Title: The Pore Space Scramble; Challenges and Opportunities For Subsurface Governance

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Abstract:

There is a rich literature on environmental governance that provides critiques and conceptual tools on how various environmental 'arenas' or overlapping global systems should be governed eg. climate, energy, oceans (Cherp et al., 2011, Berkes, 2006, Underdal, 2010). In this paper we argue that the geological subsurface should be considered as a new arena for governance in its own right. The arguments for this are presented by considering current and future challenges the subsurface will face as its utilisation evolves and intensifies, particularly in the context of both energy security and low carbon energy. Three main challenges are highlighted; ownership, access and long term stewardship. These challenges are presented using the illustrative context of subsurface pore space for the long term storage of CO_2 from Carbon Capture (CCS). This is presented in the UK context but ultimately has implication for global subsurface governance going forward.

Key words: Subsurface Governance, Pore Space, Verticality, Geosocial.

1.0 Introduction

The subsurface has a long history of industrial resource extraction and humans have been utilizing the subsurface since pre-historic times. In the modern era it has been used for mining coal, metals, salt and limestone, building materials, groundwater extraction and drilling for oil and gas. This extraction requires access to underground spaces of different kinds, used over different timescales and by different actors (Lynch, 2002, Nef, 1967). It relates to different structures (and uses) such as caverns and tunnels (suitable for human access), bore holes (to gain access to reservoirs of underground water, oil and gas fields) and pore spaces (microscopic spaces in the rock that contain liquid ie. oil or saline water, or gas).

Demand for resources such as those utilized through the subsurface (eg. oil and gas) continue to increase. Alternative methods in which to source energy producing fuel from the underground are developing rapidly and the ways in which energy systems exploit the underground are evolving and intensifying (Small et al., 2014). The most notable in terms of current controversy is hydraulic fracturing for shale gas, receiving media attention (eg, in the UK and USA) over public concerns related to safety and environmental health risks (Boudet et al., 2014). However, the subsurface also holds much value (both economically and practically) in its *storage* ability. For example, short-term (eg. Compressed air energy storage or seasonal natural gas storage) and long-term storage of natural gas or long term storage of wastes such as CO_2 resulting from carbon capture and radioactive material (Evans et al., 2009). It is in this instance where the physicality of the subsurface and the *pore space* in particular becomes important. It is these distinctive volumetric properties that shift the subsurface from a one way site of extraction to a two-way use of extraction and storage. This then reopens the subsurface as a site of new opportunity and as a site for contestation. It causes a reassessment and advancement of geological knowledge (assessment of opportunities and risk), of the role of property regimes and access, and of the implications and challenges of using the subsurface in ways which will alter the properties of the subsurface on both human and geological timescales.

To illustrate the dynamic nature of the subsurface in terms of its geological properties and the role and interchange between the geo and social, one particular proposed use of the subsurface (in the UK context) will be used throughout the paper. This will focus on the use of subsurface pore space for the storage of CO_2 as a result of carbon capture and storage (CCS). Carbon dioxide capture and storage (CCS) is a technical concept for the separation of CO_2 from industrial processes or their flue gasses in combination with long-term sequestration of the substance, typically in the pore space of geological formations. CCS technology is ideally designed for large point source emitters of CO_2 such as power plants and particular types of heavy industry. CCS therefore, has been presented as a solution for the decarbonisation of these industry sectors (IPCC 2005, IPCC 2014).

This paper has two main aims; firstly it explores emerging theoretical frameworks addressing the distinct and multiple volumetric properties of the subsurface and the role of verticality, that challenge our current conceptualisation and commodification of the subsurface and its use (Elden et al., 2013, Bridge, 2013, Braun, 2000). It also extends this thinking of geological spaces to consider the role of the 'geosocial', or in other words to consider how geological forces and it's individual properties have shaped and are continuing to shape us as a society (Clark and Yusoff, 2017, Clark, 2017).

Secondly, the paper draws on concepts from the environmental governance literature (eg. Berkes, 2006, Cherp et al., 2011; Ostrom et al., 1994; Underdal, 2010) and the earth governance literature (eg. Biermann, 2007) and reflects on the use of these concepts for exploring the subsurface, given its interplay between environmental, earth and social systems. In this sense, it is this interplay between these arenas, or where the *geo* meets the *social* (geo-social) that makes the subsurface so important, and where this paper aims to make it's contribution. It extends the current framing of governance literatures and brings them into conversation with the role of verticality and geosociality, through the case study example of pore space for carbon capture and storage (CCS). The paper ultimately argues that our existing concepts of environmental and earth governance are not currently 'fit for purpose' given that they do not capture the unique and shifting potentiality that the subsurface provides.

The following section (2) will briefly introduce the concept of the 'geosocial' before discussing the role of verticality, volume and the mapping of strata. In section (3), the emerging role of pore space for CO_2 storage will be introduced (using the UK context and regulatory frameworks as an example) and this will then be followed by introducing the governance literature in section (4). The final section (5) will bring these conceptual and theoretical debates together, and extend thought on what this might mean for subsurface governance into the future.

