At the Sharp End of Fractured Granites:

A Critical Geology for Critical Times

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The geosciences will play a key role in delivering a net zero energy future ... Nearly all forms of energy production require Earth resources, knowledge, and technologies underpinned by geoscience… The energy transition thus mandates a geoscience transition.

Gardiner et al., 2023: 1-2.

In classifying and indexing … we acknowledge the Earth as a vast geo-informatic construct. It is both geology and data, ontology and epistemology… Those material properties are essential to the Earth's ability to document its own past, and to the human ability to predict, prepare for, and even redirect its future.

Mattern, S. 2017, no page.

The geosciences have been positioned as integral to a 'whole society' transition that includes the decarbonisation of energy systems. Geothermal energy - which relies on a knowledge of the dynamism of rocks in the subsurface including the movement of fluids through fractures, physio-chemical interactions, and thermal gradients – has been offered as a potential route forward. Its realisation hinges on the work of field geology (alongside other disciplinary expertises) as well as political and economic buy in. As the geosciences reorientate around new objects of analysis, and find new lines of impact and engagement, there remains the question, however, of how the practice of field geology, integral to assessing the potential of geothermal energy development, might find new direction. That is, how might we move away from a reductive figure of the field geologist as a data collection and analysis expert whose behind the scenes exertions allow for revelatory insights into otherwise hidden depths? Can we acknowledge instead a differentially embodied and augmented expert whose knowledge is co-produced amidst a series of fleshy-technological-elemental entanglements? Drawing on our investigation of fractured granite in Helmsdale, Northern Highlands of Scotland, we provide a situated account of field geology that responds to this question. We outline the role anticipated by geothermal energy in a just and green transition before reviewing the shifting character of a 'gnostic touch' in past and current field practice. This provides a context for our *own work – inspired by conceptual debates in critical physical geography, political geology and a geohumanities – that unpacks the 'replicability' and 'shareability' of field geology work. We conclude with a 'manifesto' for a critical Geology that, while noting field geological expertise as a necessity for an energy transition, emphasises how university-based expertise might be made more inclusive, and how the knowledges derived might be situated amidst community-facing discussions as to desired futures.*

1. Introduction

With the environmental and social consequences of fossil fuels ever-more apparent on a global scale, scientific and political communities have called for a wholesale societal transition to Net Zero that encompasses the decarbonisation of energy (Määttä, 2021; Stephenson et al., 2021). Such calls demand a profound reorientation of Geology, which - as an academic discipline, as a component of the state's vertical governance of territory, and as a professional vocation - has been extensively critiqued for its role in the emergence and unfolding of extractive, fossil-fuelled economies (Braun, 2000; Hearth, 2021; Lucier, 2008; Partick, 2018; Stafford, 2002; Tolman 2016; Walker and Johnson 2018). Certainly, Geology became aligned with a formalised training in the location of fossil fuel and mineral ore deposits, and a determination of their scale and grade. Geological expertise has addressed "how and at what cost these occurrences could be made available for human use", as well the "possible development of mining technology, mine organization, production and transportation costs" (Westermann, 2015: 153). It is in this context that arguments have been made as to the need for a 'Geology Net Zero' - or 'geoscience transition' - predicated on the "(responsible) sourcing of raw materials for low carbon energy technologies … and in the near-permanent geological capture and storage of carbon through novel technology development" (Gardiner et al., 2023: 1), as well as the decarbonisation of energy, including geothermal techniques. What is more, geological expertise, alongside the knowledge base of workers in extractive industries, has been framed as enabling a *just* as well as *green* transition, in that various 'geological solutions' for decarbonisation can draw on these transferable skills (McGrath et al., 2024).

What is less acknowledged in such calls and debates, however, is that a long-held component of field geology is the *haptic expertise* of the idealised geologist, embodied in their field-based methodology (Stafford and Terpak, 2001). "The geologist on the ground can actually touch the Earth's substance", writes Dougal Dixon (1992) in their guide to the discipline. This is a knowing and authoritative touch – what Dixon & Straughan (2010) summarise as a 'gnostic touch' - that portrays a hyper-masculinised overcoming of environmental conditions (Phillips et al., 2020) and that promises access to the otherwise hidden inner truth of the Earth (O'Connor, 2019). To be sure, Geology as a discipline has become witness to sustained efforts to build inclusiveness, particularly around access to fieldwork (Bursztyn et al., 2021; Rogers et al., 2024), and a burgeoning commitment to a 'geoethics' (Mogk, 2021). Yet, there remains the question of how, amid a geoscience orientating around new, non-carbon objects of analysis and finding new, inclusive lines of impact and engagement, the practice of field geology might find new direction. How might we avoid simply substituting the search for one 'inner truth' with another? How might we reimagine and resituate the knowing hand and eye of the field geologist? And what role can field geology play in a society (hopefully) in transition toward a just as well as green energy revolution? In sum, what can a 'critical Geology for critical times' be?

Our response to these questions draws on conceptual points that are associated with a range of fields including critical physical geography, political geology, and geohumanities. First, there is a shared critique of the notion that the knowing subject occupies a distanciated and privileged place from which to scrutinise the world, and a determination instead to navigate both the situatedness of the former and the agency of the latter. As Bobbette and Donovan note, "geologists, with their tools, expedition equipment and teams, are themselves politicians operating in spaces, on behalf of others, and seeking authority" (2019: 2). Second, there is a shared concern with the 'co-production' of geological knowledge, construed from the practices and technologies of a methodology that is thoroughly immersed in the work of the world, and the materialities that allow phenomena to be located, apprehended, scoped and mapped. Epistemology is regarded here not as the sole prerogative of an agential researcher, but, as Mattern (2017) observes, a relation between researcher and world that allows knowledge to emerge in ways that are shaped by the materialities of both. And third, there is an unpacking of research practice and impact as a working with care and inclusion regarding individuals and communities that have been, are, and will be faced with profound environmental challenges. For Sharp et al., "Such engagements may be experiential, sensual, and precognitive and will eschew particular, select truths or associated judgement;" and, may well "draw inspiration from the practices of everyday life, the poetics of natural phenomena, the potentiality of experimentation, and the passions of the researcher, as these are full of creativity and possibility" (2022: 69). In what follows we provide an account of our working with these ideas in and around the town of Helmsdale in the Northern Highlands of Scotland (UK), where fractured, naturally high heat-producing granites might – perhaps - be candidates to produce low carbon geothermal energy for heating.

