Master of Teaching (MTeach)

Institute of Education, University of London

Practice Based Enquiry (PBE) Report

Constructing the Hawaiian chain: a task for tentative science

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Month and Year of Submission: September 2009

Word count: 10,687

Abstract

Widespread demands that students understand the tentative nature of science are stymied by the paucity of successful teaching strategies. This report advocates using frontier theories from geology to develop students' understanding of tentative science, and details the trialing of an activity about mantle plume theory with four pairs of Key Stage 3 students. Results indicate that students have few difficulties with accessing and understanding the geological ideas involved, applying their knowledge of plate tectonics successfully to reason with theory and evidence. Their context-based reasoning shows advanced epistemological practice, including inferential links between theory and evidence, the limitations of data sources, and using the same data source to support different stances. There is some evidence that the activity develops students' formal epistemologies about the uncertainty of theories in the short-term, although their epistemological practice demonstrates key differences from that of scientists. The results are used to suggest modifications to the resources and ways for teachers to facilitate the activity.

Acknowledgements

This report has benefited greatly from the support I have received in my research. I would particularly like to thank Caroline Daly for her advice and patience, Shirley Simon for offering me an unparalleled apprenticeship as a researcher, Catharine Parkes for teaching me how to trial resources, Anselm Aston for his geological guidance and a hundred helpful discussions, Deirdre Ruane for administrative assistance, Vicky Chapman and Helen Murtagh for their generosity in inviting me into their classrooms, and all the students who eagerly shared their thoughts with me.

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Introduction: Tasks for tentative science

Scientists, science educators (Osborne et al, 2003; Gauch, 2009), and the secondary science curriculum (QCA, 2007) all demand that students should understand that scientific theories are tentative and subject to change. However, the curriculum content undermines this intention. Scientific theories in the curriculum are the core theories of mature sciences, accepted by the scientific community and the basis for empirical observations[1] and research programmes. These theories are therefore protected from doubt (Duschl, 1990) and are generally treated as non-tentative for pragmatic purposes (Osborne et al, 2003). More controversial theories within the curriculum are often controversial for non-scientific reasons, such as evolution (Hildebrand et al, 2008), or reflect politicised or worldview commitments which are particularly resistant to change (Good and Shymansky, 2001; Johnston and Southerland, 2001), such as global warming. These theories are unlikely to engender an understanding of tentativeness within science itself, particularly since understanding these controversies requires an understanding of ethics, economics, politics and law as well as science (Albe, 2008) and many approaches to teaching controversy are either too abstract or epistemologically naïve (Hildebrand et al, 2008).

Other approaches to teaching the tentative nature of science are inadequate. Engaging in inquiry is insufficient for students to develop their nature of science (NoS) understanding (Sandoval, 2005). Teaching the history of science has been

[1] For example, to show that the volume of a liquid is a function of temperature, students will typically use a glass thermometer. However, a thermometer is itself constructed on the assumption that the volume of liquid is a function of temperature, as it uses the height of a column of alcohol as a proxy for temperature.

championed as a way of accessing NoS (eg Monk and Osborne, 1997; Thompson et al, 2000), but these approaches may give the impression that historical ideas are tentative while modern science is certain (Johnston and Southerland, 2001) and make students more likely to demand a final certain answer (Dolphin, 2009). Adapted primary literature which brings contemporary science into classrooms offers hope through acquainting students with argument and uncertainty in research reports (Phillips and Norris, 2009), but suffers practically because the tentative 'cutting-edge' of mature sciences (Hermann, 2008) are highly complex and inaccessible to students (Osborne, 2009). Further, adapting the literature for the classroom reduces the argumentative element of the paper and so masks its tentative nature (Osborne, 2009).

The current paucity of teaching approaches can reduce tentative science to a declarative statement that 'science can change' which students endorse without understanding (Havdala and Ashkenazi, 2007). This makes a mockery of curriculum intentions to educate scientifically literate citizens (QCA, 2007) who understand that the tentative and highly interrogated knowledge products of science are the source of its reliability (Johnston and Southerland, 2001). A more fruitful approach than those above would be to find current frontier theories in science, controversial within scientific communities but not beyond them, that are nonetheless accessible to students. These represent genuinely tentative forms of science, about which students are unlikely to have pre-existing commitments. Initial reading suggested that geology might include some accessible controversies, and further exploration revealed that the mantle plume theory for the formation of Hawaii was both controversial (Jordan,

2007) and accessible to KS3 students. I therefore developed a task in which students explore theories and evidence for the formation of the Hawaiian island chain.

My research will help me to develop a new series of tasks for teaching the tentative nature of scientific knowledge, based around frontier theories in science. My training in history and philosophy of science makes me well-placed to develop tasks around NoS, in contrast to many science teachers who have limited understanding of NoS (Abd-El-Khalick and Lederman, 2000). The first task examines explanations for the formation of Hawaii. Ultimately, I will use these tasks with KS3 students in my own teaching; with beginning teachers to exemplify NoS tasks and enhance their NoS understanding; and as a shared resource with other teachers. The constraints of classroom practice have therefore influenced the tasks, which are designed to be used within a single lesson.

This report focuses on the Hawaii task, which was trialled with four pairs of KS3 students in a highly successful girls' school in East London. This school is already engaged in a project on argumentation, which means that students have prior experience of working with theory and evidence. Science teachers there have recently identified students' understanding of the nature of science as an important target, though there has been minimal explicit teaching of NoS so far. The student pairs were from the upper band, and working at level 6/7 in science.

I investigated

- [RQ1] how students access the geological concepts, including misconceptions
- [RQ2] how students reason with different aspects of theory and evidence
- [RQ3] students' epistemologies of science in the task context

in order to

- [RQ4] improve the task and suggest ways for teachers to facilitate students' engagement with the task, prior to use with whole classes.

Literature review

Since the Hawaii activity is a newly-designed task, and students' conceptions of plume theory have not been studied, there is no direct evidence on how students will reason in this context. However, previous research on plume theory itself, as well as students' prior content knowledge, their coordination of theory and evidence, and their understanding of science as tentative, will provide relevant insights to frame my research.

Mantle plume theory

Mantle plume theory is a frontier theory within earth sciences which explains the existence of intra-plate or 'hot-spot' volcanoes. The Hawaiian islands are a chain of intra-plate volcanoes which are often explained using this theory. Mantle plume theory hypothesises a laterally-fixed hot plume of material rising from deep within the mantle and forming a volcano when it reaches the surface. A plate moves across this fixed plume, yielding over time a linear chain of volcanoes.

However, mantle plume theory is disputed within the earth sciences community because it lacks an accepted physical basis, and has been constantly qualified, amended and adapted to accommodate anomalous evidence to the point where it has been denigrated as 'zombie science' (Anderson and Natland, 2005). Appendix 1 lists some major predictions of plume theory and how available evidence relates to these predictions. This provides a baseline for comparing students' coordination of theory and evidence with that of scientists.

Students' understanding of plate tectonics

Despite the limited earth science in the KS3 science curriculum, Year 9 students show equally good performance in earth science compared with other sciences in international tests (Sturman, 2009). This may be because the non-statutory schemes of work for KS3 Geography feature earth science, including two units on volcanoes, the theory of plate tectonics and Earth's interior structure (QCA, 2000).

However, secondary science textbooks are riddled with geological errors (King, 2009) so students are likely to inherit some misconceptions from teaching resources. Furthermore, students' understanding of plate tectonics and related phenomena is often based on media reports of natural disasters (Marques and Thompson, 1997) which may contain simplified or distorted science.

Both studies above identified misconceptions perpetuated in teaching resources (King, 2009) or stated by students (Marques and Thompson, 1997) which are relevant for the Hawaiian task:

1) The mantle is a liquid, semi-liquid or semi-solid: these students may think that a plume could flow easily upwards from the core.

2) Vertical forces push up the bottom of the oceans to form continents: these students may believe that Hawaii could be formed by uplift within the Earth.

3) Plates rotate on an axis around a central or peripheral point: this misconception would undermine the linear pattern of volcanoes implied by linear movement of a plate across a fixed mantle plume.

Knowledge of these potential misconceptions will help me to identify them in my research. I also expect my research to identify misconceptions which relate directly to plume theory or the formation of Hawaii.