2.0 Where the *geo* meets the *social:* Geo-Social

The notion of the geo-social is beginning to emerge in the social sciences as a way of understanding the emergence of the Anthropocene (Clark, 2017, Clark & Yusoff, 2017, Yusoff, 2017). However, instead of positioning thought as to how we 'socialised' geology, the perspective is altered to consider how geology has shaped society over time, or as Yusoff (2017 p.106) puts it, 'an expression of social forms as a product of geologic forces'. While acknowledging the concept of the Anthropocene and recognising the way in which social processes have impacted and shaped earth processes in varying ways, the geosocial also recognises the way in which earth processes also shape aspects of social life. Examples of this geosocial relation will emerge, and be explained in more depth throughout the paper however the following will specifically explore this with relation to subsurface spaces and the role of the vertical.

2.1 Subsurface spaces and the role of verticality

From early modernity an intensification of engagement and transactions with the subsurface began to emerge and opportunities for exploiting subsurface resources were uncovered, for instance the 15th Century European mining boom and early industrialisation in late 18th Century. The distinction between the horizontal plane and what lies below was first made apparent through the role of property regimes and the role of the split estate, where the property rights of the surface became detached from the fuels and mineral below (Braun, 2000, Bridge, 2013). This distinction emerged to ensure access and subsequent commodification could be utilised to the max. Braun (2000), using a particular example of this in the early 19th Century Canadian context, explains that in order to optimise it's *vertical* territory, property regimes needed to 'better reflect the internal architecture of the earth' thus enabling individuals to better exploit the nation's geological resources (p. 34). In a similar vein of the geosocial's proposition, that the geology has played a part in shaping the social, Braun (2000) argues that earth science (and the changing knowledge of the earth scientist) plays a key role in developing 'political rationality' in 19th Century Canada.

Verticality and territory have been discussed in more contemporary settings also. For instance, Elden (2013) calls us to consider how the way we think about volume changes the way we think about the politics of space. The discussion in particular explores the role of territory, not just in terms of property, Sovereignty or ownership, but also through the 'exchange, use value, distribution and partition' of (volumetric) space (p.35). Moreover, it is suggested that territory is a continuous process made up the remaking of many assemblages, and not a static outcome of events.

Bridge (2013) builds on the propositions of Elden's verticality, encouraging a move beyond thinking of industrial capitalism as purely a product of horizontal or surface politics (for instance Bridge p.56, uses the example of the division of town and country). Vertical rupture and displacement, Bridge (2013) suggests, are key to conceptualising the link between subsurface and surface processes, highlighting the re-accumulation of carbon in the atmosphere, that has been vertically displaced from it's store in the rocks below (Bridge, 2013). The practices of power that enable access and exploitation of such resources are reliant on a range of geo-metrics and geological knowledge that inform estimates of voluminous structures and extents (ie. subsurface properties), allowing for volume to turn to *value*, and the subsequent political rationalities that ensue (Bridge, 2013).

It is in this sense where the subsurface's unique volume and physical structure, such as pore spaces (voids), fractures, fissures and veins, become the key component in understanding, and perhaps directing the surface and spatial political discourse, where the geo not only meets, but shapes the social. And, far from being a relic of past activity, the subsurface and its properties are opening up new ways for us to imagine and engage with it's use, and in turn leading to a new rationalisation of the governance and political-legal frameworks that are used to structure ownership, order, control, value and access. In the example presented in this paper, this is shown through the voluminous ability of its pore space (or voids) as a new storage opportunity. This example also highlights and extends the concept of carbon displacement into the atmosphere, into a more immediate cyclical process of carbon displacement, capture and then storage in the pore spaces below.

2.2 The mapping of strata

Elden (2013) and Bridge (2013), call for us to consider the ways in which verticality in the subsurface becomes bounded, play different roles and subject to different governance structures. For instance, this can be illustrated through the way the subsurface strata is mapped into bounded spaces.

From a practical utilisation or commodification perspective, the subsurface is categorised into specific geological spaces and mapped as individual parcels of strata. Each individual parcel or strata will be of interest to different stakeholders depending on the geological properties of that particular space. Over time, the diversity in use of subsurface properties has increased and so, the ‘planning’ of strata on both short and long-term timescales has become more complex. For instance, there may be other forms of subsurface use where interactions with adjacent substrata parcels are not viable, for example the deep geological burial of radioactive waste. Not only does it need to be geologically defined in term of its suitability to house this waste, thought also needs to be given to the surrounding parcels of substrata to ensure they would not be utilised now or into the future. These scales are also difficult for us as citizens and policymakers to fully comprehend, and go far beyond our imagination of the future, into geological timescales. On a practical level this void of comprehension results in a significant disconnect between the short term nature which governments, decision makers and industries currently operate (decades) compared to the geologic lifetime (millennia and beyond) that some of these societal decisions play out on.