As part of an energy ecosystem geothermal has the advantage of providing a stable baseload for heating that is independent of climate and weather conditions and produces no greenhouse gas emissions. It is based on the geothermal gradient of the Earth's crust, sometimes enhanced by excess heat production from rock types such as granite, which may be enriched in radionuclides of Th, U and K. Geothermal energy can be derived from a range of sources, including: (1) shallow heat pump systems (e.g., using water in flooded mines); and (2) deep systems (e.g., using sedimentary aquifers or fractured high heat-producing granites, typically classed as having heat production > 4.0 $\mu W\ m^{-3}$). Deep geothermal can work with heat pump technology but also, potentially, at high enough temperatures (>100°C), turbines can be installed for electricity generation. This technology is present in Iceland, which has high geothermal gradients from active magmatism. There is a further distinction between 'open' and 'closed' systems. Open systems rely on extraction of heat from sub-surface water, whereas closed or "closed loop" systems involve heat transfer from the sub-surface into piping networks filled with saline fluids. In Scotland, several locations in different geological settings have generated interest for their geothermal potential, albeit at a time when open systems were the main type considered (Brownsort and Johnson, 2017; Gillespie et al., 2013). A key question remains as to how the suitability of rocks in the subsurface for geothermal energy production - a currently minor element of the country's energy transition planning - is to be assessed. For a variety of reasons outlined in this paper, the answer to this question requires the input of field geology.

Below, we outline the push to decarbonise energy in Scotland, noting potential for associations with community empowerment amidst a monopolistic land ownership system. It is in this context that Geology is turning towards new, non-carbon objects of analysis, such as 'hot rocks' and fracture systems, and finding new, inclusive lines of impact and engagement. We briefly review and critique the emergence of an idealised, hyper-masculine field geologist figure, and the attentiveness given to a gnostic touch as the defining indicator and guarantee of geological expertise. We note how the field geologist remains central to notions of an accurate assessment of subsurface fault patterns amidst new, semi-automated methods of mapping these at surface outcrops. That is, the field geologist - albeit augmented via a compass-clinometer - remains the 'touchstone' for testing the efficacy of substitutes such as Light and Radar (LiDAR) and Unmanned [sic] Aerial Vehicle (UAVs) facilitated structure-from-motion (SfM) photogrammetry. Next, and drawing on our own efforts to assess the subsurface condition of the Helmsdale granite via a mapping of the fracture density observable at the surface, we provide insight into how the hand and the eye of the field geologist perform in practice, and how aspects of that practice might present pathways to deeper, meaningful engagement with local communities. In doing so we emphasise the entanglements of flesh, technology and elements through which a knowledge of fractures emerges.

We conclude with a 'manifesto' for a critical Geology, noting field geological expertise as a necessity for an energy transition, but also how such expertise might be more inclusive, and how the knowledges derived might be situated amidst community-led discussions as to desired futures.

2. A Critical Time for GeoEnergy in Scotland

Our field geology is undertaken in Scotland where the decarbonisation of energy has been situated amidst a whole society transition led in part through the Scottish Parliament. The Climate Change (Scotland) Act (2009) was a key initiative of the Scottish National Party's (SNP) first term in government, then the most ambitious legislative response to climate change globally, with independent advice, information and analysis to be provided by the UK's Climate Change Committee (CCC). The Act provides the statutory framework for greenhouse gas emission reductions in Scotland by setting an interim 42% reduction target for 2020 (though this could be varied based on expert advice) and an 80% reduction target for 2050, using as a baseline 1990 emission figures. Since 2009, important questions have emerged around the role of the Scottish Parliament and associated governmental infrastructure in facilitating a new, non or low carbon energy landscape (Abesser et al., 2020); the need for new business models for renewable and sustainable energy sources

(Townsend et al., 2020; Younger et al., 2016); and the location of suitable (onshore and offshore) subsurface environments for a range of decarbonising methods and technologies including geothermal (Heinemann et al., 2019).

In Scotland, “progress to date in decarbonising electricity has been remarkable” [and yet] “low carbon heat generation (as a percentage of gross consumption) is currently the lowest of any country in Europe” (Scottish Development International, 2020, no page). While the Climate Change (Emissions Reduction Targets) (Scotland) Act (2019) established new targets for a NetZero Scotland by 2045, a (2020) Scottish Parliament update acknowledged that the pace of property conversion to low carbon forms of heating would need to be increased dramatically to meet emissions targets (Energy and Climate Change Directorate, 2020). Despite potentially offering major benefits in terms of providing heating for homes, businesses and public buildings, geothermal has struggled to find a place as a prospective line of decarbonisation action in a transitioning Scotland but also the UK more broadly. Geothermal contributes just 4.5% of renewable energy used in the UK overall (McClean and Pederson, 2023). In recent years, Westminster and devolved administrations have instead promoted air source heat pumps that use electricity from the national grid to provide heating for individual homes. Just one deep open geothermal system is presently used in the UK, tapping a hot sedimentary aquifer for district heating in Southampton (Smith, 2000).

One factor that has played a role in this relative lack of visibility for geothermal is its ‘out of sight, out of mind’ status. The UK is not volcanically active and, compared to locations such as Iceland, has low crustal heat production and heat flow (Oxburgh et al., 1980). The most advanced research into geothermal resources is being undertaken in Cornwall, where ~240 Myr old granites of high radiogenic heat production have been drilled to assess their potential for a combination of electricity production, district heating, and lithium metal extraction (Farndale and Law, 2022; Leonida, 2023). In Scotland, ~450-390 Myr old granites, chiefly in the Cairngorms and Southern Uplands, are recognised as having some high heat production characteristics, and have been envisaged as potentially suitable for deep open ‘hot dry rock’ schemes (Busby et al., 2015; McCay & Younger, 2017). However, such energy recovery has a risk of induced seismicity, and the deep injection of surface water is currently under a planning moratorium in Scotland due to national bans on deep fluid injection associated with fracking (Scottish Government, 2016). Hot sedimentary aquifer schemes have been proposed for the Midland Valley (e.g., Scottish Government, 2013; Comerford et al., 2018), as well as shallow mine water heat recovery (Walls et al., 2022).

Geological knowledge gaps regarding drilling several km into sedimentary rock aquifers, or 'hot' radioactive granites, include uncertainty over the structure, porosity and permeability of the rocks at depth. As a feasibility study for one of Scotland's hottest granites - at Hill of Fare, Banchory - recognised, there are few surface data points with which to build predictive models of the sub-surface (Younger et al., 2016). Open hot sedimentary aquifer systems are subject to further uncertainty over the rate and sustainability of water flow, while hot dry rock schemes have raised questions over the recoverability of injected water (Jiang et al., 2023). From a commercial perspective, however, there have been rapid advances in closed loop deep geothermal technology, specifically the Eavor™ system (Toews et al., 2021; Beckers et al., 2022; Longfield et al., 2022), including improvements in drilling speed (Dupriest and Noynaert, 2022). These technological advances have been argued to make deep closed-loop geothermal commercially viable in the UK, avoiding uncertainty over water flow at depth and issues over induced seismicity (Abessar and Walker, 2022; Eavor, 2022). However, the feasibility of closed loop deep geothermal has not been tested in detail in Scotland or the wider UK.