Students' coordination of theory and evidence

The coordination of theory and evidence is a key part of skilled scientific reasoning (Kuhn et al, 2008). Unfortunately, the dialectic relationship between theory and evidence (Sandoval, 2005) is rarely understood by secondary students, who do not grasp the ontological difference between observed data and entities used to explain that data (Leach et al, 2003). This important distinction is complicated by

- the entanglement of theory and data: for example, through confirmation bias (Chinn and Brewer, 1993), and the theory-laden nature of observation (Feyerabend, 1981)
- lack of consensus on the relationship of theory and evidence (Osborne et al, 2003; Good and Shymansky, 2001)
- the gap between science's philosophy and its historical practice (Kuhn, 1996).

Secondary students' coordination of theory and evidence can be classified interpretively in three categories (Driver et al, 1996). Phenomenon-based reasoning shows no distinction between theory and evidence, as noted by Leach et al (2003). Relation-based reasoning suggests that explanations fall neatly out of experimental results, and amount to empirical laws (related to inductive reasoning). Model-based reasoning acknowledges that theory is always underdetermined by data (related to abductive reasoning).

At a more descriptive level, students' coordination of theory and evidence can be typified by Toulmin's (1958) argumentation pattern, which relates a piece of data to a claim through one or more warrants, backings to these warrants, and qualifications. This scheme has been widely applied in science education research (see Erduran et al, 2004, for a fuller account). Due to the limited data available in this study, I will focus on analysis at this descriptive level, although some tentative interpretation may also be possible.

Secondary students' use of evidence in socio-scientific reasoning seems to be more sophisticated than in scientific reasoning. For example, most secondary students can distinguish a range of more and less tentative claims, differentiating between established conclusions and uncertain claims (Ratcliffe, 1999). When asked to explain why scientists had formed different theories about global warming, students identified differences in data, analysis, personal beliefs and research focus as potential reasons for the difference in theories (Sadler et al, 2004), revealing a multi-layered understanding of how theories are formed.

Students' conceptions of science as tentative

The coordination of theory and evidence is also related to students' epistemologies, which include ideas about how to use reasoning and evidence, as well as the tentative or certain nature of knowledge. The nature of students' epistemological beliefs is hotly contested, with dispute over whether these beliefs are entirely domain-general

(Kuhn, 1991) or have domain-specific elements (Buehl and Alexander, 2005), whether they correspond to formal philosophical viewpoints (Lederman et al, 2002) and whether they form a coherent framework or are fragmented (Lederman et al, 2002). Some question whether students have rigid internalised beliefs about epistemology, or whether they simply adopt more fluid epistemological stances (Hammer and Elby, 2002) or enact epistemological moves within situated practices (Lider et al, 2005). This last question reflects a broader debate about whether learning should be framed as conceptual change internal to the learner (eg Driver, 1990) or the development of strategy use in a situated social practice (eg Caravita & Hallden, 1994). These debates also have implications for methodological decisions, which I discuss later in this report.

The disputed nature of students' epistemology has not prevented a wealth of research describing them. Studies of primary students' epistemology show that students believe that science knowledge has changed over time, but do not understand the central role of inferential explanation (Conley et al, 2004; Elder, 2002), which is the key to its science's tentative nature. This mismatch between a sophisticated conclusion (science changes) and naive reasoning is common, as questionnaire studies in particular are wont to overestimate students' epistemological sophistication (Sandoval, 2005). For example, some studies assume that an agreement that 'science changes' reflects a coherent set of philosophical beliefs which has been pre-determined by the researcher (Johnston and Southerland, 2001). As more qualitative investigations have shown, learners who agree that 'science changes' give a variety of reasons for why science is tentative, including some fundamental misconceptions. For example, they may believe that science is tentative because of errors which will be corrected, that past science is tentative but present science is correct, or that science is tentative when it conflicts with worldviews such as religious beliefs (Johnston and Southerland, 2001). Can these beliefs be considered more sophisticated than a naive empiricism in which scientific knowledge is certain and unchanging? As not all science is considered equally tentative (Osborne et al, 2003), an un-nuanced belief that science is tentative may be undesirable (Hammer and Elby, 2002) and even imply a relativist philosophy for science (Good and Shymansky, 2001). Therefore we must go beyond teaching students that science is tentative, to helping them understand the reasons for its tentativeness. Kuhn et al (2008) point towards evaluativism as the holy grail: understanding that knowledge claims are tentative and worth contesting (unlike absolutism), but can be evaluated as better or worse than other knowledge claims (unlike multiplism).

How can we help students to reach evaluativism? Interventions to improve students' NoS understanding suggest that an extended intervention with explicit reflection on NoS is needed for stable changes in understanding. After a one lesson teaching intervention, there was some improvement in KS5 students' understanding of the relationship between models and evidence, but students' new ideas remained hesitant and unstable compared with previous ideas, and some students did not progress at all (Leach et al, 2003). After a three-month intervention, KS3 students showed some progress in understanding the tentative nature of science. For example, they moved away from suggesting that scientists could only be certain about events they had seen to understanding how scientists make inferences about historical events. Again, these new conceptions proved insecure when probed via interviews (Khishfe, 2008). A single activity is unlikely to embed stable changes in epistemology, so I will focus on describing any new epistemological statements which emerge during or after the activity, rather than probing their stability. Once a range of activities have been developed, I will be able to assess their cumulative effect on students' understanding of tentative science.

Methodology

My work here is located firmly within action research: practical, change-focused, cyclical and participatory (Denscombe, 2003). *Practicality* and *change-focus* encapsulate both the process and outcomes of the research: engaging students in learning to see how their ideas change, in order to change the instructional design and develop my classroom practice. This report focuses on one *cycle* of action research, in which the activity is trialled with student pairs and modified before classroom trials. The work is *participatory* because I draw on my professional roles as a science expert, a teacher and a researcher to respond to students' unanticipated questions or ideas during data collection (Steffe and Thompson, 2000), to support and probe their learning and to make meaning from the resulting data:

> "it is only because she knows how to do her job as a practitioner that she is in a position to pursue her questions as researcher" (Duckworth, 1996)

This conflation of roles can cause difficulties when the roles of teacher and researcher are in conflict (Lesh and Kelly, 2000). For example, where a teacher may give directive feedback about learners' misconceptions, a researcher might avoid it to encourage students' exploration and elucidation of those ideas.

Strategically, inductive research (Blaikie, 2007) is most appropriate for my research as I am exploring a new area and will seek generalisations in order to inform my future practice and generate predictions for further trials. To ensure that I collect rich data for forming generalisations, I have chosen a case study approach, examining how the Hawaii task encourages reasoning in practice from several theoretical perspectives and with different student pairs (Denscombe, 2003). Unfortunately, my research strategy and approach is limited by the problem of induction (Hume, 1748) in extrapolating both from specific students to other students and from one NoS activity to the other activities I am designing. The labour-intensive nature of data collection and analysis with each pair reduces my sample size.

Structurally, my research forms one cycle of a teaching experiment, which integrates both research and development to gain insights into teaching and learning (Lesh and Kelly, 2000). I based my development cycle on test development (Clausen-May, 2001) and instructional design cycles (Battista and Clements, 2000), which recommend exploratory teaching or discussion with small numbers of students before large-scale trialling. These 'informal trials' allow the researcher to

- [Research Questions 1-3] develop or enhance a model of students' knowledge and learning within the domain (Battista and Clements, 2000);
- [RQ1-4] investigate different components of the activity and the activity as a whole (Battista and Clements, 2000);
- [RQ1-4] gain a reflexive account of students' engagement with the task and any difficulties encountered (Lesh and Kelly, 2000; Clausen-May, 2001); and
- [RQ1,4] identify flaws within the activity (Clausen-May, 2001).

Methods of data collection and analysis

Description of data collection

I collected data by engaging pairs of students in a tutorial on the Hawaii activity, lasting 40 minutes, in order to analyse students' ideas and reasoning within this context [RQ1-3]. Each tutorial was supplemented by a five-minute pair interview on theory and evidence [RQ3] which was undertaken twice during the tutorial, to compare answers before and after engaging with the evidence. A five-minute post-activity interview about the activity gathered data about students' self-reports on engagement with the evidence (to compare with their reasoning) and their evaluations of the task [RQ1, RQ4]. Appendix 2 contains a full data collection schedule, and my research design is summarised in the table below and discussed further below.