For instance, Monaghan (2017) considers the crowded nature of the subsurface in Scotland with respect to the use of unconventional energy sources. She emphasises not only on the many uses of the strata within a particular rock volume, including prospective shale, hybrid oil and gas, coal bed methane, geothermal and the possibility of shallow aquifers used for heat storage, but also the particularities of the dynamic (and moving) physical environment of that space defined by its Carboniferous geology. Monaghan (2017 p.47) describes the ‘interbedded coals, mudstones, siltstones, sandstones and limestones’ and how they are stacked and spatially overlapping. Also the particular geological properties and it’s various intrusions and the nature of its faults, can lead to uncertainties for particular uses (such as unconventional shale gas) of the subsurface, at depth.

This planning or parcelling of the strata is readily relatable to the ‘socailization of geological forces of the substratum’ that Yusoff refers to when theorising on the role of the geosocial and the extent to which forces or the potentiality of the subsurface have to shape social and political relations on the surface (Yusoff, 2017 p. 108). In relation to the planning, bounding and access to pore space then, the following section describes pore space in technical terms and highlights its position as a growing commodity through the role of geo-metrics, legal frameworks and policies.

3.0 In The Subsurface: The Pore Space As A Growing Commodity

Pore space is derived from the geological notion of porosity as the fraction of void space in the rock (eg. sedimentary rock such as sandstone) that may contain liquid (eg. saline water, oil) or gas. When pores are connected, they form a network of microscopic pathways which form reservoir rocks within which allow water, oil or gas to collect or flow over geologic time (Evans et al., 2009). Voids occur naturally, or can be induced by hydraulic fracturing. The useful capacity of pore space is relative to the intended use, and varies with for example, pressure or gain size of the rock.

Typically in terms of conventional extraction, these pore spaces would house the resource eg. oil or gas, however, now they are becoming of particular interest due of their potential new role as storage spaces. Pore space in particular is of value due to its potential to store different materials, such as gases, heat and water (Evans et al., 2009) and is becoming increasing used when discussing the utilisation of underground spaces. Evans et al., (2009) give a good description of the potential users and suitability of geological formations of underground storage, including the need to assess spaces on their technical, environmental and economic potential, and the necessity of these spaces to produce minimal or no leakage of the substance being stored. This is imperative from a public legislative perspective and for environmental compliance. Underground storage also operates over various timescales. In the context of pore space it is already used for short-term storage (where the substance stored will at some point be retrieved) such as for natural gas, and now there is also growing interest for longer-term disposal of 'wastes' such as CO_2 (for instance from carbon capture) and radioactive material, often referred to as 'geological storage' (Article 25 – Directorate on Geological Storage). In the case of the latter, retrieval is unwarranted and unwanted and would need to be designated in spaces that would not be interfered with by future users or for access to potential future resources (Evans et al., 2009).

3.1 An illustrative case study: Pore Space for Carbon Capture & Storage

Carbon Capture and Storage (CCS) is considered a technical solution to help reduce the amount of CO_2 entering the atmosphere and contributing to climate change (DECC, 2012). In particular CCS would be used for the industrial sector that would otherwise face high carbon taxing (DECC-BIS, 2015). Given the uncertainty surrounding the energy transition it has been widely debated whether or not CCS would continue the ‘lock-in’ to a carbon intensive energy system (Unruh, 2000, Markusson et al., 2012). This has been considered through an ethical and risk perspective by Medvecky et al., (2014) and quantitatively by McGlade and Ekins (2015) who present results that indicate large proportions of reserve and resource base of fossil fuels should not be burned (even with CCS) if we are to remain below the 2°C target of average global temperature rise. Alternatively, others would argue that CCS is an essential component in the transition to low carbon technologies as fossil fuels use is reduced and should be used in due course, in conjunction with other low carbon technologies (DECC, 2012).

There has been UK political interest in CCS since 2000 (detailed in more depth in section 3.2 below), with the main rationale of decarbonising fossil fuelled power production. UK ambitions in the area of climate change policy domestically and internationally then coincided with renewed interest in building coal-fired power plants (Scrase and Watson 2009; Winskel 2012). Recent interest has risen in decarbonising natural gas fuelled power plants with CCS, driven by changing fuel price balance between coal and gas. Alongside these rationales, CCS has also been framed as an opportunity for industry building (HMG 2009) and technology export (DECC 2012) to global markets. However, the UK government took a U-turn on this support announcing a £1Bil cut to the UK CCS programme towards the end of 2015 (DECC, 2015). In contrast to this, CCS is facing renewed international support as a result of new international agreements around carbon reductions at the 21st Conference of Parties (COP21) of the United Nations Convention on Climate Change in Paris (COP21, 2015, Lipponen, 2017). Even within this global context, the UK continues to have political and economic uncertainty given that European partnerships may now also be called into question as the implications of Brexit, the UK'S withdrawal from the European Union, emerge. The UK is part of a European Research Area Network (ERA-NET) on CCS under the Horizon 2020 Programme and is the recipient of funding from the European Commission for UK based CCS research. Notwithstanding this, the UK government has pledged to continue support for CCS research, innovation and development with the Secretary of State for the department of Business, Energy and Industrial Strategy known as 'BEIS' (DECC, the Department for Energy and Climate Change, previously responsible for UK Energy strategy including CCS, was superseded by BEIS in 2016) suggesting that in some instances funding that is withdrawn from the EU for ongoing projects may be supported directly from UK funds (House of Commons, 2017).