Intersecting with this dearth of research is the profound issue of land ownership. Scotland has a strongly monopolistic land ownership structure, constraining who can decide to do what (Glenn et al., 2019). Hindle et al. (2014) report that 70% of Scotland's rural land - 4.1 million hectares - is held by 1,125 owners. Moreover, of the estates held by these owners, 87 are estimated to be larger than 10,000ha: 67 of these large estates are in the Highlands. "Community action towards decarbonization frequently requires access to land and natural resources", Revell and Dinnie note, and yet, "Most Scottish communities of place remain disconnected from decisions that affect them and from local land and resources, limiting their ability to self-organize and develop the fully rounded resilience necessary to proactively engage with rapid decarbonization" (2018: 223, 232). Regarding the climate emergency, the SNP has "a long term-focus on encouraging of community and renewable energy, linked to Scotland's aspirations of independence and rooted in rural community empowerment and land use reform" (Maatta, 2021: 4). The Community Empowerment (Scotland) Act (2015), for example, has sought to address power imbalances by promoting involvement in planning and the provision of public services, and giving community organizations new powers to acquire land and buildings. Moreover, community bodies will have the right to request to buy, lease, manage or use land and buildings belonging to local authorities, Scottish public bodies or Scottish Ministers. One of the SNP's showcase examples of such community empowerment is in the Helmsdale area, where the Scottish Land Fund facilitated the buyout in 2018 of the 3000-acre West Helmsdale Estate by the *Garbh Allt* Community Initiative, a locally managed registered charity that is committed to environmental sustainability (Scottish Government, 2019).

If communities are indeed to have more of a voice regarding how the subsurface is woven into a new energy landscape for Scotland, then the question arises as to how, moving forward, geoscientific knowledge concerning geothermal potential is to be produced, shared and even replicated in as inclusive a way as possible. The aim for Geology at this critical time is not simply for further - ideally low cost – research that can inform government and business decision-making, but for research that can enrol local communities at the 'sharp end' of both climate change impacts and the call to transition.

3. A Method and an Activity

Field geology as currently practised can be tracked back to developments in the 19th century, wherein the professionalisation of Geology (including the establishment of the male-only Geological Society in 1807), "spurred by Romanticism and muscular Christianity … celebrated 'doing geology on your feet' … fieldwork became a cult, an obsession" (Porter, 1978: 820). Fieldwork informed the hands-on description and analysis of specimens, their sequential order through time, and a uniform system of nomenclature, over and against grand theorising as to the shaping of the Earth. As Secord writes, "...the gentlemanly Fellows of the Geological Society of London claimed that their science should be centred, not on a cosmological theory, but rather on a method and an activity — Geological fieldwork, the tracing of rock strata over particular areas" (1986: 4). Accompanying this turn towards the field was the enrolment of Geology in state-building, imperialist expansion and classic geopolitical debate and practice. Abraham Gottlob Werner's (1791) mineral survey of Saxony ushered in a plethora of 'geognostic' assessments of mineral and fossil fuel reserves for the benefit of state mining operations, while geological maps combined a fascination for dramatic landscapes with the geographic extents of 'primitive' rocks such as granite that contained valuable mining materials (Trower, 2014). These maps, Stafford emphasises, were crucial to the authoritative role of Geology in scoping and explaining not only the formation of landscape features evident in the present, but also of past landscapes, buried but uncovered by the discerning work of the field geologist. “Mapping demanded the ability to visualise complex spatial relationships,” Stafford notes, “and to generalise, from widely scattered data, explanations for processes occurring over millions of years. As blueprints of its structure, Geological maps spread scientific order over the earth’s surface” (1984: 5).

The key field instrument of the 18th and 19th centuries that allowed outcrop samples to be chipped out, cleaved and smashed, if need be, was the geological hammer. An expert wielding of the hammer helped rock classification as well as the shaping of samples. According to Klemun (2011: 98), “in the course of a geologist’s life his tool, the hammer, gains personal significance … Every respected geologist in the 19th century possessed his own hammer, especially to meet his own requirements.” Magnetic compasses (which take bearings) and clinometers (which hinge on trigonometry to measure slope) - both technologies long associated with the military - aided the measurement and mapping of the strike and dip of bedding surfaces, as well as metamorphic foliation planes, and fracture/fault lines in prospective mining areas. Through the 20th century instrumental developments in the geological field have focused on combining various measuring functions into as portable and hardy a device as possible. Clar’s (1954) geological compass-clinometer for example, allows for the measurement of strike and dip in one step. The introduction of the lightweight, plastic compass-clinometer post-1960s provided a cheaper as well as more portable instrument.

Both the hammer and the compass-clinometer are hand-held. As extensions of the body, they become a part of the gnostic touch of a field geology concerned with locating, sorting, and classifying lithic materials amidst a landscape the broad sweep of which also provides clues as to the geological setting of these materials. This is an embodied knowledge-making that hinges on the hand and eye, but it is also one that “tends to objectify or separate the subject from his or her own body” (Dixon and Jones, 2015: 227) by framing these also as instruments that can be trained to perform repeated, replicable actions amidst an otherwise dynamic and singular field setting. What is more, “despite the presence of physical contact” such a touch establishes “‘distance’ between the one who touches and that which is touched” *(ibid*.). In Geology, this separation has been facilitated by the repeated coding of an active, knowing subject as masculinised, and their passive object of study, broadly categorised as ‘nature,’ as feminised. In his comments on the shared metaphysical concerns between geology and landscape art, for example, given as the 1890 Anniversary Address to the Edinburgh Society of Geological Society, Hugh Miller observed that, “Nature is greater than our knowledge of Nature, by whatever name we call it” – artists with their own specialist expertise as well as geologist will look “into her unfathomable eyes – all the more intense in their meaning, all the more alluring, and all the more fathomless to him whose knowledge is great” (1890: 367). Writing just over a hundred years later Dixon extolls the nature-taming capacities of the hard-bodied field geologist. They “should be physically fit, and be able to cope with outdoor conditions,” he advises. “Camping should be second nature. It would be useful to have several of the outdoor skills, such as rock-climbing and mountaineering, and to be able to handle a four-wheel-drive vehicle. It is also useful to know how to ride a horse. This all sounds as if the practical geologist should be a marine commando, or at the very least a boy scout” (1992: 42).

