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EDITORIAL

Subsurface energy systems in China: production, storage and conversion

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The Thematic Issue is dedicated to different aspects of using the potential of the geologic subsurface as a resource for energy production (e.g., hydrothermal and petrothermal resources), energy storage as well as for safe deposition of energy waste, and energy conversion (e.g., as biochemical reactors to convert hydrogen and carbon dioxide into methane).

Figure 1 shows an overview map of hydrothermal systems in China including a classification to high-, mid- and low-temperature reservoirs and basins (Kong et al. 2014). Current research efforts concerning hydrothermal resources focus on the sustainable development of large-scale geothermal fields. Pang et al. (2012) designed a roadmap of geothermal energy development in China and reported the recent progress in geothermal research in China (Pang et al. 2014). Recently, Pang et al. (2015) presented a new classification of geothermal resources based on the type of heat source and followed by the mechanisms of heat transfer. The present Thematic Issue is focusing on petrothermal resources and particularly enhanced geothermal systems. Some of the basins indicated in Fig. 1 are also of interest for unconventional gas resources which is discussed in a separate Thematic Issue in Environmental Earth Sciences (Hou et al. 2015a).

Geothermal energy resources are considered to provide a significant contribution to renewable energy supply from both shallow and deep systems (Arola et al. 2014; Huenges et al. 2013; Kolditz et al. 2013; Scheck-Wenderoth et al. 2013). Understanding the thermally induced coupled processes is important for reservoir operations (McDermott et al. 2006; Kolditz and Diersch 1993). Breede et al. (2014) provide a systematic review of enhanced or engineered geothermal systems (EGS).

Ramos et al. (2015) provide a systematic review of projects implemented worldwide and a methodology for screening geothermal projects. Geothermal shallow surface systems based on ground source heat pumps have already proved to be a feasible option for the heating and cooling of buildings. The present work studies the concept of using abandoned mines for geothermal heat recovery in various countries such as Germany, the Netherlands, Norway, Russia, Spain, UK and United States. De Filippis et al. (2015) are discussing the geothermal potential of the Salento peninsula in southern Italy. They propose a simple methodology for the assessment of low-enthalpy geothermal energy systems based on stochastic approaches. They found that coastal areas might lower potential due to saltwater intrusion problems. Hou et al. (2015b) introduce the first

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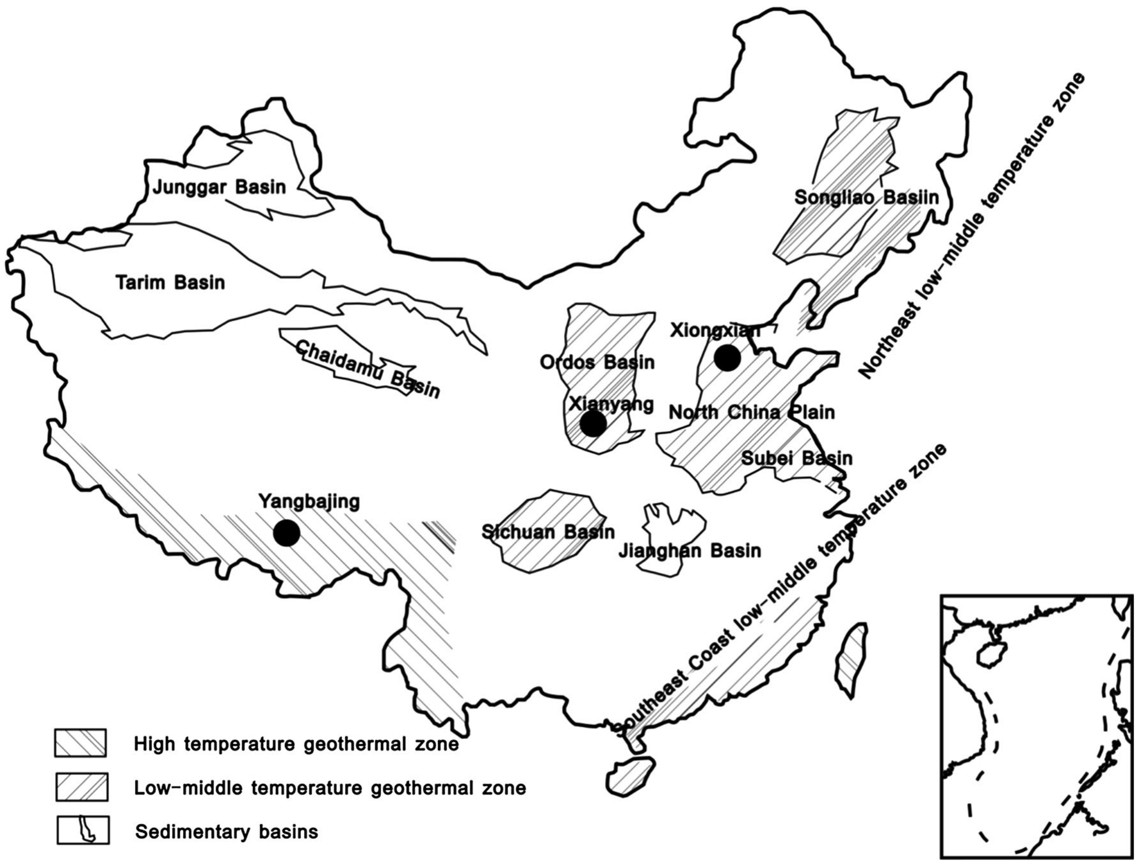