Research feature	Description
Structural design	Theory and evidence activity, bracketed by a pre- and post-task epistemological interview and a task self-report and evaluation.
Sampling	4 pairs of students, chosen by purposive sampling
Elements of triangulation	• across four student pairs for each evidence source • between exhibited reasoning and self-reported engagement for individual pieces of evidence • between formal and practical epistemologies [RQ3] for

	each pair
Reliability	Reliability is ensured by the multiple perspectives explored through triangulation and by using 4 different pairs of students and multiple pieces of evidence within the activity.
Generalisation	Generalisation is threatened by the purposive sampling approach and the small sample size, but will be aided by the further research planned to test emerging patterns from this research. A 'fuzzy' generalisation (Bassey, 1998) will be made from the ideas generated by eight students.

Locating and justifying the data collection methods

The tutorial was somewhere between an interview and a lesson. There was more direct questioning of the student pair than in a lesson, in order to collect specific data and probe students' ideas. However, students were encouraged to talk with each other, and carried out practical activities with minimal supervision. I hoped to find a middle ground between the rich naturalistic data of observations and the more specific data collected via interviews (Denscombe, 2003). This compromise means that I will gather more comprehensive data about learners' ideas than with a non-intervention method, but introduces some artificiality to the learning situation which makes it less comparable with classroom practice. Another viable compromise would be to record students working independently with the activity and then interview students to probe their decision-making. I decided against this because it was important to be able to clarify and explain during the activity, to see how students responded. Furthermore, the resource is intended for classroom use, so the role of the teacher during this activity is a vital element.

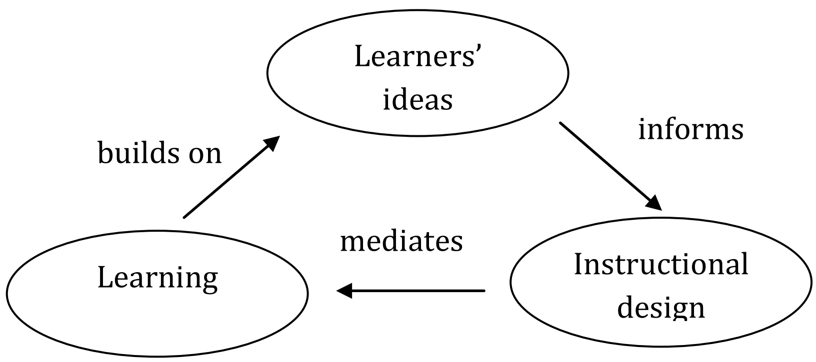
Methodological issues

There are four main methodological issues which affect data collection and analysis in this activity:

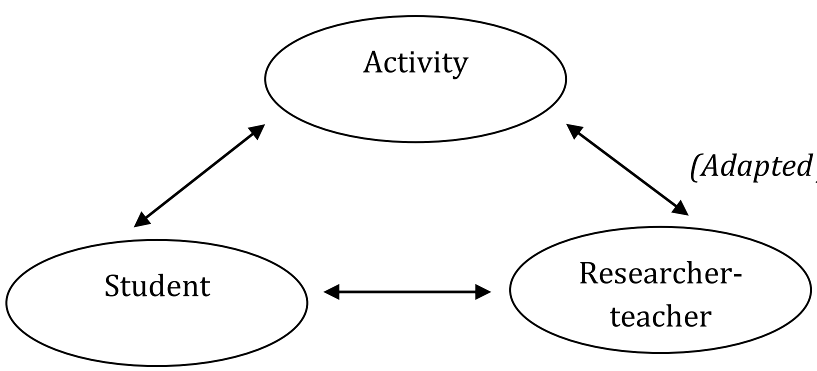
- the complex interactions involved in teaching experiments
- methodological difficulties in investigating epistemology
- the lack of a theoretical framework in task design
- critiques of novice-expert comparisons

Further, the limitations of clinical interviews aimed at exploring learners' ideas are relevant to this research. If students' speech is taken at face value, it is difficult to distinguish a students' genuine reasoning and convictions from researcher suggestion and idle speculation (Piaget, 1967). Some clinical interviews also isolate a learner from the normal contexts of their thinking, and so may not adequately reflect situated problem-solving (Treagust, 1998). I tried to mitigate this difficulty by presenting the work in the context of a classroom activity, but I cannot be sure if this was close enough to typical science lessons to comprise a normal context for the students.

The attempted 'normality' of the context causes its own complexities. Within models of teaching experiments and teaching as research, learners' ideas, learning and instructional design are co-dependent (Duckworth, 1996; Lesh and Kelly, 2000; Battista and Clements, 2000) and therefore the research yields an entangled mixture of information about instructional design, the nature of learners' ideas, and the nature of learning within the context, which cannot clearly be divorced from one another.



Further, the teaching situation comprises complex interactions between the students, the activity and the researcher-teacher (Lesh & Kelly, 2000). This limits the use of analysis which focuses on any factor in isolation. The basic unit for the analysis is the student pair, but my analysis must consider how the pair is influenced by the task and the researcher-teacher.



(Adapted from Lesh & Kelly, 2000)

Further issues emerge from investigating students' epistemology. As discussed in the literature review, qualitative exploration is essential for providing a descriptive account of epistemological beliefs or practices, and to avoid inferring pre-defined or coherent philosophical positions from statements or decisions. Therefore my coding of the transcripts for epistemological ideas is primarily inductive and descriptive. I hope that my focus on describing beliefs-in-action will help build "a rich catalogue of observed conceptions, not presumptions about what people think about a science that they do not know" (Sandoval, 2005). My interview questions avoid probing the stability of different ideas, as I do not expect to find stable change after a single activity. The interview's purpose is to describe any new epistemological ideas which emerge after the activity.

It is also important to distinguish between students' formal epistemologies and practical epistemologies. Formal epistemologies are students' ideas about professional science and scientists, while practical epistemologies are students' ideas and practices as they engage in science themselves (Sandoval, 2005). Therefore my research design triangulates these two dimensions by considering students' practical epistemologies as they coordinate theory and evidence within the task, and probing their formal epistemologies *in the same scientific context* through the pre- and post-activity interviews.

My task design for the activity itself, and therefore my research, is hampered by a lack of theoretical underpinning, as 'research into the nuances of task design is in its infancy' (Howe and Mercer, 2007) and research methods into task development are only now emerging (Kelly, 2004). However, drawing on a model for the analysis of argumentation activities which I helped develop (Simon and Richardson, 2009), my analysis considers how the argumentation framework, the relevant science, the teaching resource and the teacher's enactment can best be developed and aligned.

Finally, there is some doubt about whether a novice-expert methodology which compares students with scientists is appropriate. While this is a traditional approach within science education (Pozo and Carretero, 1992), it has been critiqued because researchers risk prematurely determining a 'best' outcome and analysing novices only in terms of their deficiencies rather than trying to make sense of novices' reasoning. I avoided making an *a priori* decision about this strategy in order to consider both approaches with my data, so this issue is revisited within the analysis section.

Before data collection: sampling, pilot and ethical considerations

I trialled the resource with my previous teaching school because developing students' NoS is a departmental focus, and because familiarity with the teachers meant I could easily arrange access. Within this school, I worked with students from Years 8 and 9, the target year groups for the resource. Within each year group I chose one class through purposive sampling (Denscombe, 2003), choosing classes with prior experience of justifying stances and considering evidence and theory, as this is a pre-requisite for engaging quickly with the task. Within each class, students were selected purposefully by the class teacher: I asked for students who would work well in a pair, who could articulate their ideas, and were willing to participate. These criteria enabled me to gather useful data how students engage with the activities, but do limit the generalisation of my results beyond willing and articulate students who are able to work well in pairs. Four pairs were interviewed in total.

A pilot tutorial with a fifth student pair used both written work and discussion. When students were asked to write, their discussion was very limited, and their written explanations were less rich than their discussions. I therefore decided to focus entirely on discussion, with no written outcomes. So that students could access an external representation of their previous decisions (Suthers, 2003), I asked students to sort the evidence as pro-plume, anti-plume theory, or unhelpful in deciding, and to indicate the evidence strength with a large, medium or small star-sticker.