3.2 UK Policy on CCS

The European Commission (2009) put in place a directive focusing on the demonstration of storage technologies and in particular the storage element of the supply chain. The UK aimed to be a key player in the development and implementation of CCS and in 2012 The Department of Energy and Climate Change (DECC) announced that they were making £1 billion capital funding available to support the design, construction and operation of the UK's first commercial-scale CCS project[1]. They hoped to develop CCS to a stage in which it provides a cost competitive alternative to other low carbon technologies and provide tens of GWs of installed capacity in the power sector and CCS on a variety of industrial applications, in order to help the UK meet legally binding targets to reduce CO_2 emissions and other greenhouse gases by 80% from 1990 levels, by 2050 (DECC. 2012).

DECC's roadmap outlines a three phase approach to enable this position, the first being a commercialisation programme, the second, a transition phase through which state subsidy will be minimised and the final phase whereby CCS is commercially competitive and can compete with other low carbon technologies. The UK was proceeding with the beginning of its first phase and two projects were selected to start the beginning of the

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[1] UK Governments have attempted previously during the 2000s to stimulate large-scale demonstration projects. For a historical account see Scrase and Watson (2009).

[2] https://www.gov.uk/government/news/peterhead-carbon-capture-and-storage-project

commercialisation programme. In 2013 the two preferred bidders for these projects were announced as the White Rose Project and the Peterhead project [2].

In addition to support promised for the Phase 1 projects, the UK government initiative to support CCS included the Electricity Market reform, which aims to allow CCS to compete with other low carbon technologies fairly on price. Vincent, et al. (2017) estimate that up between 40 and 80 Mt of CO_2 will need to be stored each year by 2030 and up to 480 Mt each year by 2050. This would require a significant number of storage sites to be in operation to securely store CO_2.

In the autumn statement the government announced the funding for the commercialisation project was no longer available, which was promptly followed by calls to device a new strategy to reduce the damage to the CCS programme (House of Commons, 2016). A number of alliances were being made for international engagement and knowledge sharing, including collaborating with individual countries on research and development such as Canada, and international co-operations such as the North Sea Basin Task Force and Clean Energy Ministerial, a high-level global forum on designed to enable the transition to a global clean energy economy.

3.3 CCS Capabilities in the UK

CCS technology is ideally designed for large point source emitters of CO_2 such as power plants and particular types of heavy industry. CCS therefore, has been presented as a solution for the decarbonisation of these industry sectors (IPCC 2005). The concept has been realised using proven technologies, and the first integrated system at full scale capturing CO_2 from a fossil fuelled power plants, came online in 2014. In this case however, the captured CO_2 is used for enhanced oil recovery (EOR), rather than straight into geological storage (GCCSI 2014).

The main R&D spend has focussed on the capture element of CCS however, development efforts have also been devoted to geological storage, exploring potential in geological formations such as depleted oil and gas fields or storage in saline formations. Oil and gas fields make good potential storage sites as they have a proven ability (in the form of a caprock or sealing unit) to store buoyant fluids over geological timescales. Due to the exploration and production process they are well understood geologically and have data associated with them which can help to understand the dynamic fluid production. Saline formations usually have no economic value and as a result much less data is available for the assessment of these sites (unless specifically acquired at cost), meaning that often the geology is less well understood. Globally and in the UK, saline aquifers are thought to offer the greatest storage resource with an estimated 60 Gt of CO_2 storage in saline aquifers in the UK (Bentham et al., 2014).

CO_2 storage can be realised alongside production of fossil fuels. CO_2 can be injected into underground coal seams, where it would replace and drive out natural gas. Such enhanced coal bed methane recovery (ECBM), would thus both store CO_2 and produce natural gas. Similarly, CO_2 can be used for enhanced extraction from oil and gas fields.

In DECC's (2012) CCS roadmap it was noted that the UK has extensive storage capacity in the North Sea, clusters of power stations and industrial plants that could share infrastructure, expertise that could be transferred from the oil and gas industries and academic excellence in CCS research. The storage roadmap covers the research and development activities described below, the electricity market reforms described above and specific interventions to address key barriers to the deployment of CCS, which are described in this section.