Fig. 1 Hydrothermal system in China—a classification by high- and mid–low-temperature reservoirs and basis (Kong et al. 2014)

enhanced geothermal system projects in Turkey, which is being implemented at the license area of SDS Energy Incorporation in Dikili of the İzmir province which has remarkable high thermal gradient of about 70 °C/km. Extensive geological, paleoseismic, geophysical and geochemical studies, paleo-stress measurements as well as modeling of hydraulic fracturing and geothermal energy production have been conducted in this area within the scope of this project. Induced seismicity is one of the possible georisks of underground operations such as EGS (Schmittbuhl et al. 2014). Luo et al. (2015b) investigate the Unterhaching geothermal site near Munich (Germany), where several micro-seismic events have been observed. One of the possible reasons for the observed micro-seismic events could be the reinjection of cold water into the hotter underground by stress redistribution and shear failures in the formations around and near the injection wellbore Uha GT-2.

Geo-reservoirs can be also used for dampening effects of fossil energy by new technologies, e.g., the transition from carbon intensive fossils to low-carbon new energy-like unconventional gas and non-carbon renewable energy resources via *carbon capture utilization and storage (CCUS)*. Carbon utilization via CCUS has a large potential including chemical, biological and geological utilization options, like enhanced oil/gas/coalbed methane/geothermal recovery and carbon mineralization.

The topic of *CO_2 storage (CCS)* has been recently discussed in the Thematic Issue "The CLEAN project in the context of CO_2 storage and enhanced gas recovery" (Kuehn et al. 2012) where particularly studies from Germany, Korea, United States and Norway have been presented including benchmark and model comparison studies (Bauer et al. 2012; Kolditz et al. 2012; Park et al. 2012; Mukhopadhyay et al. 2012; Mykkeltvedt and Nordbotten 2012). Beside of CCS (Fang and Li 2014; Singh et al. 2014; Tian et al. 2014), the Special Issue "Underground storage of CO_2 and energy" in the framework of the third Sino-German conference in May 2013 (Hou et al. 2014) focused on comparison of CCS with CCUS (Harrison and Falcone 2014), carbon geological utilization (Xie et al. 2014; Ganzer et al. 2014; Gou et al. 2014; Pudlo et al. 2015; Shen et al. 2015), and energy storage (Bérest et al. 2014; Zhang et al. 2014).

Bai et al. (2015a) investigate the storage of CO_2 in depleted oil and gas reservoirs, coal seams or saline aquifers. A special focus is set on research of the well integrity with topics such as chemical degradation of casing and cement materials. Liu et al. (2015b) are studying CO_2 sequestration in deep saline formations in low–medium-temperature geothermal reservoirs (Ordos Basin). The authors believe that a win–win situation can arise from combined CO_2 injection and hot brine extraction in a long-term assessment. Furthermore, the heat extraction efficiency might be higher for CO_2-based than purely H_2O-based systems. Bai et al. (2015b) assess the risk of abandoned wells affected by CO_2 storage operations. They investigate the long-term integrity of open and abandoned wells and review the combination of relevant geological and technical issues and develop a corresponding workflow for risk assessment. Liu et al. (2015c) present a preliminary site selection system for a CO_2-AGES project. The authors provide an idea about a combined geothermal production-CO_2 sequestration introduced in Kuehn et al. (2012). Moreover, they discuss a general evaluation procedure for a pure CO_2 sequestration project including a map for large CO_2 point sources and heat fluxes (ACCA21 2014).