Throughout my research, I used the BERA guidelines (2004) to explore the ethical issues involved. I sought voluntary informed consent from all participants (11). Participants were given a letter of consent in advance, so they had ample time to consider whether they wished to participate. Students who chose to participate were asked to sign the letter, which was kept as a record of consent. Parents or carers of these students were also sent a letter of consent to sign (16). I also introduced my research verbally and sought affirmation of consent before beginning the activity. I decided that any participant choosing to withdraw would not be re-engaged (13), due to the potential power-relationship between myself and the students. In one case, a student pair decided not to take part after initially giving permission, as they did not want to miss their science lesson that day. Students were taken out of class for up to one hour for this research, but any detriment was minimized as I engaged them in science learning during the activity, and ensured that the class teacher did not require any catch-up work (21). Protecting students' data is another aspect of my responsibilities to the students involved. All data was anonymised at the point of collection, and no personal data was stored for any participants (24). This ensured confidentiality and anonymity (23). No sensitive data was collected.

Beyond the students I have a wider responsibility to the school which is helping me. Verbal permission was sought from school management and the teachers involved

(34). No risks were foreseen (or, to my knowledge, have arisen) from participating in this research. The likely benefit to students is a greater understanding of coordinating theory and evidence. The long-term benefit to the school is access to the final resource.

Data collection and processing

Students were audio-recorded throughout the activity, and I also noted the decisions students made about the relevance and strength of each evidence source. In all cases, the audio commentary of the students matched their written decisions.

Audio recordings were transcribed and analysed in NVivo 8. Coding was carried out inductively on the whole transcript to answer the research questions, including researcher's comments, in recognition of the co-dependency of all speakers within the conversation (Steffe and Thompson, 2000) and to avoid attributing comments to students which were wholly or partially suggested by the researcher (Posner and Gertzog, 1982). To ensure coding reliability, coding was continued iteratively until a 90% agreement was achieved by the researcher on two rounds of blind-coding three days apart.

Results and analysis

[RQ1] How students access the geological concepts

Initial ideas about Hawaii

In initially explaining the formation of Hawaii, three of the four pairs recognised that Hawaii was volcanic. Two pairs went mentioned plates, although neither related plates to the volcanoes, and one pair talked about lava hardening to form rock. Two pairs interpreted mantle plume theory as inter-plate volcanism, suggesting that the plume was a magma chamber or that the magma came through a pre-existing gap in the crust. As no students referred to Hawaii as an *intra-plate* volcano chain, so this should be made clearer. For example, as well as the picture of the islands, students could start with a world map showing the intra-plate location of Hawaii to emphasise that it is unusual and requires a different mechanism.

The final pair did not mention volcanoes, and suggested the islands were formed when they broke apart from a continent, akin to the continental drift from Pangaea. This is another phenomenon caused by plate movement, and shows excellent analogical reasoning by the students based on the evidence and their prior knowledge. If students come up with divergent theories such as this idea (rather than something based on volcanism), it may be worth having a short class plenary after the initial suggestions to consider how evidence for each of these ideas could be collected.

For the rest of the activity, I have focused on elements which students found difficult to access, particularly conceptions which differ from scientific consensus. However, in line with Steffe and Thompson's (2000) critique of this novice-expert comparison, I aim to make sense of these differences from the students' perspective rather than dismissing them. For the sake of balance, it is worth noting that all the student pairs were able to access the majority of geological concepts embedded in the task. Therefore the activity as a whole appears suitably pitched, although this may not hold true for schools with a significantly different Geography curriculum.

Misconceptions or questions arising during the activity are discussed below. Where misconceptions arise from difficulties in interpreting the activity, it is best to prevent them. However, where the activity elicits a previously-held misconception, it is often better to elicit that misconception so that it can be directly addressed.

Some misconceptions or lack of understanding emerged through student questions. In total, the eight students asked 14 spontaneous questions during the activity. Three related to unfamiliar words (seamount, lithosphere and crust; plate was also unfamiliar to one student until identified as 'tectonic plate'). Three concerned misconceptions about Hawaii - students didn't know that Hawaii was volcanic, had more than one island, or had underwater islands as well. One appeared to be a question of personal interest: how did people get on to Hawaii?

The other questions related to specific pieces of evidence or theory, and are discussed below, along with other misconceptions relating to a particular element of the activity:

- [graph] *Who were Barger and Jackson, what was ma?* The graph should include an explanation of how it was made, and 'ma' on the axis should be changed to 'million years ago'.

- [animation] One student asked whether the warmest bit of magma broke through at a new spot once the plume line was broken. The animation text could be altered to say that the magma rises directly upwards after the plume line is broken. Several students were not sure what the different layers were in the animation, so these should be labelled.

- [prediction that volcanoes will form a straight line] One student asked whether this meant that - adding a picture to the prediction should help with this.

- [lava lamp] *Is the lava [in the lamp] representing the magma?* The student answered this herself.

- [helium] *What is Helium-3? Does it mean they think helium comes up instead of magma?* This evidence should be reworded to explain helium-3 and to make it clear that helium is carried in the magma.

- [tadpole prediction] One student asked what a tadpole was, and two other pairs were not convinced that the plume looked like a tadpole. This could be ameliorated by drawing the tadpole shape on the prediction card.

- [magma will decrease prediction] This prediction needs to refer to the rate of magma emitted rather than the amount, as this caused confusion.

- [older volcanoes are smaller prediction] Some students thought that volcanoes sank or sea levels rose, rather than volcanoes getting smaller. One student suggested that the absence of new magma would cause the volcano to get smaller. This section needs to be clearer in the animation.

- [alternative theory evidence] The crack propagation theory was only recognised as different from plume theory by one pair, with two pairs explicitly saying it was the same as plume theory and about 'rising magma': perhaps because they did not appreciate the distinction between magma from just below the crust and magma from the mantle-core boundary.

Discussion

While I was initially surprised by students' strong international test performance in earth sciences (Sturman, 2009), this was confirmed and exceeded by students' knowledge of plate tectonics in this activity. In contrast to previous research, I found a very low level of misconceptions, and none of those identified by Marques and Thompson (1997) or King (2009).

The dominant themes were a lack of distinction between inter-plate and intra-plate volcanism, identifying earth's layers and understanding their role in plume theory, and what happened when volcanoes became extinct. The first two were probably artefacts of the activity, and can be helped by framing the activity in terms of a different mechanism from inter-plate volcanism (as suggested above) and labelling the layers more carefully within the animation and evidence. The ideas about extinct volcanoes are more interesting and varied, and seem to be drawn from a range of experience. They are not recorded within the research literature, and it is possible that they are an artefact of the small sample, so I shall look for these ideas during the larger classroom trials.

[RQ2] How students reason with different aspects of theory and evidence

Item analysis was carried out for each prediction and piece of evidence, including

- [evidence only] students' assessment of the stance of each piece of evidence: for(+), against(-), or unhelpful (0)
- [evidence only] students' statements on the strength of each piece of evidence as strong, medium or weak (shown by the number of +,- or 0 symbols used, strong (3), medium (2) or weak (1))
- the level of argumentation, according to Toulmin's Argumentation Pattern (Toulmin, 1958)
- [evidence only] which evidence was marked as most enjoyable (E), interesting (I), helpful for learning (L), and persuasive (P)
- a qualitative analysis of students' reasoning and evaluations

I devised a new level system for assessing argumentation, as Erduran et al's system (2004) is for extended arguments with multiple evidence sources. The new levels A-D are described below.

Level A: Data is not linked to the claimed theory.

Level B: Data is linked to the claimed theory (as supporting, rejecting or neutral) in a way consistent with an accepted explanation, but no warrant is given.

Level C: Data is linked to the claimed theory and a reasoned warrant is given. This may or may not be a scientifically accepted warrant.

Level D: Data is problematised by (a) linking to the claimed theory in more than one way (supporting, rejecting or neutral) with multiple warrants given, or (b) qualifying the warrant or data.

The later levels reflect increasing sophistication in dealing with data. Levels C and D are more likely to promote an understanding of tentative science, since they make explicit the chain of inferential reasoning between data and claim (C) and offer the possibility of multiple reasoned interpretations (D). As mentioned earlier, the level of argumentation is considered a product of the interaction between the students and the task, rather than arising solely from one or the other. For example, argumentation levels will be limited both by the students' knowledge of relevant science and by the unequivocal stance of some evidence.

In the case of predictions, the predictions are treated as claims and plume theory as data. In the case of evidence, plume theory is treated as a claim and the evidence sources as data.