DECC's visions for CCS in the UK was for tens of gigawatts of installed electricity generating capacity. Due to the UK's industrial development over the past 200 years, including the development of the UK's oil and gas industry, there exists potential for CCS clusters to develop in several regions which have been identified in the CCS Roadmap: the east coast of Scotland, Yorkshire & Humber, Teesside, and around the East Irish Sea, where there are large concentrations of industry close to potential storage capacity. These clusters of sources could utilise common transport networks and exploit clusters of CO_2 storage sites, including sites that could potentially use CO_2 in enhanced oil recovery, in the North Sea and Irish Sea.

Alongside the CCS Roadmap, an accompanying short note was published on DECC's Storage Strategy. This strategy recognises the challenge of future storage deployment including the scale of possible storage needed including the uncertainties associated with predicting likely amounts of CO_2 that might need to be stored and the current lack of validation for saline aquifers. Assessment of saline aquifers should begin soon to avoid a pinch point in the late 2020s since the availability of individual hydrocarbon fields is difficult to predict due to the close links between close of production dates and oil prices, taken together with an element of competition from gas storage, and the long lead times for the assessment (quoted as 6-10 years). The Storage Roadmap therefore sets out specific activities on which the UK Government will focus. These include providing support to reduce the level of technical uncertainties, regulatory issues (including facilitating the reuse of offshore assets and geological features and defining the leasing/ licensing approach) and, commercial/policy issues including secure rights to investigate off-shore storage locations and to develop the Government's approach to the use of the UK offshore area to store CO_2 from other countries.

4.0 Theoretical Governance Frameworks

Given that we are at the beginning of utilising pore space for long term storage of substances such as CO_2, the opportunity presents itself to consider possible ways in which governance of this space should go forward. It is here that we consider existing governance frameworks, specifically with relation to CCS and pore space, before considering how the role of verticality and the geosocial challenge these frameworks. Gamborg et al., (2014) define governance as 'the steering of social systems by state and non-state actors' and this reflects the multiplicity of stakeholders implicated in the subsurface and its future from government bodies, private industry, and the public and civil society. Here we particularly discuss and consider conceptualising the subsurface as a complex system, using the work of Cherp et al., (2011) who frame governance thinking around 'arenas' rather than 'actors' (section 4.1), and Ostrom's governance of common-pool resources (section 4.2), to help frame thinking about its governance.

4.1 Governance for Complexity

The term complexity is often used in conjunction with governance particularly when considering the challenges of long-term environmental governance. Goldthau (2014 p.134) suggests that infrastructure acts and becomes part of a complex system, 'interacting with multi-layered set of institutions, laws, regulations and policies'.

Subsurface ‘pore space’ could be defined as part of our energy infrastructure given that it is a physical structure with properties that enable it to be used for a societal ‘need’, through the utilisation of this physical space as a storage facility, as in the context of this example, for CO_2 storage from CCS. Building on this concept therefore, the arguments for governance as a complex system can be more easily defined. Complexity as a conceptual tool with which to explore governance could be used in reference to governing pore space but also the subsurface more broadly given the multi-faceted properties and utilisation of subsurface including spaces on a range of scales (form microscopic pore spaces to cavernous tunnels) and for utilisation for a diversity of uses and users.

Cherp et al., (2011) frame global energy transitions around the need for flexibility and creative partnership and highlight the necessity for co-ordination across scales and sectors. Cherp et al., (2011) also emphasise the need to readjust the focus of governance on ‘what’ should be governed and how it should be governed rather than ‘who’ should govern, positioning governance for complexity around interconnecting arenas, such as energy security, energy access and climate change. One could argue therefore that the subsurface, which is implicated in the three aforementioned arenas, and constantly evolving in terms of how it shapes society, not just for energy resources and its products (ie. wastes) but also for minerals and water resources, should be classified as an arena for governance in and of itself. Subsurface governance echos that of energy systems governance given that the subsurface (or its governance) needs to keep up with an evolving system. Similarities with energy systems governance continue, given that subsurface governance also needs to operate across scales, spaces and sectors. The use of pore space for storage of CO_2 from CCS is a good example of this given the technical, regulatory, economic and political uncertainty that surrounds the use of the subsurface in this way. The uncertainty that surrounds the use of the subsurface, can be explained by it simultaneously interacting with (and being) many systems in its own right including; an earth, environmental, energy and societal system.

This highlights the complexity, nature and unpredictability of the subsurface (system) and its use, which is defined and utilised by its unique physical properties such as its pores, fractures, fissures, voids and diversity of minerality (ranging in the simplest descriptions from water, metals, minerals, carbon and gas). Society's past and present use of these abundant properties has had and continues to have implications across many socio, economic and environmental spheres both within and beyond energy and low carbon transitions. Societal development and technological innovation both require and enable the ability for us to go deeper and more extreme, as in the case of deep burial or radioactive waste and deep geothermal energy (Elders et al., 2014) and the evolving long term use of spaces or voids, such as pore space. Indeed it is the unique properties that the subsurface presents that adds to the argument for governance as complexity, given that changes to the subsurface in terms of its use can be non-linear, with a change in use being disproportionate to the potential consequences (eg. through the escape of hazardous wastes or gases in unforeseen ways) and through its path dependent nature. Such as society's dependence and continued use of fossil fuels but also in terms of the degenerative effect of extraction or long term burial of wastes. This builds on Cherp et al.'s (2011 p. 77) assertion that governance for complexity should be defined by characteristics of a system including (amongst others), interconnectedness, unpredictability, non-linearity and path dependency.