Xu et al. (2015) discuss the CO_2-based geothermal systems as a way to achieve CO_2 resource utilization and geological sequestration. The study is related to the Songliao Basin in northeastern China. In this article, a classic idealized "five-spot" reservoir model coupled with wellbores is used for simulations and analyses (Wang et al. 2011). Xie et al. (2015a) study the carbonation of kaolinite cluster models with or without water on the atomic scale. Gas–solid interfacial phenomena play a significant role in the multiphase process in atmospheric chemistry. Mineral aerosols have desirable interfacial reactivity on the carbonation of kaolinite which may play an important role in carbon dioxide capture. Xie et al. (2015b) propose a novel method for carbonation and separation of calcium and magnesium ions based on membrane electrolysis from hard water in low voltage. By this way, CO_2 can be transformed into marketable pure magnesium carbonate and precipitated calcium carbonate. This method may open a new route for CO_2 mineralization by transforming hard water into high value-added industrial products with low energy consumption.

Rock salt and particularly salt caverns are considered to be a suitable medium for *energy storage*. The prediction and control of surface subsidence above storage caverns are the key issues that require steady attention to ensure their long-term safety and stable operation (Zhou et al. 2011, 2013; Xing et al. 2015; Zhao et al. 2015; Hagemann et al. 2015). Li et al. (2015) derive theoretical models for the volume convergence rates in spherical and cylindrical caverns, and thereby developing a new concept "equivalent internal pressure" that also considers cyclic internal pressure. Unlike the presence of thick domes and thick layers of rock salt deposits in Europe and the USA, rock salt in China is mainly composed of thin layers (80–300 m), characterized by a high content of water-insoluble impurities. Wang et al. (2015b) investigate the influence of water-insoluble content on the short-term strength of bedded rock salt, based on a series of combined laboratory tests including solubility, chemical analysis, uniaxial and triaxial compression tests, on bedded rock salt samples from different locations in China (Jiangsu, Henan and Yunnan Provinces). Ma et al. (2015) present an experimental study dealing with material properties of salt rock (from the Jianghan area) including a yield–dilatancy–failure model. This is important basic knowledge for energy storage purposes (e.g., underground gas storage) in salt caverns. Liu et al. (2015a) investigate creep properties of limestone in the presence of water as it might become a threat to safe operation of underground constructions because of the increasing hydraulic pressure in deep reservoirs. Water may migrate into rocks through fissures, cracks and damaging the rock as well as accelerating rock failure processes. Wu et al. (2015) address the scientific question how to describe creep processes in rocks and present an improved Maxwell creep model. Shi et al. (2015) [CAS Wuhan] study the influence of filling abandoned salt caverns with waste on land subsidence effects (Jingshen salt mine). Alkali waste with high pH values is problematic to the environment due to their solubility properties. The authors show based on laboratory and numerical experiments that volume convergence of salt caverns can be slowed down by refilling techniques.

Reitenbach et al. (2015) discuss the influence of added hydrogen on underground gas storage. They found that the existing infrastructure of the natural gas transportation pipeline network and underground gas storage (UGS) facilities in Germany provides an opportunity and huge capacity to feed, transport and store hydrogen and synthetic fuel gases containing hydrogen, produced from renewable sources. Zhang et al. (2015) investigate mechanical properties by a systematic characterization of the differences in acoustic emission (AE) characteristics among rock salt and other common rocks. In this study, the AE characteristics of the full-regime uniaxial compression of rock salt and common rocks such as granite and marble are determined. Rock salt cavities are important elements for energy storage and energy supply management.