Prediction item	**Arg level** (pr1-4)	**Discussion**

P1: Plumes are warmer than surrounding rock.	CCCB	All pairs agreed this followed from plume theory, either because the plume would need heat to melt, or because the plume would need to be warmer in order to rise. Both these warrants show good scientific reasoning, and the first was unexpected.
P2: Islands formed by plumes contain materials from deep within the Earth.	CCCB	All pairs agreed this followed from plume theory. Three pairs referred to the plume's movement up from the centre of the Earth as the reason. One went further to say the plume carried these materials. This could be picked up by a teacher counter-arguing that these materials would precipitate rather than remain suspended, to suggest an alternative interpretation that plume theory does not support this prediction.
P3: Hot rock under the Earth will rise through other rock.	CCCB	All pairs agreed this followed from plume theory. Three pairs pointed back to the animation to show that the plume was rising. One of these went further to talk about the process of convection which would cause this, which provided an extra backing by explaining the physical reason for this rising.

P4: Rising rock forms a tadpole shape.	CCCC	All pairs agreed this followed from plume theory, after some initial confusion about tadpoles, and referred to the tadpole shape shown in the animation.
P5: The oldest volcano in a chain will make a giant underwater rock, like Kergeluen plateau. After this first volcano, the amount of magma emitted will decrease.	CCCC	Students ignored the first sentence, and interpreted the second sentence as meaning that the magma to a particular volcano would decrease. They explained this in terms of the mantle plume had moving on, and the volcano becoming extinct. The mantle plume head which causes the underwater plateau was not shown on the animation, which may explain students' difficulty. Either the head should be shown reaching the surface, or this prediction should be removed.
P6: Volcanoes will form a single straight line.	BBCA	Students were less confident in dealing with this prediction, although most said it followed from the theory. Two pairs referred to the plume line extending vertically through the mantle, rather than a line of volcanoes, so a picture may be helpful here. Also, the straight line was not clearly shown on the animation, so required students to think

		through the implications of a plate moving at constant speed. This was a challenging item, but one pair dealt with it successfully, and it sets the scene for the Card Model Experiment which follows - therefore it should remain.
P7: Volcanoes will be evenly spaced.	DCCC	This prediction provoked a variety of stances and would therefore be very useful in starting argument within the class - this is reflected in the high levels of argumentation. One pair argued that the plume is like a water fountain, so would not spread evenly to give evenly spaced volcanoes. One pair referred back to the animation, which showed evenly spaced volcanoes as the plume thread broke and reformed. One pair said they would be evenly spaced because the plates were moving, and the other pair suggested that it may or may not follow, depending on whether the plates moved at constant speed.
P8: Below the surface of the water, old volcanoes will be found.	CCCC	All pairs agreed this followed from plume theory, although they referred to sea levels rising or the volcanoes sinking to justify this process, rather than erosion.
P9: Older volcanoes	CCCC	All pairs agreed this followed from plume theory,

will be smaller.		although again they believed that the volcanoes sank rather than getting smaller. On further probing, one pair said that hot magma caused the nearby land to melt, while another pair correctly referred to erosion. These last two items were particularly fruitful in eliciting misconceptions about the process, so I would recommend a quick plenary to discuss ideas about these before moving on.

Evidence	**Stance/ strength** (pr1-4)	**Arg. level** (pr 1-4)	**Eval- uation**	**Discussion**
Card Model	1. ++ 2. ++ 3. 00 4.++	D B C B	 E I E	Most students agreed this was a medium pro-plume source. Two pairs talked about specific limitations of the model as reasons it was not good evidence – including one pair who thought this made it neutral. Students' reasoning here was often not very advanced, perhaps because they saw no need to defend their 'obvious' interpretation that the card model is pro-

				plume. Teachers may therefore need to prompt students to explain their stance more fully. This piece of evidence was very popular and engaging. Students also reported that it made the theory clear and was an unexpected analogy for volcanoes.
Times Article and alternate theory	1. - - - 2. - - 3. 00 4. none	C C C C	E L	Two pairs agreed this was an anti-plume source, although they wanted more 'proof'. One pair thought the alternate theory was arguing for plume theory, so thought the source was neutral overall. The last pair could not decide. Only one pair independently understood that the alternate theory was different from plume theory: this could be made clearer by including a diagram to compare. One pair noted that the absence (from their perspective) of an alternate theory would cause people to agree with plume theory, as 'people would rather believe a reason than just say we don't know'.

				One pair enjoyed the article because it was 'gossipy', and another said it was very clear and helped them to learn.
Helium	1. 0 2. ++ 3. +++ 4. +++	D C D C		Pair 1 was convinced that this evidence did not support plume theory: 'it's not actually telling us about it, it's just giving us another fact', although they explained why it might be seen to support plume theory in terms of containing deep-Earth material. The other pairs thought it was pro-plume, citing the same reasoning. Two pairs said that they were persuaded because the source itself mentioned plumes: this is discussed further in the epistemology section below. This evidence was not mentioned by any of the students in their evaluation, so it may need altering to be more engaging or persuasive, as it has raised some interesting epistemological issues and students reasoned well with it.
Lava	1. + +	D	P	Students agreed that this was a medium

lamp	2. + 3. ++ 4. +	D D D	I E	or weak pro-plume theory. The direct questions on the evidence card seem to have facilitated sophisticated argument, as all students examined the strength and limitations of the lava lamp model. They explained the strengths as a physical explanation and analogue for rising magma, and the limitations caused by different scales and materials. The lava lamp was considered either persuasive or engaging by three of the pairs. Students liked that it 'made you think', that it was simple and gave a clear explanation of why the plume rises.
Rocks	1. 00 2. ++ 3. + 4. none	C C B B		This was one of the two most obviously contradictory pieces of evidence, but in its present form students found it very difficult to reason with. The two contradictory research results seemed to leave students confused rather than able to construct an argument for both stances. Students could be encouraged to

				consider how pro-plume and anti-plume scientists would interpret this evidence. This evidence was not mentioned by any of the students in their evaluation, so it may need altering to be more engaging or persuasive.
Map	1. + 2. 00 3. - - 4. none	D D D none	I P P	Compared with the previous piece of evidence, this was reasoned with much more successfully, with all three pairs explaining how it could be interpreted as both pro- and anti-plume. The map was mentioned by three pairs as engaging or persuasive: one pair liked the possibility of interpreting the map as either pro-plume or anti-plume, another hadn't realised that Hawaii had more than one island, and the last changed their mind about whether the the chain was not a straight line. **NB**: Pair 4 did not look at either of the last two evidence sources, as we ran out of

				time for that section of the activity.
Magma graphs	1. 00 2. 0 3. 0 4. none	B B B none	E,L L	Students struggled to interpret these graphs, which are complex and unusual in several ways. Even after teacher help in interpreting the graphs, no student could explain clearly how they related to the theory. The graphs need to be simplified and possibly the students will need some guidance in linking them to plume theory. Nonetheless, two pairs mentioned the graph as engaging or helpful for learning. One of these pairs enjoyed 'having to work things out' and felt they had learnt a lot.

Discussion

Students' coordination of theory and evidence varied widely according to the evidence. Among evidence they could access successfully, more controversial and limited evidence elicited more complex reasoning, which matches previous research showing that students show more sophisticated reasoning with socio-scientific issues and uncertain claims (Ratcliffe, 1999). The two most successful pieces of evidence for provoking complex reasoning were the lava lamp and the map, both of which were strongly visual and accessible pieces of evidence which could be interpreted from multiple stances. The evidence from rocks also had multiple interpretations, but involved more difficult geological reasoning. This suggests that students' reasoning may be stronger when they do not have to work hard to access the evidence. I was surprised by the popularity of several written pieces of evidence, as I had previously assumed that all the students would prefer the practical evidence to the written sources.

I have deliberately not interpreted students' coordination of theory and evidence beyond a description at item-level, because it varied so much according to teacher-researcher questions and the evidence sources. The tables above show that the variation of reasoning level in one student pair across evidence sources was greater than the variation of reasoning level about one evidence source by different students. This variation in itself could be considered evidence that students' epistemologies of theory and evidence are fragmented and inconsistent (Lederman et al, 2002) but it could equally reflect the nuances in tentativeness of different types of scientific evidence (Osborne et al, 2003). Students' epistemologies are considered in more detail in the following section.

