumes of injected CO_2 within the storage horizon. In this regard, the caprock is an important component that will ensure the development of such plumes. The presence of a stable plume can enhance the activation of other trapping mechanisms, which require time scales substantially longer than the injection period. The injected fluids can, however, initiate interactions between the caprock and the surrounding geologic media, including both the

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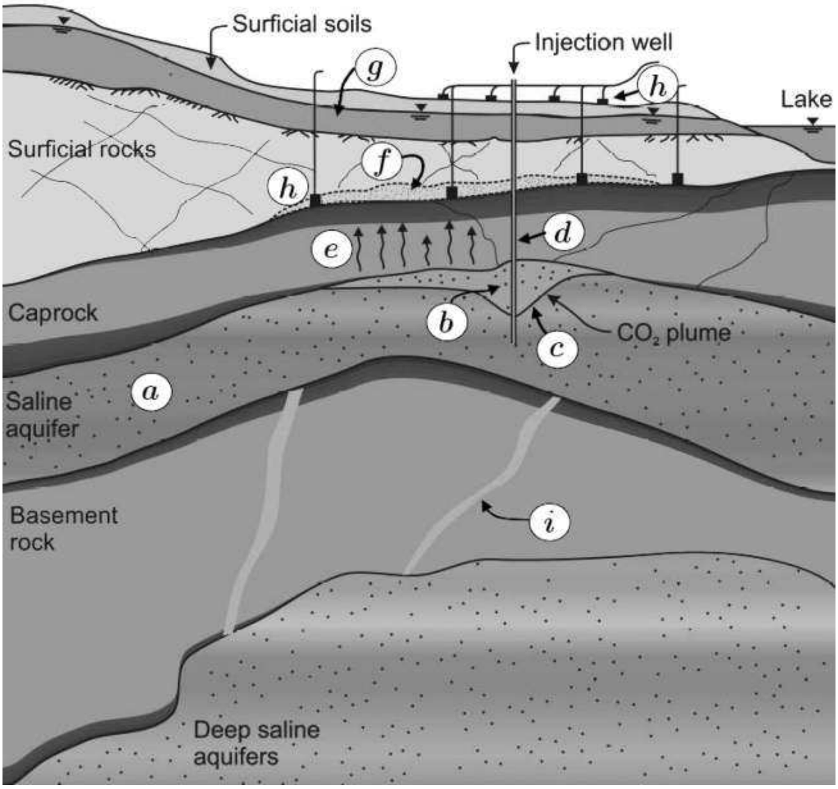

Figure 1.2. Schematic view of $scCO_2$ injection into a saline aquifer: (*a*) geochemistry and geomechanics of the saline aquifer; (*b*) plume development, trapping, pore fabric alterations during $scCO_2$ injection; (*c*) stability of $scCO_2$–saline pore fluid interfaces in rock; (*d*) geochemistry and geomechanics of caprock and interface seals; (*e*) CO_2 diffusion and transport through caprock defects and interface seals; (*f*) plume development in surficial rocks; (*g*) CO_2 contamination of groundwater regime; (*h*) monitoring of caprock; (*i*) movement of saline fluids from deep saline aquifer to the storage horizon (Selvadurai, 2013).

storage formation and the overburden rocks. The interaction can lead to the initiation of damage and fracture that can pose a threat to geologic sequestration.

Referring to Figure 1.2, the research themes relevant to assessing secure geologic storage could include: (*a*) geochemistry and geomechanics of a virgin saline storage formation; (*b*) plume development, trapping, and pore fabric alterations during injection; (*c*) stability of supercritical CO_2 ($scCO_2$)–saline pore fluid interfaces in the porous media; (*d*) geochemistry and geomechanics of caprock and interface seals; (*e*) CO_2 diffusion and transport through caprock

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