Several papers of the Thematic Issue are dealing with more fundamental experimental and theoretical works, which are related to several aspects of subsurface energy systems. Jin et al. (2015) investigate the structure of coal-rock mass in particular the network of fractures. The database comes from the Tashan Mine Datong (Shanxi Province) which is used for model validation. Guo et al. (2015) are presenting a fundamental study on generation and verification of three-dimensional network of fractured rock masses stochastic discontinuities based on digitalization. The conceptual model is based on the discrete fracture network (DFN) approach. This work is related to Beishan (Gansu Province). Teodoriu et al. (2015) discuss important technical details concerning cement slurry mixing energy in field and laboratory conditions for CCS. They found whether the mixing energy concept can be relied on to reconcile laboratory and field results. Luo et al. (2015a) provide a fundamental study on stability evaluation of the underground gas storage in rock salts based on new partitions of the surrounding rock. They found that more scientific studies (including the international expertise) are necessary to proceed with renewable energy topics (RET) particularly in China (Zhang 2005). Results to date suggest that adequate reconciliation cannot be achieved using calculated mixing energies only, and the authors propose the use of shear rate instead. Xie et al. (2015) numerically investigate geometrical and hydraulic properties of single rock fractures during shear displacement. They consider fluid flow (solving Navier–Stokes equations) with shear displacement in a single fracture including roughness. Computational efficiency is still an issue for real-world application of numerical modeling (Wang et al. 2015a).

Hydraulic fracturing is an important technology for accessing to unconventional energy resources. Several basic and applied studies are dedicated to better understand the consequences of applying those underground technologies including mechanical (Eshiet and Sheng 2014a, b) hydrological and ecotoxicological effects (Gordalla et al. 2013; Olsson et al. 2013; Riedl et al. 2013). For safe and sustainable subsurface management, holistic concepts have to be developed and to be implemented including the legislation framework (Bauer et al. 2012, 2013; Hammes et al. 2013; Kerschke and Schulz 2013).

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References

Arola T, Eskola L, Hellen J, Korkka-Niemi K (2014) Mapping the low enthalpy geothermal potential of shallow Quaternary aquifers in Finland. Geotherm Energy 2:9. doi:10.1186/s40517-014-0009-x

Bai M, Sun J, Song K, Reinicke KM, Teodoriu C (2015a) Evaluation of mechanical well integrity during CO_2 underground storage. Environ Earth Sci. doi:10.1007/s12665-015-4157-5

Bai M, Sun J, Song K, Reinicke KM, Teodoriu C (2015b) Risk assessment of abandoned wells affected by CO_2. Environ Earth Sci. doi:10.1007/s12665-015-4163-7

Bauer S, Class H, Ebert M et al (2012) Modeling, parameterization and evaluation of monitoring methods for CO_2 storage in deep saline formations: the CO_2-MoPa project. Environ Earth Sci 67(2):351–367

Bauer S, Beyer C, Dethlefsen F (2013) Impacts of the use of the geological subsurface for energy storage: an investigation concept. Environ Earth Sci 70(8):3935–3943

Bérest P, Brouard B, Djakeun-Djizanne H, Hévin G (2014) Thermo-mechanical effects of a rapid depressurization in a gas cavern. Acta Geotech 9(1):181–186

Breede K, Dzebisashvili K, Liu X, Falcone G (2014) A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geotherm Energy 2013 1:4. doi:10.1186/2195-9706-1-4

De Filippis G, Margiotta S, Negri S, Giudici M (2015) The geothermal potential of the underground of the Salento peninsula (southern Italy). Environ Earth Sci. doi:10.1007/s12665-014-4011-1

Eshiet K, Sheng Y (2014a) Investigation of geomechanical responses of reservoirs induced by carbon dioxide storage. Environ Earth Sci 71(9):3999–4020

Eshiet K, Sheng Y (2014b) Carbon dioxide injection and associated hydraulic fracturing of reservoir formations. Environ Earth Sci 72(4):1011–1024

Fang ZM, Li XC (2014) A preliminary evaluation of the carbon dioxide storage capacity in unmineable coal beds in China. Acta Geotech 9(1):109–114

Ganzer L, Reitenbach V, Pudlo D, Albrecht D, Singhe AT, Awemo KN, Wienand J, Gaupp R (2014) Experimental and numerical investigations on CO_2 injection and enhanced gas recovery effects in Altmark gas field (Central Germany). Acta Geotech 9(1):39–47

Gordalla BC, Ewers U, Frimmel FH (2013) Hydraulic fracturing: a toxicological threat for groundwater and drinking-water? Environ Earth Sci 70(8):3875–3893