The arrival of smartphones (with Android software) and iPhones (with iOS loaded software) and installed geological mapping apps retains this emphasis on a hand-help device that can augment the assessing eye of the field geologist, but effectively redistributes decision-making as a form of agency. That is, compass programs rely on vector algebra generated by human labour elsewhere to compute plane and lineation orientations from data acquired by the magnetometer, gyroscope, and accelerometer sensors. The speed of this processing permits a much more rapid collection of bearing, strike and dip measurements; the accuracy of such sensed data does vary, however, particularly with regard to the strikes of planes (Novakova & Pavlis, 2019). Lost to immediate view is the labour that lies behind the development not only of generations of such apps and their dashboards but also the compensatory mechanisms built into the smartphone to offset its own strong magnetic field (which would upset the precision of measurements) - all of which is now enrolled in the making of a field geology.

This redistribution of decision-making is shuffled again with the deployment of Light Detection and Ranging (LiDAR), which Cawood et al. (2017) note has become the principal technique for acquiring data that can be used to generate virtual outcrops. This is a technique that is dependent on expensive instrumentation, as well as knowledge of data processing. Geological features are converted into 3D point cloud data from the air and on the ground. A mesh model of the outcrop can be generated through triangulation of the point data and matched with a high-resolution picture to generate a 3D digital outcrop model. While the triangulation and matching are done 'automatically' through programming – a phrasing of automated that again belies the human labour involved in programming - as yet no fully automatic interpretation and characterization tools for features such as fractures, and so the expert gaze of the geologist is called into play (Liang et al., 2022). Similarly, Unmanned [sic] Aerial Vehicle (UAVs) facilitated structure-from-motion (SfM) photogrammetry is heavily dependent on algorithmic processing. SfM is an optical remote sensing technique that estimates 3D surfaces from sequences of overlapping 2D images by identifying matching features in them and tracing their trajectories. This process is 'semi-automatic' in the sense that the actual data processing does not require decision-making by the user.

Though LiDAR and SfM data outputs were initially analysed back in the 'office' or 'lab' the development of high-spec portable devices has allowed for a return to the field, and a complex flow and translation of device-sensed data and the gnostic touch of the trained and experienced geologist. As Kehl et al. note, "The advent of handheld devices puts an arsenal of physical and local sensors, high-resolution cameras, powerful general and graphics processors, and touch-technology interfaces into the hands of geoscientists" (2022: 71). This handheld software brings the semi-automated processing power of software into the field, where the field geologist is envisioned as deploying it at their fingertips alongside their own reading of the landscape. The design of the touch interface and its dashboard is a core concern here, insofar as the field geologist is further imagined as able to readily select various data operations and outputs as tasks, all underpinned by the 'invisible' work of algorithms. "Fieldwork is a physically demanding activity," Kehl et al. remind us, "so the geologist is expected not to devote unconstrained attention constantly to the mobile device… the discussed app needs to facilitate a simple and intuitive interaction scheme to engage field experts in its utilization" (75). This 'intuition,' however, is of course constructed accumulated embodied knowledge and training in field mapping techniques.

The appeal of such apps and algorithms lies in a desire to replace what is often viewed as the "frustratingly qualitative and incomplete" work, as Glazner and Walker (2020: 1) put it, of human observation in field geology. Even experienced field geologists, they add, can produce different evaluations of lithic properties such as strength of fabric. Software that comes with the promise of "Quantitative and repeatable measurements" has been valorised as "the backbone of much of scientific inquiry [but] field geologists have few tools available for making them on many types of features" (*ibid*.). For some, LiDAR and SfM are thus "more accurate, efficient, and intelligent approaches" to fault mapping (Liang et al., 2022: 1), a phrasing that firmly situates expertise in the algorithmic capacities of these, while also reducing the corporealities of those engaged in field geology practice to a machinic instrumentality. Yet, when assessing the accuracy of both LiDAR and SfM facilitated outputs some have returned to the gnostic touch of the field geologist - augmented with a compass-clinometer – as providing a baseline for measurement. As Cawood et al. note in their own use of this 'control', "Experienced users ... are reckoned to achieve measurement accuracy within 1° of compass bearings and 2° on dip measurements" (2017: 69). The instrument – as a guided extension of the trained, instrumentalised hand and eye – becomes the guarantor of an overall methodology.

4. A Gnostic Encounter with Fractured Granites

These above two sections provide a context for our own in-the-field research practice, which centres on identifying and measuring various characteristics of rock structures found in granite, previously identified as of 'high heat producing' type, in the Helmsdale area of the Northern Highlands, Scotland (Figure 1).