One way of arranging this diversity and complexity, that needs flexibility and coordination in its approach, is through finding a balance between traditional centralised and decentralised forms of governance. Centralised forms that take on a hierarchal top-down arrangement, are perceived as being highly suitable when dealing with uncertainty given its strong centralised power and leadership (Kooiman, 2003 cited in Cherp et al., 2011 p.79). Another approach calls for a softer set of principles when governing for complexity, favouring a mix of horizontal and vertical interaction across scales and sectors (Cash et al., 2006). An open flow of information and knowledge are core principles in this mixed governance practice, but equally important is the involvement of multiple stakeholders in formulating and planning long-term goals. Cherp et al., (2011) notes that complexity governance is not only useful for examining energy systems, is it also useful when trying to understand energy governance as they 'evolve as complex systems with their own histories, fluid boundaries, dynamic connections, intricate networks and feedback loops, uncertainties and nonlinearities' (Cherp et al 2011, p. 80). This is especially apparent with the subsurface given its evolving interweaving of both its physical and societal complexities and dependencies.

4.2 Governance as a Common-pool Resource

Governing for complexity is commonly linked with the governance of common-pool resources. Common-pool resources are defined by Ostrom (1994) as having two key aspects 1) the ability to exclude people other than a pre-defined group, or, control of access to an area is difficult and 2) that users are capable of subtracting from the welfare of other users (Berkes, 2008). The concept of common-pool resources has also over recent years developed from applications of the principle for small-scale community commons (most notably applied to fisheries and forests for example), to exploring whether such common-pool principles can be applied to larger scale and even global systems (Berkes, 2008). Dietz et al., (2003) call these global systems or global commons, such as the oceans and atmosphere, ‘critical commons’. These commons are deemed ‘critical’, as the implications of their degradation can be influenced by non-local drivers, and have implications across boundaries and with effects across large (and sometimes global) scales. These critical commons, although distinct from Cherp et al.’s (2011) governance ‘arenas’ as described in the section above, are significantly inter-connected given their utilisation and protection for societal need eg. oceans for food and biodiversity but also as a source of energy (wave, tidal, water resources for large-scale power plants) and mineral resources, and both the ocean and atmosphere’s role linked to climate regulation. The argument can then be put forward that the subsurface, in a similar way to the oceans and atmosphere, can be considered to be a global and ‘critical’ common that should employ an adaptive governance system for the ‘effective stewardship of many resources’ (Dietz et al., 2003) and can also be considered as a governance ‘arena’ linked to energy security, access to resources and climate.

The subsurface provides many resources used by many user groups, however in this paper we explore one evolving use through the illustrative example of subsurface pore space, to explore the characteristics of complexity and as a common-pool with respect to the subsurface and its governance. When considering parcels of substrata (some of which contain pore space), it is possible to conceptualise them as resource units. These units can have different 'uses' that are enabled by the geological properties of that particular parcel of strata. For example, specific units used for mineral extraction, water extraction, or as we highlight in this paper, strata that is geologically defined as suitable for storage. In this instance, parcels might be utilised by different users (eg. industries or institutions) and be subject to different laws or regulating policies. Not only as the geological properties differ and change over national and global spatial scales (eg. both horizontally and vertically, with depth), so too does the societal drive (or utilisation) and the subsequent laws and regulations, which also adapt and change over time. To add to the complexity, the same geological strata can be subdivided into different units depending on it's purpose. This division could be according to it's geological age, or the same rock unit may be subdivided in terms of its resource and prospectivity. This then fits well with Ostrom's (1994 p.4) description of common-pool resources 'Resource units from a resource shared with other users in many guises in diverse resource systems throughout time and space'.

To better understand the position of the subsurface as both a complex system and as a global common, the following section (5.0) brings the governance concepts outlined in this section, into conversation with the theoretical concepts around verticality and the geo-social outlined in section (2). To do this the following proposes three challenges that future governance may face with respect to ownership, access and long term stewardship. Although pore space is highlighted here, the wider use of the subsurface fits well with the evolving concepts of a common-pool involving multiple resources and user groups (Dolsak and Ostrom, 2003).