Gou Y, Hou Z, Liu HJ, Zhou L, Were P (2014) Numerical simulation of carbon dioxide injection for enhanced gas recovery (CO_2-EGR) in Altmark natural gas field. Acta Geotech 9(1):49–58

Guo L, Li X, Zhou Y, Zhang Y (2015) Generation and verification of three-dimensional network of fractured rock masses stochastic discontinuities based on digitalization. Environ Earth Sci. doi:10.1007/s12665-015-4175-3

Hagemann B, Rasoulzadeh M, Panfilov M, Ganzer L, Reitenbach V (2015) Mathematical modeling of unstable transport in underground hydrogen storage. Environ Earth Sci. doi:10.1007/s12665-015-4414-7

Hammes U, Krause M, Mutti M (2013) Unconventional reservoir potential of the upper Permian Zechstein Group: a slope to basin sequence stratigraphic and sedimentological evaluation of carbonates and organic-rich mudrocks, Northern Germany. Environ Earth Sci 70(8):3797–3816

Harrison B, Falcone G (2014) Carbon capture and sequestration versus carbon capture utilisation and storage for enhanced oil recovery. Acta Geotech 9(1):29–38

Hou Z, Xie H, Were P (2014) The special issue ''Underground storage of CO_2 and energy'' in the framework of the 3rd Sino-German conference in May 2013. Acta Geotech 9(1):1–5

Hou Z, Xie H, Zhou HW, Were P, Kolditz O (2015a) Unconventional gas resources in China. Environ Earth Sci. doi:10.1007/s12665-015-4393-8

Hou Z, Şen O, Gou Y, Eker AM, Li M, Yal GP, Cambazoğlu S, Were P (2015b) Preliminary geological, geochemical and numerical study on the first EGS project in turkey. Environ Earth Sci. doi:10.1007/s12665-015-4407-6

Huenges E, Kohl T, Kolditz O et al (2013) Geothermal energy systems: research perspective for domestic energy provision. Environ Earth Sci 70(8):3927–3933

Jin W, Gao M, Yu B, Zhang R, Xie J, Qiu Z (2015) Elliptical fracture network modeling with validation in Datong Mine, China. Environ Earth Sci. doi:10.1007/s12665-015-4158-4

Kerschke DI, Schulz HM (2013) The shale gas potential of Tournaisian, Visean, and Namurian black shales in North Germany: baseline parameters in a geological context. Environ Earth Sci 70(8):3817–3837

Kolditz O, Diersch H-J (1993) Quasi steady-state strategy for numerical simulation of geothermal circulation processes in hot dry rock fracture. Int J Non-Linear Mech 28(4):467–481

Kolditz O, Bauer S, Beyer C et al (2012) A systematic benchmarking approach for geologic CO_2 injection and storage. Environ Earth Sci 67(2):613–632

Kolditz O, Jakobs LA, Huenges E, Kohl T (2013) Geothermal energy: a glimpse at the state of the field and an introduction to the journal. Geotherm Energy 1:1. doi:10.1186/2195-9706-1-1

Kong Y, Pang Z, Shao HB et al (2014) Recent studies on hydrothermal systems in China: a review. Geotherm Energy 2:19. doi:10.1186/s40517-014-0019-8

Kuehn M, Goerke UJ, Birkholzer JT et al (2012) The CLEAN project in the context of CO_2 storage and enhanced gas recovery. Environ Earth Sci 67(2):307–310

Li M, Zhang H, Xing W, Hou Z, Were P (2015) Study of the relationship between surface subsidence and internal pressure in salt caverns. Environ Earth Sci. doi:10.1007/s12665-015-4405-8

Liu Y, Liu C, Kang Y, Wang D, Ye D (2015a) Experimental research on creep properties of limestone under fluid–solid coupling. Environ Earth Sci. doi:10.1007/s12665-015-4022-6

Liu H, Hou Z, Were P, Sun X, Gou Y (2015b) Numerical studies on CO_2 injection–brine extraction process in a low-medium temperature reservoir system. Environ Earth Sci. doi:10.1007/s12665-015-4086-3

Liu H, Hou Z, Li X, Wei N, Tan X, Were P (2015c) A preliminary site selection system for a CO_2-AGES project and its application in China. Environ Earth Sci. doi:10.1007/s12665-015-4249-2