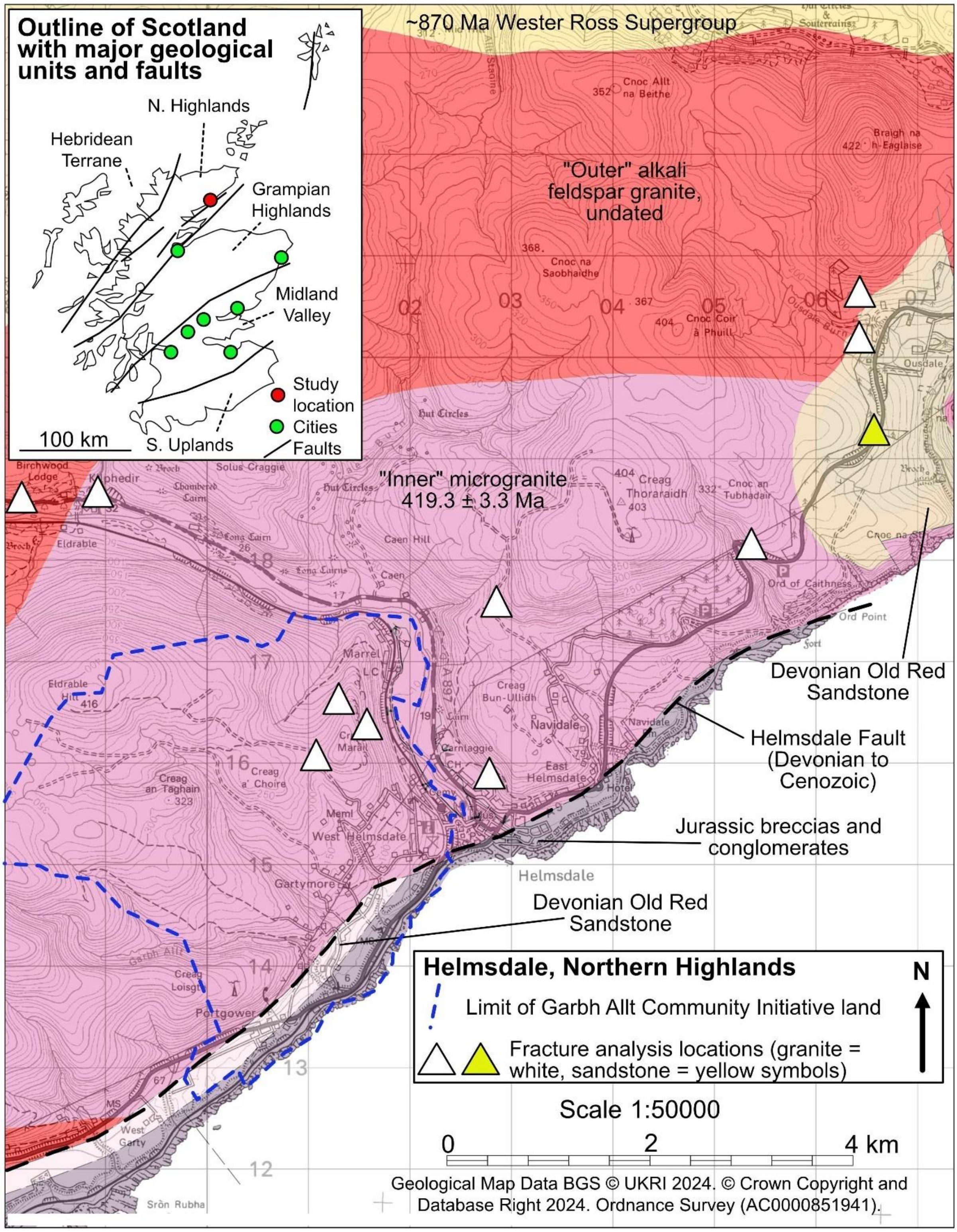

Figure 1. The geology of the Helmsdale area, modified from Geology Digimap (Geological Map Data BGS © UKRI 2022), and augmented with our fracture analysis locations (triangles) and the extent of land owned by the Garbh Allt Community Initiative (blue dashes).

During and immediately after the Scandian Orogeny (~437 – 415 Myr ago; Strachan et al., 2020), the Northern Highlands were intruded by magmas, which crystallised into veins, stocks, and plutons, the latter bodies with surface areas >100 km^2 each. Among these is the Helmsdale granite, emplaced at 419.3 ± 3.3 Ma (MacRae et al., 2023), comprising an 'outer', earlier, coarse-grained pink granite and an 'inner', finer-grained type; small outcrops of each can be found in the Helmsdale area (Figure 1). The radiogenic heat production of the granite exceeds $4\mu W/m^3$, a commonly cited threshold for sustaining geothermal energy potential (Scottish Government, 2013; Younger et al., 2016). The south-eastern margin of the granite is cut by the Helmsdale Fault, one of many NE-SW trending faults which are regarded as part of a "Great Glen fault network", initiated during the Scandian Orogeny and re-activated multiple times during tectonic activity since (Figure 1; Tamas et al., 2023). The location of the granite raises the prospect that the rocks have been fractured heavily as part of the wider Helmsdale Fault damage zone and might therefore have promising porosity and permeability at depth.

Helmsdale is a 'modern' settlement. It was planned - along with a new harbour - in 1814 by the 19th Countess of Sutherland (1765-1839) and her husband and factors to resettle communities that had been removed by agents of the Sutherland Estate from the surrounding river valleys amid the Highland Clearances. What had been open fields for arable farming and shared grazing were enclosed for the higher income of tenanted sheep farming. In a radical piece of social engineering that makes clear the power and resources leveraged by the Sutherland Estate, and the reach of an "Improvement mania" (Tindley and Haynes, 2014), the households displaced onto small crofts were expected to turn to fishing or kelp harvesting to supplement incomes, while paying annual feu-duties. Helmsdale did become a seasonal fishing port, July through September, hosting one of largest Atlantic herring fleets, with over 200 boats, in Europe by the mid-19th century. In 1919, and facing high land taxes following World War One, the 5th Duke of Sutherland (1888-1963) sold off 115,000 acres comprising the Estate of Helmsdale and Navidale (with grouse moor, modern village and harbour), the Estate of Loth and West Helmsdale, and five other 'sporting' estates running inland from Dornoch to Cambusmore, Rovie, Lairg and Shinness (National Records of Scotland, 1919).

In 2018 the area was to be heralded as an example of another radical transformation, this intended to combine community empowerment and resilience with a move towards environmental sustainability. A bid by the *Garbh Allt* Community Initiative to purchase 3000 acres of land (including the townships of West Helmsdale, Marrel, Portgower, and Gartymoret) from Sutherland Estates was achieved with a £273,025 grant from the Scottish Land Fund. According to the then Cabinet Secretary for Environment, Climate Change and Land Reform, Roseanna Cunningham, “This is a significant phase in the history of the area, and I am pleased that the Scottish Government can support the ambitions that this community has for their local area” (*The Northern Times*, 17 February, 2017).

Currently Helmsdale has a population of just under 800, mostly fitting into <1 km^2, with a primary school, a Heritage and Arts Centre, and council depot. The small settlements of West Helmsdale, Marrel, Gartymore and Portgower lie across the river, Old Helmsdale is to the north, and East Helmsdale and Navidale are less than a mile to the east. If geothermal is to play a role in the future of these communities, then it is the physical character and associated potentialities of rock that require investigation predicated on field geological practice.

Extant literature built from prior geological work indicates the age of the granites, their surficial distribution and shape, the different tectonic events that are likely to have faulted and fractured these since magmatic emplacement, and their heat production (British Geological Survey, 1998; MacRae et al., 2023; Pigeon and Aftalion, 1978; Scottish Government, 2013; Tamas et al., 2023; Tweedie, 1979). However, the granite’s *physical potential* for geothermal development cannot be realised without a range of additional datasets about its structure and heat flow potential. One dataset can come from knowledge of the faults and fractures evident in surface outcrops, as these are presumed to be reflective of those which will influence the subsurface passage of heat and fluids. This data gathering would represent a cost-effective prelude to more costly geophysical, modelling, or drilling-based approaches. Using a combination of lived experience of the local geology, Google Earth satellite imagery, published British Geological Survey maps and the Ordnance Survey Digimap Portal (https://digimap.edina.ac.uk), we identified locations of visibly exposed and accessible rock to build a list of potential field locations, as well as the driving and walking routes to these.

There is an extensive literature on the assessment of diverse characteristics of fracture sets in bedrock and we opted principally to follow data-gathering approaches set out by Andrews et al. (2019). Their ‘circular scanline’ methods "provide estimates of fracture attributes based on the number of fractures intersecting a circular scanline, *n*, and the number of fracture trace end points, *m*, within a circular window … The fracture density, intensity, and an estimate of mean trace length for the scanline can be calculated from the *n* and *m* values” (*ibid*.). This measurement does hinge on clearly exposed rock – a quality that was difficult to find in practice during our fieldwork in March (2024) because of vegetative cover and scree. At each of the areas noted in Figure 1. there was considerable debate as to which specific exposures would indeed provide a view of enough faulting to be helpful. In our project, radii ranged from ~1 to ~3 m. The actual radius does not need be replicated because it is the density of faulting that will be calculated. This emphasis on calculation does, however, require a particular density of fractures – observed initially in choice of site - to be present, in that to be statistically valid the number of fracture end points (*m*) should be 20-30 or more. In each area we looked for several exposures that would allow measurement (Figure 2.). In all, we took measurements at 11 sites, selecting between 2 and 4 circular scanlines at each site. This produced more than 1000 individual pieces of fracture data.