5.0 Challenges Arising for Subsurface Governance: Ownership, Access and Stewardship

Here we considers three challenges that arise when considering subsurface governance. These questions use subsurface pore space (for CCS storage) as context but are applicable to other subsurface uses. This does not intend to be an exhaustive list of challenges but does highlight these as key areas for thought and provocation, and that cross a range of spatial and both human and geological timescales. This brings us back to the opening aims of this paper, by reflecting on concepts provided by the governance literature (as discussed above) and again drawing attention to the interplay between social, earth and environmental systems. Or, as we posit in the introduction to this paper, where governance arenas overlap, and where the geo meets and shapes the social.

In the context of our illustrative case study, this drive for continued and new subsurface use is coupled not only with high resource demand but also with the rhetoric around the 'transition' to a more secure, low carbon and economically viable energy system (ETI, 2015). As such, the subsurface and its use (or potentiality), directs many actors including and beyond those who directly use the subsurface, and across national and global scales. These include the subsurface users themselves (eg. extractive bodies and now including geological storage industries delimited by geometric and depth of knowledge), surface infrastructure and industries (eg. Energy industry, Manufacturing and Utilities), global commodity chains, scientists, policymakers, the regulatory community and the public (both as communities and consumers). Once again, this emphasises the complexity of the subsurface, made up of parcels of strata with different geological properties, fractures, fissures and pore spaces, and the complex social systems that collide with them. It also highlights that the alignment of a multitude of actors at the surface, across spatial, political, legal and socio-cultural scales, is reliant on, and shaped by the potentiality of the geophysical properties below. In other words, the extent to which geological knowledge enables volume (in this case pore space) to be derived as value, and in turn shape and change the political-legal structures that enable its' access.

A specific example of this geo-social collide, occurs around the legal ownership of the subsurface or particular parcels (units) of substrata within it. Pore space in particular usefully highlights this challenge. Using subsurface pore space for long-term storage of gases such as CO_2 is a relatively new concept and presents using the subsurface in a new way. This has posed questions for legal scholars, legislators, extractive industries and landowners, that are centred around two main issues; firstly, whether 'voids' ie. the pore spaces themselves, are subject to existing legislation, since they are neither material, mineral or gas, and secondly, the depths within the subsurface to which legal ownership can fundamentally still exist.

With regard to the ownership of 'voids', legal scholars have centred the debates around the application of the Roman maxim *cuius est solum, eius est usque ad coelom et ad inferos* ('he who owns the soils owns also up to the heavens and down to the centre of the earth') and the way its applicability changes spatially and through time. A recent UK case study, Bocardo v Star Energy, helps to illustrate this point. During this case, Bocardo (the land owner) sued Star Energy (the oil company) for trespass. Under the existing legislation, Bocardo owned everything below the surface apart from the mineral rights, which in the UK are held and leased by The Crown Estate (2017). In this instance, Star Energy held a lease for mineral extraction and had used directional drilling underneath Bocardo's land to gain access to the apex of an oil field. Bocardo saw this as trespass as everything except the minerals below the surface should be his. The court agreed and ruled in favour of the land owner and raised a key point in relation to the ruling around the ability of the subsurface to do work; the court took the position that if the land (subsurface material) could 'be worked', then ownership can be defined. This raises theoretical and legislative discussions on what constitutes the ability of material to 'be worked' and the evolving need for legislation to keep pace with the continued advancement of technology enabling society to go increasingly deeper and seemingly more extreme into the subsurface. It also raises interesting questions of how the ability of subsurface material 'to be worked' could also evolve and relate to its ability to 'do work' (therefore creating value), particularly with respect to the commodification of 'voids' or pore spaces for long term storage of waste CO_2.

Authors have discussed this evolving ownership issue in specific jurisdictional contexts (eg. See Bankes and Roggerkamp, 2008, Richards et al., 2012, Kennett et al., 2005, Wilson and Figeiredo, 2006, Bradbrook, 2014) and future rulings may differ depending on how jurisdictions interpret current and future legislation and the specific particulars of individual cases (Richards et al., 2012, Graham, 2010). However, challenges about ownership also have significance for access, as can be implicitly applied to the above. As an example, consider the way in which the subsurface is categorised for its management and use by a variety of stakeholders. Geological spaces are mapped into individual parcels or (sub)strata depending on the geological properties of that particular space. These properties hold different value and interest for different actors or stakeholders involved in utilising the resources the subsurface provides. For instance, in the UK, operators involved in storage of CO_2 from carbon and capture need to acquire a permit for storage from the Oil and Gas Authority, who are the regulators and licensing authority for off-shore CO_2 storage (OGA, 2017). They also need to acquire the relevant lease (known as the storage agreement for lease) to use the pore space within a particular parcel of strata (The Crown Estate, 2017). However, they also need to acquire access to that parcel of substrata that have the required geological properties (ie. pore space) and given that they are commonly located in areas that are also being utilised for mineral extraction, for instance in areas of depleted oil and gas fields; negotiating access between users would need to take place. Currently in the UK, holders of such a storage lease are unable to interfere with the rights of a petroleum licence, so their access would only be allowed through negotiations with the licensees of adjacent parcels (The Crown Estate, 2017).