[RQ3] Students' epistemologies of science in the task context

Epistemology in practice

Activity transcripts were analysed for statements where students' ideas or moves were different from those of scientists. This novice-expert comparison was again used due to the overwhelming number of epistemological moves; again I aim to describe these moves and value reasoning. Two differences were either dominant in one pair or prevalent across multiple pairs: these are discussed below.

Stances as evidence

Students did not clearly differentiate evidence of someone taking a pro-plume stance from primary evidence for plumes' existence. This is not necessarily a detriment, as we all rely on the expertise of others as evidence, but it does contrast with philosophies of science which emphasise empirical evidence above all.

> S1: But… they're saying stuff about the stuff coming up, like that the plume is bringing up, so it sounds like they're for it because they're talking about it as if the plume does exist.
>
> T: Can I ask you a slightly different question? For each piece of evidence, I want you to say, does it persuade you? So does it make you think a plume exists? Don't worry about whether they think the plume exists. What I want you to focus on is, does it persuade you that this theory is right, does it persuade you the theory is wrong? Or does it not really help you?
>
> S1: I think it persuades for, because they said about how – they're saying that the plume is bringing up the helium, so then it sounds like that the plume does exist. So put it on 'for'.

Extension of models

In a scientific model, some elements are deliberately set up to be analogous to the studied phenomena, and the model may then reveal other analogous elements which are considered evidence. For example, a lava lamp can model a mantle plume: in the set-up, the lava is heated from below like magma deep in the mantle. The lava forms a tadpole shape, which is used as evidence for the shape of mantle plumes. The distinction between set-up and evidential elements is akin to the distinction between independent and dependent variables. One pair made no distinction between these two elements. For example, the Card Model is set up with a candle (which is warmer than the surroundings) and a damp card is passed slowly across it in a straight line, to model a tectonic plate moving across a plume. The candle makes brown spots, which are spaced and aligned in the same way as volcanoes.   However, students picked up on the temperature difference (part of the set-up) as evidence in support of plume theory.

> S2: This [the candle] is the plume. This is the plume – OK, this is warmer than that – warmer than the surrounding rock. . . .Obviously the flame is warmer than the – the thing.
>
> T: Okay.
>
> S1: …so that supports it [plume theory].

Similarly, the students thought this model provided evidence about the relative size of old and new volcanoes, despite the fact that the size of the brown spots is within their control (part of the set-up).

New epistemological ideas

Students' epistemological moves provided one perspective on their epistemologies: another emerged from the interviews. A descriptive account of these interviews focuses on new ideas which emerged after the activity, to glean a preliminary idea about how this task might influence students' epistemological statements. No assumptions are made about the stability or prevalence of new ideas.

There were mixed changes in students' opinions of plume theory after the activity. Two pairs became less certain about plume theory: while they had previously thought it was 'fact' or 'reasonable', the presence of dissenting opinions, evidence or argument made them less sure. The other two pairs became more pro- plume after engaging with the evidence. One pair said that most of the evidence supported the theory, and that this was 'how it happened'. The other pair said they agreed with the theory because there was 'more evidence for than against'.

Interestingly, their personal stances in favour of plume theory did not prevent them from articulating new ideas about uncertainty in science. In their pre-activity interview, one pair described theory as 'just an idea' and evidence as 'proof', but later they articulated the importance of interpreting evidence and the possibility of different interpretations of the same evidence:

> "you've got to really kind of look at the evidence – because it might be obviously to your first intention or instincts about it is that it's *for*, but you can actually kind of change it and look – it could be *against* as well. So it's just interpreting the evidence properly." [emphasis added]

The three other pairs made similar distinctions between theory and evidence in their first interview: theory is tentative but evidence is certain, and showed no changes to this in their second interviews, although one pair did alter their chronology of theory and evidence, realizing that more evidence can be found after a theory is formed.

The students' statements that theory is tentative fit well with students' ideas about the uncertainty of the Hawaii theory. Three of the four pairs initially suggested that scientists cannot be sure about Hawaii because they did not see it first-hand: 'they weren't around at the time, so they don't actually know what happened'. Pair 2 suggested using a small-scale model or looking underwater as one way of being sure. In the post-interviews, three pairs introduced the new ideas of contradictory evidence, finding new evidence (Pair 3), limitations of modeling (Pair 2), and the possibility of being disproved in the future (Pair 4) as extra reasons for uncertainty.

The specific uncertainties of Hawaii were not always matched by a general belief in the inherent uncertainty of theories, although three of the four pairs showed a marked shift towards expressing this uncertainty after the activity. The example below is typical:

> T: Some people say you can never be 100% sure that a theory is right. What do you think?
>
> (Pre-activity) A: [disagrees] If there's so many ev – there's so much evidence saying that this theory is correct, then why not? I mean, obviously in the future if more comes up then it can kind of change, but if you have a theory and it's right and there's loads of evidence to kind of say it is, then why not, I think?

(Post-activity) B: I – I agree, you can't be 100% sure.

A: Yeah, I agree. There's nothing you can be really sure apart from mathematics. Two plus two is four, that's about it.

The fourth pair agreed from the start that theories could never be made 100% certain, citing the falsification of the historical theory that the world is flat, and arguing that all theories are similarly vulnerable to being disproved.

In their evaluations, most students referred mainly to epistemological aspects of their learning, including analyzing evidence, relating evidence and theory, and that 'not all theories' can be proven.

Discussion

Student's practical and formal epistemologies appear to be matched in this context, perhaps because the activity involves reasoning with genuine evidence and uncertain theories. This suggests a hypothesis that a gap between these two epistemologies (Sandoval, 2005) might be lessened if students spent more time reasoning with complex and uncertain theories and evidence. This might also help students to reach the evaluativist stance that knowledge is contestable, in contrast to much absolutist classroom practice in which a correct and undoubted theory is handed down by the end of the lesson.

My research confirms the findings of Johnston and Southerland (2001) that students have a range of reasons for believing that science is tentative, and that not all of them are educationally valuable. For example, a black-and-white belief that 'if you didn't see it, you can't know' is quite naïve compared with an understanding of how scientists collect evidence and make inferences about non-observable phenomena (Khishfe, 2008).

A particularly interesting finding is that the activity encouraged a more sophisticated understanding of tentative science for all students, irrespective of their final stances on plume theory. This is a useful message for science teachers who 'fix' experiments to obtain the desired result (Nott and Wellington, 1997), as it suggests that by closing down evidence they are missing the opportunity to help students question and challenge knowledge claims. For some scientific issues, does it matters what stance students take, if by taking a stance they become more open to debate and uncertainty? For example, controversial issues such as global warming and the MMR/autism debate can be taught in a corrosively dogmatic way (Hildebrand et al, 2008), despite a benign intention of ensuring that students make scientifically-based personal decisions. Ironically, by closing down debate in the name of a correct answer, they may be encouraging absolutist students who will unthinkingly accept all knowledge claims, scientific or unscientific.

Leach et al (2003) remind me that the new ideas expressed by students after this task are likely to collapse under further pressure or probing. Therefore it is vital that students are given further opportunities to build on these ideas, both by exploring other areas of tentative science and through reflection on their learning.

[RQ4] Suggested improvements and teacher facilitation

While many improvements and possible teacher facilitation have been suggested in the previous sections, the students' evaluations raised further ideas. Students particularly enjoyed setting things on fire (three pairs), the independent and practical work, and thinking and discussion: 'you let us do things for ourselves . . . we talk and do stuff, and then we've got to think about it'. On a more trivial note, one pair really enjoyed using the star-stickers to rank the evidence.

Only two aspects of the activity were cited as 'least enjoyable': three pairs thought there was too much reading, and one pair had not enjoyed the graph work because they didn't understand the graph. The reading can be cut down by removing pieces of evidence, by replacing some predictions with pictures, and by cutting out redundant aspects of the writing. The graph was the most challenging piece of evidence, but was quite popular - I would recommend making it an optional evidence source for students to consider.

Students also suggested that the activity could be improved by having a greater variety of evidence and more hands-on learning. To achieve this, the rock evidence (rocks) could be turned into a hands-on activity, with students completing the temperature analysis via graph work, and students could also work more extensively with the lava lamp. The card model was very engaging and drew students in, so it remains a good start to the activity. However, every single student pair set their cards on fire at least once. Teachers should prepare accordingly, and substitute a demonstration if absolutely needed, although this may reduce engagement levels.