Luo X, Were P, Liu J, Hou Z (2015a) Estimation of Biot's effective stress coefficient from well logs. Environ Earth Sci. doi:10.1007/s12665-015-4219-8

Luo X, Hou Z, Kracke T, Gou Y, Were P (2015b) Development of a semi-analytical method to calculate depth dependent temperature and stress changes: investigation of micro-seismicity at Unterhaching Uha GT-2 geothermal well. Environ Earth Sci. doi:10.1007/s12665-015-4392-9

Ma H, Yang C, Li Y, Shi X, Liu J, Wang T (2015) Stability evaluation of the underground gas storage in rock salts based on new partitions of the surrounding rock. Environ Earth Sci. doi:10.1007/s12665-015-4019-1

McDermott CI, Randriamanjatosoa ARL, Tenzer H et al (2006) Simulation of heat extraction from crystalline rocks: the influence of coupled processes on differential reservoir cooling. Geothermics 35(3):321–344

Mukhopadhyay S, Birkholzer JT, Nicot J-P, Hosseini SA (2012) A model comparison initiative for a CO_2 injection field test: an introduction to Sim-SEQ. Environ Earth Sci 67(2):601–611

Mykkeltvedt TS, Nordbotten JM (2012) Estimating effective rates of convective mixing from commercial-scale injection. Environ Earth Sci 67(2):527–535

Olsson O, Weichgrebe D, Rosenwinkel KH (2013) Hydraulic fracturing wastewater in Germany: composition, treatment, concerns. Environ Earth Sci 70(8):3895–3906

Pang Z, Hu S, Wang J (2012) A roadmap to geothermal energy in China. Sci Technol Rev 30(32):18–24

Pang Z, Huang S, Hu S, Zhao P, He L (2014) Geothermal studies in China: progress and prospects 1995–2014. Chin J Geol 49:719–727

Pang Z, Luo J, Pang J (2015) Towards a New classification scheme of geothermal systems in China. In: Proceedings World Geothermal Congress 2015, Melbourne, Australia, April, 19–25

Park Y-C, Huh D-G, Park C-H (2012) A pressure-monitoring method to warn CO_2 leakage in geological storage sites. Environ Earth Sci 67(2):425–433

Pudlo D, Henkel S, Reitenbach V, Albrecht D, Enzmann F, Heister K, Pronk G, Ganzer L, Gaupp R (2015) The chemical dissolution und physical migration of minerals induced during CO_2-laboratory experiments - their relevance for reservoir quality. Environ Earth Sci. doi:10.1007/s12665-015-4411-x

Ramos EP, Breede K, Falcone G (2015) Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. Environ Earth Sci. doi:10.1007/s12665-015-4285-y

Reitenbach V, Ganzer L, Albrecht D, Hagemann B (2015) Influence of added hydrogen on underground gas storage: a review of key issues. Environ Earth Sci. doi:10.1007/s12665-015-4176-2

Riedl J, Rotter S, Faetsch S et al (2013) Proposal for applying a component-based mixture approach for ecotoxicological assessment of fracturing fluids. Environ Earth Sci 70(8):3907–3920

Scheck-Wenderoth M, Schmeisser D, Mutti M et al (2013) Geoenergy: new concepts for utilization of geo-reservoirs as potential energy sources. Environ Earth Sci 70(8):3427–3431

Schmittbuhl J, Lengliné O, Cornet F, Cuenot N, Genter A (2014) Induced seismicity in EGS reservoir: the creep route. Geothermal Energy 2:14. doi:10.1186/s40517-014-0014-0

Sheng H, Lv L, Liang B, Li C, Yuan B, Ye L, Yue H, Liu C, Wang Y, Zhu L, Xie H (2015) Aqueous carbonation of the potassium-depleted residue from potassium feldspar-CaCl2 calcination for CO_2 sequestration. Environ Earth Sci. doi:10.1007/s12665-015-4412-9

Shi X, Li Y, Yang C, Xu Y, Ma H, Liu W, Ji G (2015) Influences of filling abandoned salt caverns with alkali wastes on surface subsidence. Environ Earth Sci. doi:10.1007/s12665-015-4135-y

Singh AK, Delfs JO, Görke UJ et al (2014) Toward physical aspects affecting a possible leakage of geologically stored CO_2 into the shallow subsurface. Acta Geotech 9(1):81–86