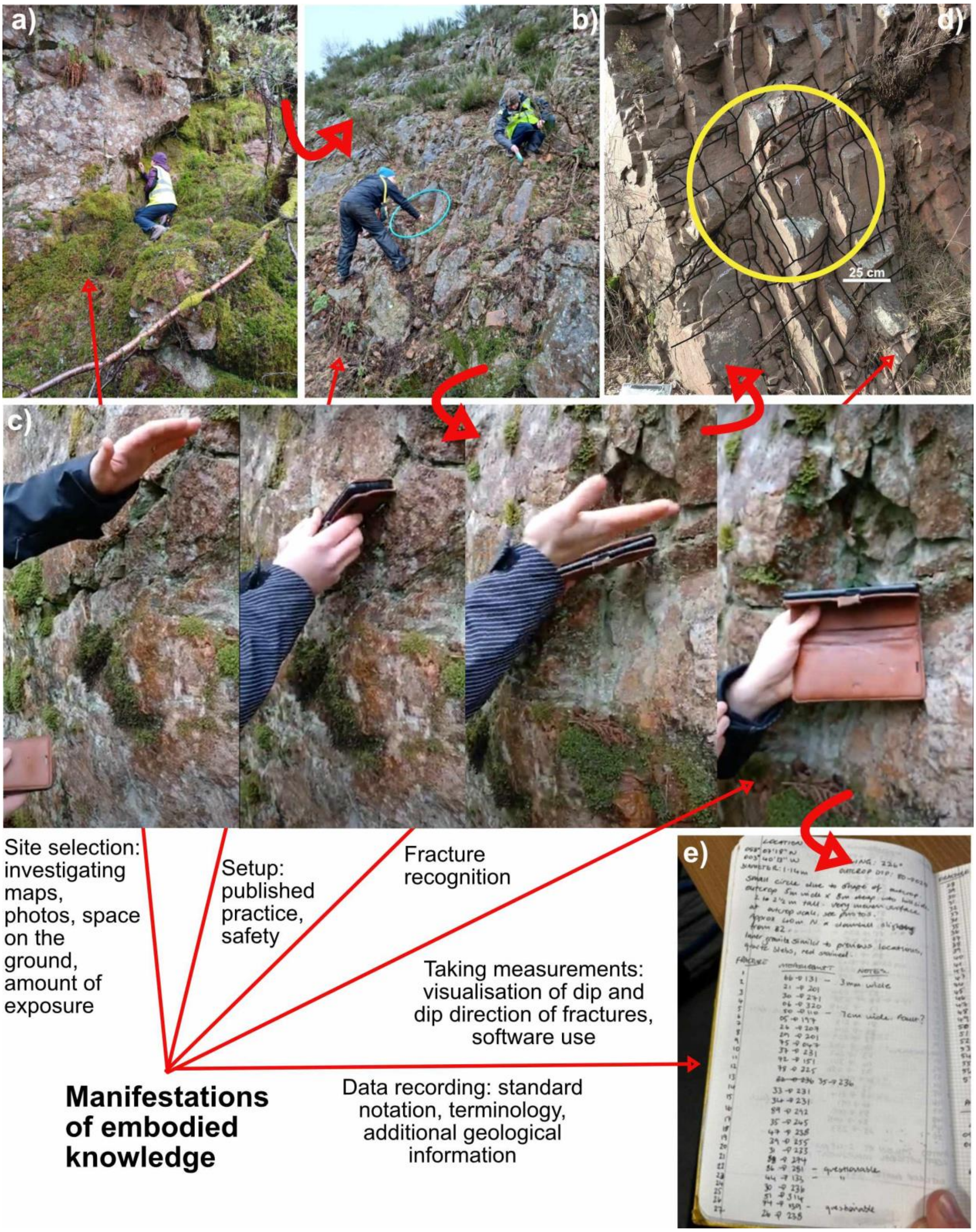

Figure 2. Field-based process of: a) site selection, b) preparation of the site for data collection, c) data collection using an Android smartphone, d) visualisation of post-fieldwork markup showing the anatomy of the fracture network measured, and e) recording of data and additional site information.

To produce measurements we chalked out circles, holding a given length of string in the chosen centre of our circle and moving the other end, tied to a chalk, through 360 degrees (Figure 2a, b). Each circle was photographed with a readily identifiable object for scale, allowing further elements of the fracture system, such as intersections between fracture planes, to be determined by visual inspection back in the office (Figure 2c). Aside from wading through boggy heathland and heather to reach exposures - sometimes across steep hill slopes - the chalking sometimes required scrambling or balancing on steep inclines, testing hand and foot holds (Figure 2b). After several of these chalkings in icy temperatures, with gloves off to allow the easier manipulation of string and chalk, fingers were cold, wet and sore; the growing numbness offset by a sharp ache, centring our attention on the fragile nature of dexterity. At times two people carefully balanced either side to pass the chalk back and forth and complete a full sweep.

Next, the orientation of each fracture that intersected the margin of the chalked circle was measured (Figure 2c), alongside the overall orientation of the circle area and its diameter. As Andrews et al. (2019) observe in their trial of fault identification among small groups of relatively inexperienced/experienced individuals, there are significant differences evident in who identified what as a fault. While they speculate as to the 'mental model' held by individuals regarding detailed observational styles, they do also note "practical and physical factors such as the quality of an operator's eyesight, whether or not it is easy for them to repeatedly crouch down to get a closer view and stand up to move around, spatial coordination that affects the ease with which they cover the scanline, and the time available to gather the data" (2019: 507), all of which foreground the collaboration of body, instrument and rock in the making of information.

Fracture and circle orientations were taken using the FieldMove Clino app on Android and iPhone smartphones (Figure 2c). FieldMove is primarily designed for digital mapping, where measurements are assigned to different properties and rock units and recorded on the app. In practice, it was quicker to use the software as a compass clinometer only, with one person taking measurements while another logged these in a notebook for later digitisation (Figure 2d). The alignment of the smartphone over and against the fracture is again a judgement call borne of experience. The hand holding the instrument orientates this back and forth in tiny movements, each responding to the work of the eye as it sights along the barely glimpsed plane of the fracture – a plane that plunges into rocky depths – until a determination of 'best fit' is made (Figure 2c). Button hit, the measurement was taken and called out. Amidst the reams of numbers, the recorder would occasionally ask for a repeat as the wind muffled a vocalisation. The hand was ungloved to allow both the fine-tuning of the clinometer and the use of pen for some and pencils for others (Figure 2d).