Each parcel therefore will be subject to different forms of ownership, legislation and access rights, and this has implications beyond mineral extraction and CO_2 storage. There are forms of subsurface use where interactions with adjacent substrata parcels are not viable eg. deep burial of radioactive waste. Burial sites should be inaccessible and stable over long periods of time and at no risk of interference in future searches for natural resources, therefore isolated from interactions with humans and the environment (Defra, 2008, Chapman and Hopper, 2012). Current and future decisions over energy systems then (investment in new nuclear, CCS and fossil fuel-fired power stations) will impact on the demands on the subsurface both in terms of extraction and in terms of its use for long term storage of wastes and to the extent to which conflicts might arise.

Leading on from the challenges of ownership and access, the final point highlighted here is around the long-term stewardship of the subsurface. It’s multi-faceted properties and evolving role adds to its complexity as an object of governance. There is a disconnect due to the short term nature to which governments and companies currently operate (decades) compared to the lifetime of the CO_2 storage (millennia) and it is this disconnect that can cause concern for the long-term monitoring of such spaces (Zakkour and Haines, 2007). Ambiguity, particularly over liability should accidents (such as leakage) occur, can lead to further uncertainty and distrust from wider stakeholders such as the public and local communities (Mabon, et al., 2013).

The stewardship of pore space for CO_2 storage usefully highlights the complexity of issues facing the evolving use of the subsurface. This mode of thought also resonates with those aforementioned theorising the subsurface, with calls to consider the particular unique and volumetric subsurface properties, of pore space, fractures, fissures and veins, the way they might be bounded, accessed and territorialised, and so how politics becomes a key factor in the geo-social collide (Dalby, 2013; Bridge, 2013; Elden, 2013; Clark, 2016). It becomes a politics of volume and a politics of strata (Bridge, 2013 and Clark, 2016). This leads us back to Cherp et al.'s (2011) assertion that it should not be who does the governing but what should be governed that is the focus. The specific example of pore space for CO_2 storage emphasises that societal use of the subsurface is not static and will continue to evolve over time, led by drivers that currently exists (mineral extraction), those that we can foresee (burial of wastes) but also perhaps some that we have not. For instance, there are many other new and evolving uses of subsurface spaces from the small (ie. pore space) to the much bigger such as caverns and mines. These include explorations into the re-use of past mine spaces for geothermal heat storage (Hall et al., 2011), and the 'urbanising' of the subsurface for underground pedestrian systems such as in Tokyo, Japan and Shanghai and other mega-cities as urbanisation increases (Cui et al., 2013). There are also those that cause us to go deeper and more extreme, such as deep geothermal energy (Busby, 2014) and the use of magma for electricity, through the drilling into an active magma chamber that is currently being investigated principally in Iceland but also at other suitable sites world-wide (Elders et al., 2014).

6.0 Conclusion

Through the examples of ownership, access and stewardship, we would argue that it is this evolving and changing potentiality of the subsurface, that drives and shapes the political, legal and governance processes that emerge on the surface. Indeed, many of these actions will be directed by local place-based decisions based on geological assessments, and socio-political and economic drivers, however the implications of these are far reaching into regional and global scales. The geo-social into the future then transcends particular place-based discussions of ownership, access and legislation and calls for a collective appraisal of what subsurface stewardship and governance should look like for the near and far term future. The subsurface, or as we emphasise here this geo-social collide, can be explained by it simultaneously interacting with (and being) many systems in its own right including; an earth, environmental, energy and societal system. It is at this juncture that we can link theoretical conceptualisations of verticality, formulated by the unique questions of volume, power and politics, with the more traditional frameworks of earth and environmental governance. Building on the governance frameworks explored in section (4), we would call for the subsurface to be conceptualised as a governance arena in its own right.

Moreover this leads to a re-assemblage of such a conceptualisation, given that existing frameworks do not encapsulate the way in which verticality and volume dictate society's engagement with the geo. As argued in section (4), both governance for complexity and common-pool provide useful approaches for thinking through how the subsurface might be conceptually governed. However, these approaches do not fully encapsulate the voluminous physicality of the subsurface. While the atmosphere and oceans are too volumetric (and considered to be critical commons in their own right, Dietz (2003)), the subsurface can be argued to be distinctive by not only it's volume but also it's diverse physicality and depth. And with regards the subsurface, it is this diverse nature that directs the need for complexity within governance but that also inhabits the ways in which the geo shapes surface politics or actors. Ultimately, we suggest that to be fully reflective of the potentiality of the subsurface's volumetric properties, governance in this context needs to acknowledge the place of the geosocial in shaping our evolving politics, territory, power relations and transitions. Clark (2017) suggests that there is a 'politics of strata', and much in the way that earth system science now adheres to their being a politics to climate, so too does that of the geologic. We would argue that this is where earth and environmental governance needs to evolve.

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