Teodoriu C, Okolieocha PA, Falcone G (2015) A theoretical comparison of cement slurry mixing energy in field and laboratory conditions. Environ Earth Sci. doi:10.1007/s12665-015-4229-6

Tian HL, Xu T, Wang FG, Patil VV, Sun Y, Yue GF (2014) A numerical study of mineral alteration and self-sealing efficiency of a caprock for CO_2 geological storage. Acta Geotech 9(1):87–100

Wang W, Rutqvist J, Gorke U-J et al (2011) Non-isothermal flow in low permeable porous media: a comparison of unsaturated and two-phase flow approaches. Environ Earth Sci 62(6):1197–1207. doi:10.1007/s12665-010-0608-1

Wang W, Fischer T, Zehner B et al (2015a) A parallel finite element method for two-phase flow processes in porous media: OpenGeoSys with PETSc. Environ Earth Sci 73(5):2269–2285

Wang G, Xing W, Liu J, Hou Z, Were P (2015b) Influence of water-insoluble content on the short-term strength of bedded rock salt from three locations in China. Environ Earth Sci. doi:10.1007/s12665-015-4403-x

Wu F, Liu JF, Wang J (2015) An improved Maxwell creep model for rock based on variable-order fractional derivatives. Environ Earth Sci. doi:10.1007/s12665-015-4137-9

Xie H, Li XC, Fang ZM, Wang YF, Li Q, Shi L, Bai B, Wei N, Hou Z (2014) Carbon geological utilization and storage in China: current status and perspectives. Acta Geotech 9(1):7–27

Xie LZ, Gao C, Ren L, Li CB (2015) Numerical investigation of geometrical and hydraulic properties in a single rock fracture during shear displacement with the Navier-Stokes equations. Environ Earth Sci. doi:10.1007/s12665-015-4256-3

Xie H, Jiang W, Xue Y, Hou Z, Wang Y, Wu D, Liu T, Wang J, Tang L (2015a) Effect of water on carbonation of mineral aerosol surface models of kaolinite: a density functional theory study. Environ Earth Sci. doi:10.1007/s12665-015-4404-9

Xie H, Liu T, Hou Z, Wang Y, Wang J, Tang L, Jiang W, He Y (2015b) Using electrochemical process to mineralize CO2 and separate Ca^{2+}/Mg^{2+} ions from hard water to produce high value-added carbonates. Environ Earth Sci. doi:10.1007/s12665-015-4401-z

Xing W, Zhao J, Hou Z, Were P, Li M, Wang G (2015) Horizontal natural gas caverns in thin bedded rock salt formations. Environ Earth Sci. doi:10.1007/s12665-015-4410-y

Xu T, Feng G, Hou Z, Tian H, Shi Y, Lei H (2015) Wellbore–reservoir coupled simulation to study thermal and fluid processes in a CO_2-based geothermal system: identifying favorable and unfavorable conditions in comparison with water. Environ Earth Sci. doi:10.1007/s12665-015-4293-y

Zhang ZL (2005) Comment on "Sputtering transport theory: the mean energy". Physical Rev B 71(2):026101

Zhang GM, Li YP, Yang CH, Daemen JJK (2014) Stability and tightness evaluation of bedded rock salt formations for underground gas/oil storage. Acta Geotech 9(1):161–180

Zhang Z, Zhang R, Xie H, Liu J, Were P (2015) Differences in the acoustic emission characteristics of rock salt compared with granite and marble during the damage evolution process. Environ Earth Sci. doi:10.1007/s12665-015-4406-7

Zhao Y, Song K, Bai M, Sun N (2015) A novel approach to obtaining relative permeability curves during chemical flooding in a low-permeable reservoir. Environ Earth Sci. doi:10.1007/s12665-015-4413-8

Zhou HW, Wang CP, Han BB, Duan ZQ (2011) A creep constitutive model for salt rock based on fractional derivatives. Int J Rock Mech Min 48(1):116–121. doi:10.1016/j.ijrmms.2010.11.004

Zhou HW, Wang CP, Mishnaevsky L Jr, Duan ZQ, Ding JY (2013) A fractional derivative approach to full creep regions in salt rock. Mech Time-Depend Mat 17(3):413–425. doi:10.1007/s11043-012-9193-x