Basic characteristics of each fracture, such as the open-ness of the fractures, whether they contained any mineralisation (none did), and whether we suspected them to be natural or anthropogenic (from quarry blasting or road cutting), were also recorded. Not every reading characterised a fracture, with some planar breaks in the rock representing cms-wide 'crush zones', manifesting what are incipient faults. A few of the breaks in the rock showed slickenlines, groove marks indicative of fault movement.

Back in the office, the measurements were digitised (Figure 3a). For each circle, the measurements were translated into a stereonet that foregrounds the general trend of faulting dip and slope at that site (Figure 3b). These trends allow a block diagram to be drawn (Figure 3c) that again shows the general trend of faulting, but situates this in a visual that is legible to a more inclusive audience.

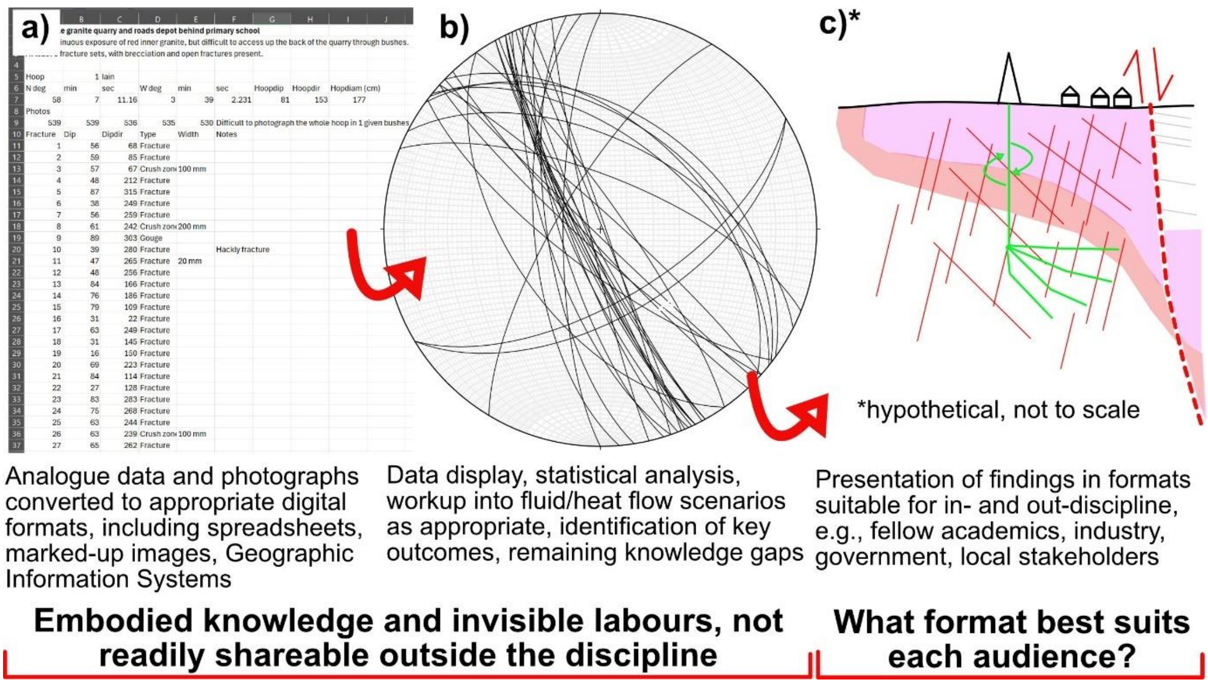

Figure 3. Post-field process of: a) data translation into digital format, b) visualisation of fracture planes in the form of stereographic projections, c) design of a more inclusive visual.

In drawing on Andrews et al.'s (2019) methodology for circular scanning we explicitly aimed for *reproducibility* as understood in a strict scientific sense. That ids, the designing of a set of experimental protocols that can be understood and repeated to varying degrees by field geologists at the same or similar sites, (acknowledging that variations can be identified and their impact thus assessed) such that the same kind of sample data might be reproduced and hence evaluated as a representative part of a population. Here, the differing senser capacities of the android and older iOS-loaded phones, as well as the different ways in which the sensitive instrumentality of devices interacts with the environment, become factors to control for. But also, there is an acknowledged bias in determining the sample site and the identification of phenomena such as faults. One response to such bias is to try and ascertain its extent – the degrees of uncertainty within the methodology – so that results can be offered with this qualification in mind; and this speculative process is mapped out in Andrews et al. (2019).

Eschewing such forays into explaining and controlling for what inevitably is described as singular research practice another response is to understand reproducibility in a more expanded sense. That is, to consider who is able to bring the same resources, capacities and specialities to bear in their research? Are there aspects of our own process, for example, that might be shared with interested community members in and around Helmsdale? This is an aspect we pondered in the field, scrutinising the embodied expertise that shaped the choice of locations and the taking of measurements. Might community engagement be deepened by inviting participants to try out some of our methods, facilitating discussions on the science behind potential geothermal energy systems? Each stage depicted in Figure 2. - site selection, setup, data generation and logging - manifests embodied knowledge derived from past training in the principles of geological enquiry, and lived experiences during the careers of the participants. However, might some of the practices involved - identifying a clean site, chalking out a circle, identifying planes, using a smartphone to measure their orientation, and writing the readings down in a notebook – be shared with diverse community members who might then undertake their own practice? Might the findings from our own research be shared in such a way that this work resonates with how diverse community members engage with local geologies? Reproducibility here might be reconfigured as the reiteration of aims and ambitions rather than protocols, such that a shared valuing of a line of inquiry – for example, the potential for geothermal energy as part of a just as well as green transition - emerges.

In similar vein, *shareability per se* might be understood in constrained terms as the production of data that can be apprehended in terms of its origins, character and significance in the same way each time it is encountered. Key to such a shareability is learning and adhering to 'discipline agreed' forms of data tabulation and visualisation – such as the stereonet – as well as the ways in which different modes of instrumentation - from field book to app – actualise these. These are all evident in Figure 3. Shareability might also be understood, however, as the enrolment of diverse audiences such that each gleans something meaningful - and on their terms - from the process. How might data be translated in an inclusive manner, such that its wide-ranging significance for community futures might be realised? What new kinds of 'outreach' should universities support and offer, addressing a range of diversely motivated audiences? To be sure, the stages of data digitisation, display, and modelling (Figure 3.), seem less 'shareable' in that they are reflective of particular embodied knowledges in concert with a series of 'hidden labours' that animate soft and hardware. The software involved, the training necessary for their effective use, the geological backgrounds and learned skills necessary to make meaningful interpretations of data generated, seem abstracted from a wider audience. Nevertheless, the application of 'citizen science' in many other fields – from the contributory collection practices of bird or butterfly identification drives to the more participatory work of embedding vernacular knowledges of the environment into risk assessments – provides considerable resource as to how a more collaborative relationship might well be fostered.