Conclusion

Conclusions from the research

Is the Hawaiian activity an appropriate learning experience for improving students' epistemology? Early indications suggest that it is. The eight KS3 students I worked with all had prior knowledge of the geological concepts needed and were able to apply the majority of these ideas in context. Many of the misconceptions arising from the activity should be eliminated by modifying the resource and framing the activity more clearly in the context of previous work on volcanoes. Most of the remaining misconceptions are of interest in their own right, with several displaying quite complex reasoning, and thus worthy of consideration within a lesson structured around argumentation. Students' coordination of theory and evidence was sophisticated and showed advanced elements of argumentation which should help to develop their epistemology, such as making explicit and reasoned links between data and theories, looking at the limitations of different evidence sources, and forming multiple interpretations of the same data source to support different stances. Students' statements about tentative science became more sophisticated after the activity. More students agreed that the theory of Hawaii would remain tentative, and that theories in general were inherently tentative, and they gave a greater range of reasons for this tentativeness. These findings will benefit from further testing with whole-class trials.

Implications for my development as a researcher

This research forced me to justify intuitive conceptions of 'how things are done', such as hunting down methodological literature on design-based research. It has also been an overwhelming induction into the high emotions of running my own research project, where every delay in data collection or ambiguous statement is a cause for despair, but every new insight or unexpected statement is a delight.

In the ideal world where schools are not infected with swine flu, I intended to work with six student pairs. However, the data from four pairs could easily have filled another report, and four pairs were sufficient to establish a range of ideas about the activity and to improve it for whole-class trials.

The strengths of my research were being clear about my research before data collection, which enabled me to ask appropriate prepared and impromptu questions, and my knowledge of science and its philosophy, which were invaluable in framing the research, collecting data, and the final analysis. The biggest limitation was the lack of an iterative cycle within this element of research – it might have been better to work with two or three student pairs, then modify the resource and try it with two more pairs. I may do this before whole-class trialling, but it would have greatly strengthened my recommendations and given extra assurance to some of my inferences.

Implications for my professional practice in science teaching

As well as the specific research outcomes, the research has more broadly influenced my practice in science teaching through 'fuzzy generalisations' (Bassey, 1998) which considering the general aspects of students' practice which surprised me. Specifically, I was impressed with students' knowledge of plate tectonics and their application of that knowledge in a scientific context. This has made me determined to broaden my diagnoses of students already know beyond the science curriculum, and to use students' existing expertise from other subjects in my teaching. Realising the gap between the oral reasoning and written reasoning of students has helped me reconsider the best ways of assessing students' understanding. I purchased audio recorders to assess students' discussions directly, rather than relying on students' written accounts. Finally, I have realised that I often accept 'right answers' from students without probing 'right reasoning', which is arguably more valuable. Listening to learners' ideas has helped me to realise the complexity of reasoning that can underpin seemingly casual statements in my science lesson.

Implications for further research

I now intend to modify the resource using the suggestions from this research, and try it out with KS3 classes and trainee teachers. I expect that modifying the resource will make it more accessible to all students, including those in other contexts. However, I may encounter different misconceptions, or need to pitch it differently, according to students' prior knowledge of plate tectonics and argumentation skills. I would also expect to see similar uses of theory and evidence, and epistemological practices, in different schools, since my findings matched those from other studies. In any case, my aim is not to make a teacher-proof or context-proof resource which will work for all students, but to gain a rich understanding of how different learners work with the resource. This will allow me to create a 'teacher-transparent' resource which is explicit about the thinking behind the activities, so that it can be adapted for use with a variety of learners and contexts. I am optimistic that this research will help me to develop other resources, and ultimately to improve pupils' understanding that science is tentative and contestable: an important goal for appreciating the role and limitations of science in our lives.

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Appendix 1: Theory and evidence in the Hawaiian chain

(Adapted from Aston A, 2009, personal communication)

Progression and fixity

Plume theory predicts a fixed column of material rising from the core-mantle boundary while plates move over it. This results in a chain of islands younging in one direction. The plume is a fixed plane of reference which shows plate motions.

Consistent evidence: the Hawaiian islands are linear and young consistently southeast.

Inconsistent evidence: the island chain bends between Hawaii and the Emperor sea chains, but there is no other indication of a change in plate direction at 50 Ma.

Lava flux

Plume theory predicts a large outpouring of lava (the plume head) at the start of any plume trail, usually in the form of ~100km^3 of flood basalts. of 100 km^3. If erupted in the ocean, this will form a submarine plateau which is too large to be subducted into an ocean trench, and should therefore be present at the head of the island chain. After this eruption, lava flux should decrease through time.

Inconsistent evidence: No such plateau is seen, and lava flux increases with time.

Temperature

Plume theory predicts a hotter mantle (>225K above normal) where an active plume is present. This can be tested using the composition of rocks on volcanic islands.

Inconclusive evidence: Studies of olivine composition produce very different results.

Modelling

Plume theory makes predictions of plume shape and behaviour based on lab experiments. In particular, a large mushroom-shaped head followed by a thin tail.

Evidence: Lava lamps and other small-scale model show this shape and behaviour. However, they cannot replicate high-pressure conditions in the mantle.

Tomography

Plume theory predicts a funnel of hot material moving from the core-mantle boundary to active volcanoes. This can be studied using earthquake waves.

Confused evidence: There is a 'plume signature' under Hawaii, as well as all over the Pacific. However, this plume signature isn't located under the currently active volcanic zone, but *behind* it in the age progression. Across the world, the correlation between hot mantle and volcanoes is not strong.

Helium

Plume theory predicts that plumes come from deep inside the Earth, therefore their geochemical signature should be that of material trapped inside the Earth since it formed.

Consistent evidence: high $^{3}He/^{4}He$ ratios in rocks (^{3}He is a primitive form of He).

Appendix 2: Data Collection Schedule

Introduction

- Use the consent letter to explain the research
- Check consent again with both students
- Explain that the aim of the research is to improve the task for use with whole classes, so questions where things are unclear and suggestions about how to improve the task are very helpful.
- Reiterate that no assessment is being made of their work as an individual
- Explain that I want to gather as much information as possible about how they approach the task, so thinking out loud, write things down.

Phenomena

- Present picture of Hawaii (Source 1).
- What do you know about Hawaii?
- Do you have any ideas about how Hawaii was formed?

Theory

- Here is one possible explanation or theory of how Hawaii was formed.

- Present mantle plume animation (Source 2a). Please watch it and read it as many times as you like, and ask me any questions about it.

- When you are ready, I would like you to explain the theory back to me.

- After the students' explanation, lay out the five theory cards (Source 2b).

Pre-task interview questions

- What do you think of the mantle plume theory? Why?

- What is the difference between evidence and theory?

- Do you think scientists will ever be sure how Hawaii was formed? Why?

- Some people say you can never be 100% sure that a theory is right. What do you think?

Predictions

Present predictions (Source 3). For each prediction:

- Does this prediction follow from the theory?

- Why or why not?

Evidence

Present evidence (Sources 4). For each piece of evidence:

- Thinking about mantle plume theory, is the evidence for the theory, against the theory, or unhelpful?
- What is the link between the evidence and the theory?
- How strong is the evidence (strong/medium/weak)? Why?

Post-task interview questions

- What do you think of the mantle plume theory? Why?
- What is the difference between evidence and theory?
- Do you think scientists will ever be sure how Hawaii was formed? Why?
- Some people say you can never be 100% sure that a theory is right. What do you think?

Activity

- What did you enjoy most about the activity?
- What did you enjoy least about the activity?
- What did you learn from doing the activity?
- How could it be improved?

Evidence

- Which piece of evidence did you enjoy working with most? Why?

- Which piece of evidence was most interesting? Why?

- Which piece of evidence did you learn the most from? Why?

- Which piece of evidence did you find the most persuasive? Why?

Appendix 3: Evidence Sources

Source 1: Hawaiian islands

Source 2a: Mantle plume animation

Flash animation, available online at

http://www.wwnorton.com/college/geo/egeo/flash/2_10.swf

Source 2b: Mantle plume theory

A plume is a column of hot rock that rises from the mantle-core boundary.
The mantle plume spreads out when it reaches the base of the crust, forming a tadpole shape.
The hot rock moves up through the crust and erupts through a volcano when it

reaches the surface – first underwater, then on land.
Over time, movement of the plate carries the volcano off the plume. A new volcano is formed directly above the plume.
Old volcanoes are eroded and sink below the water.