5. Broader Implications for a 'Critical Geology'

Moving forward the Net Zero transition envisioned by the Scottish government comprises the growth of onshore and offshore wind energy, the development of new hydro-electricity schemes, offshore carbon storage, and planning for more interconnectors and transmission lines. For Northern Scotland this means that the region is intended to be mass exporter of electricity (SSEN, 2023). Though by no means a wholesale answer to Scotland's geoenergy futures, geothermal energy might be attractive in specific circumstances, both urban and rural. Geothermal energy production has modest surface impact, and is near-to-zero carbon. Such opportunities, however, are shaped by the rocky subsurface as much as economic, political and social imperatives and ambitions. Are the granites and the communities near them amenable to such efforts?

In asking this question we firmly situate Geology – as a field of expertise concerned with lithic materialities and capacities – within debates on Scotland's planning for a whole social transformation of energy sources and supplies. This role extends beyond the issue of geothermal potential, encompassing, as Gardiner et al. (2023) emphasise, the identification and subsurface mapping of raw materials for low carbon energy technologies, and the geological capture of carbon in various forms. Though our own project takes geothermal potential as its substantive concern, we take the opportunity in this last section to articulate concerns and hopes on what a 'critical Geology' might be that also extend into these areas, drawing on our reflections and practices around methodology as outlined above.

Looking across the history, current situation, and future of the discipline as it is taught and undertaken in universities - a crucial incubator for innovation as well as tradition - we would urge a 'critical Geology for critical times' that works to understand how the authoritative voice of Geology is situated amid power relations that give meaning and value to geological materials and capacities. Drawing on the burgeoning field of geoethics in the geosciences, there is considerable potential for collaborative work with academics working in political geology, critical physical geography, and the geohumanities. What these collectively foreground is a consideration of how access to lithic materials is granted (and who is marginalised from this); how research into these is undertaken such that the authoritative voice of some is recognised, and with what consequence; and the intended impact of the research on individual and collective capacities for action. Inspired by manifestos for change produced across academia, we would urge:

A. Making Geology More Inclusive

In geological communities, marginalising practices such as ableism, sexism, racism, and classism are increasingly being called out, even as political efforts in some quarters seek to underplay them. We should commit to careful consideration of how 'the field' is understood and engaged with, so that diverse bodies, ideas and approaches can be valued. This shift requires practical change on various levels.

We need to break away from a language of 'accommodating' difference, which reiterates an idealised geologist subject, towards a celebration of diverse capacities and curiosities. At university level, this shift requires 'whole person' evaluations regarding applications and funding, rather than a metric valuing of a tiered system of 'world class' institutions. 'Soft skills' should be reflected in a portfolio of assessment modes that allow diverse strengths, abilities, and capacities to be valued, as well as ethical training that situates academia amid socio-environmental problematics.

In schools, Geology remains at best, backgrounded, at worst, absent. Moreover, it is frequently fee-paying schools, with flexible curriculum delivery and time for external engagement, which have the best opportunities to engage. Access to fieldwork and class activities that allow substantive practical training and deeper levels of engagement are critical to the 'whole society' transition our climate emergency demands. And, the range of future employment opportunities involving a 'critical geology' needs to be shown to be far broader than is presently perceived by pupils (Rogers et al., 2024).Government has a key role to play in ensuring the elevation of geological science as an integral and equal component within STEM (Science, Technology, Engineering, and Mathematics) discourse. In the process, Geologists can work more consistently with schoolteachers and pupils to generate an awareness of past, present, and, crucially, future working with lithic materials and capacities. But, such efforts require university support.

B. Fostering 'Slow' Action in Universities

Universities, as progressive, secure, and diverse workplaces, are part and parcel of a society in transition, and can establish longer-term research and development strategies. Countering the growing tendency to invest in and fetishise large, mono-vision projects, a research ecology in research institutions should include diversely scaled projects that enable a myriad of approaches, practices, and collaborations.

Regarding funding this means opening up 'interdisciplinarity' beyond a teamwork model or apparently unifying concepts (such as 'systems'); establishing a promotions process that situates large grants, and outlets via a capitalist publishing system, amidst multiple possible trajectories; and recognising and mitigating the constraints placed upon fixed term service and teaching roles. Efforts to build sustainable cultures of responsibility, respect and trust between universities and communities can encompass balancing ethical divestment from fossil fuels with investment in renewable energy portfolios *alongside* an investment in transition-focused research, teaching, and associated facilities. In addition to a 'blue skies' and cutting-edge research, disciplines should be valued for a 'slow,' civic-minded commitment that responds to challenges facing communities and the gradual build-up of relations of trust and accountability that spans generations.

Within departments and professional societies the place and role of the 'hard' sciences can be revised by shifts towards the valuing of these subjects as a means of social change. In practice this can include favouring meaningful and ongoing debate as to the actual work in the world that research and teaching undertakes, as well as the welcoming into Geology and other subjects of 'soft' disciplines that help foster critical thinking, a sense of social responsibility, and an historical and geographical awareness of the background to geological knowledge, with a view to shaping its potential to help make the world better.

C. Engaging Deeply with Communities

In Geological communities, outreach has long been valued, despite proliferating expectations upon staff. Committing to ensuring meaningful outreach, so that Geology becomes a more effective agent of change for a just and green transition, requires that Geologists advocate for inclusion through provision of better outdoor access and engagement between school pupils and university; and, an awareness of how research can connect with people already marginalised through various structures. Geologists have much to gain from a critical approach to the idea of 'community' itself, and how the term can be used to obscure power relations that marginalise and exclude.

Impact is increasingly evident but can be narrowly defined or underplayed. It is important to frame impact as including looking for and facilitating 'windows of opportunity' where community-engaged research can shape local, regional, and national policy. This can comprise a shift away from the aggregated, metric, and territorialised language of ‘targets’ and towards the cultivation of practices that reshape localised as well as regional/national-scale power relations; and, the recognition that change is empowered by collectives and allegiances between and betwixt community organisations, unions, and NGOs as well as the formal world of council/parliamentary entities.

Site matters to Geology as an investigative science. But, *place* also matters to communities in terms of a sense of past, present belonging, and hope for the future. The ‘best place’ for research can also encompass work sited where large-scale infrastructural planning can be realised. What is more, the expertise of university researchers can be situated amidst local, vernacular, and Indigenous Knowledges of rock. The university-led professionalisation of geological collectives can be reanimated as a community-facing initiative that recognises a range of (sometimes aligned, sometimes antimonious) knowledges, and modes of knowing, and that explicitly facilitates the decolonisation of the geosciences.

Acknowledgements

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