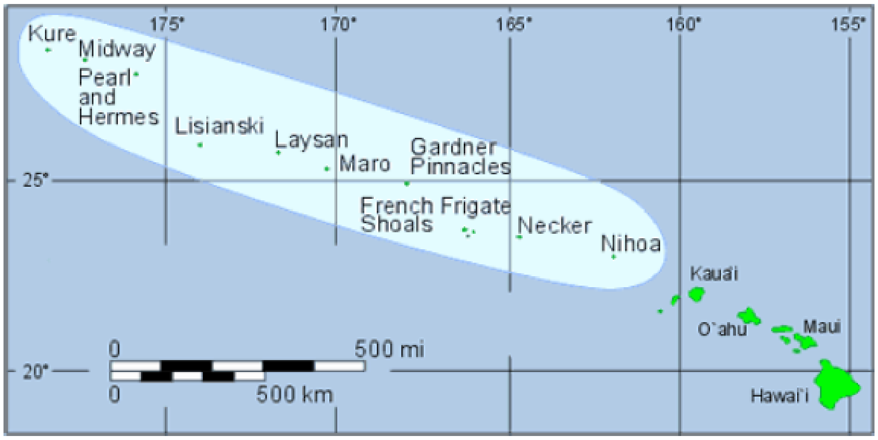
Source 3: Predictions

Plumes are warmer than surrounding rock.
Islands formed by plumes contain materials from deep within the Earth.
Hot rock under the Earth will rise through other rock.
Rising rock forms a tadpole shape.
The oldest volcano in a chain will make a giant underwater rock, like Kergeluen plateau. After this first volcano, the amount of magma emitted will decrease.
Volcanoes will form a single straight line.
Volcanoes will be evenly spaced.
Below the surface of the water, old volcanoes will be found.
Older volcanoes will be smaller.

Source 4: Evidence

4a: Card Model

Card Model



1. Pour water over the card until it is all wet.
2. Light the candle.
3. Move the card very slowly over the candle, just above the flame.
4. You will see a pattern of burnt spots.

Look at the pattern formed. Does this help you to argue for or against mantle plumes forming Hawaii?

4b. Times Article and Alternative Theory

Times Online: **Fuming over Plumes**
http://www.timesonline.co.uk/tol/life_and_style/education/article1159928.ece

"because experiments have not yet proved their existence, a group of geologists is raising the possibility that mantle plumes do not exist at all. Led by Dr Don Anderson, from the California Institute of Technology, and Dr Gillian Foulger, from Durham University, they argue that plate tectonics can also explain anomalous, mid-plate island chains such as Hawaii. There is no need to complicate matters, they say, with the addition of hot plumes rising mysteriously from nearly 3,000 km (1,864 miles) down in the bowels of the planet. There is, they protest, no evidence of narrow columns piercing the whole mantle and emerging at the Earth's surface, and, moreover, they argue that unbelievably high pressures in the mantle stop rock from rising, let alone in the suggested plumes. But they cast their net of criticism considerably wider — they accuse the plumatic lobby of discarding or ignoring evidence that does not fit with their cause."

Don Anderson

Gillian Foulger

How does this article help you to argue for or against the plume theory?

An Alternative Theory for Hawaii's formation

A crack in the crust could have formed the Hawaiian volcanic islands. Calculations done in a 2007 research study found the area had the form necessary to maintain a crack in the Earth's crust which moved along, allowing magma to rise from just below the crust and form volcanic islands.

Adapted from *Stuart, William D., Gillian R. Foulger, Michael Barall. 2007. Propagation of the Hawaiian-Emperor volcano chain by Pacific plate cooling stress. in Geological Society of America Special Paper 430, eds. G.R. Foulger and D.M. Jurdy, pp. 497-506*

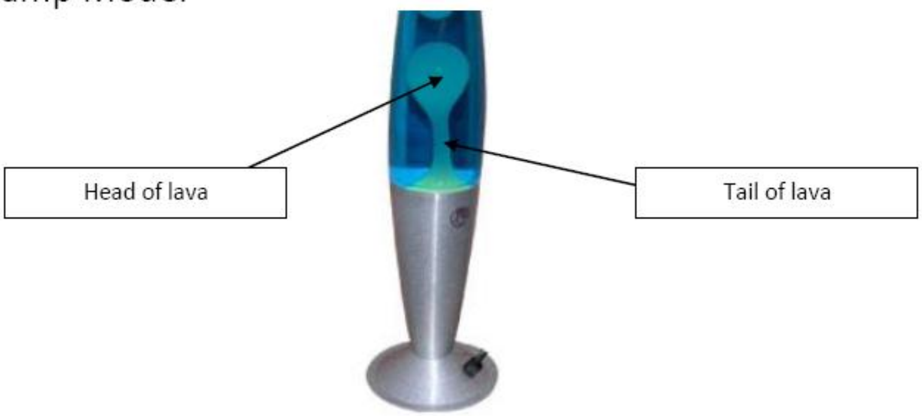
4c. Helium-4

A Window on the Inner Earth
http://www.nature.com/nature/journal/v421/n6918/full/421010a.html

"Studies of volcanic gas trapped in bubbles in rock at volcanoes on the Hawaiian islands, and dissolved in water from hydrothermal vents on the Loihi seamount, have shown that there is much more helium-3 trapped in Hawaiian rocks to helium- — 30 times as much at Mauna Loa on the Big Island, and 20 times as much at Loihi — than in the atmosphere. Geochemists theorize that this shows that the plume is bringing up helium-3 from deep within the Earth."

4d. Lava Lamp

Lava Lamp Model



The lamp is heated from the bottom. As the wax or 'lava' is heated, it expands and floats towards the surface. The diagram shows the shape of the 'lava' as it rises.

How could you use this experiment to argue for or against the mantle plume theory?

What might be different if the 'wax' were rising from underneath millions of kgs of rock?

4e. Hawaiian rocks

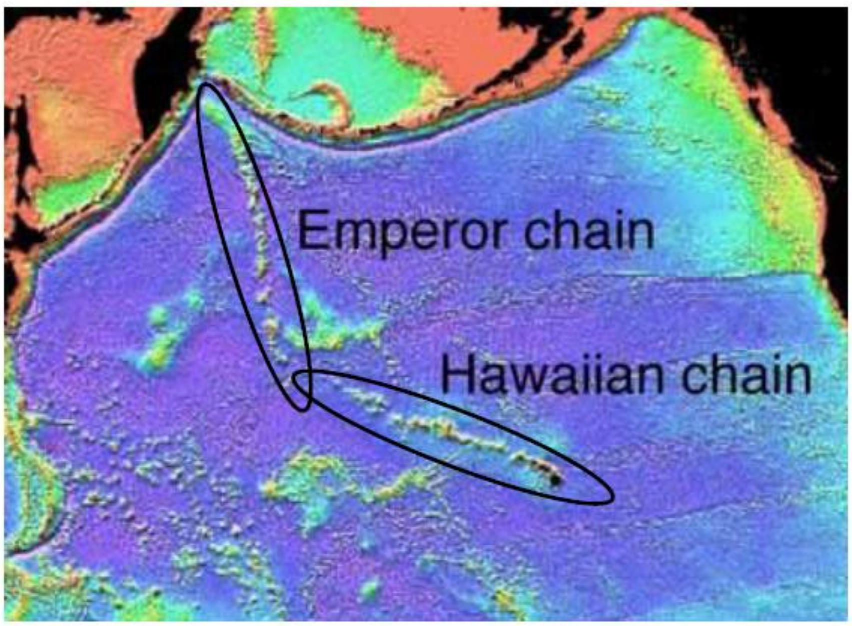
Olivine rock composition

The composition of olivine rocks on Hawaii can be compared with surrounding olivine rocks. This allows geologists to estimate the temperature at which the rock originally melted. If Hawaii was formed from a plume, then the Hawaiian rock should have melted at a warmer temperature than the surrounding rock.

Trevor Falloon's research team found that there was no difference in initial melt temperature between rocks on Hawaii and surrounding rocks.

Keith Putirka's research team used the same rock samples, but found that Hawaiian rock melted at a temperature 268°C higher than surrounding rock.

4f. Map of the island chain



Map of Hawaiian and Emperor island chains

4g. Magma graphs

Graph showing how the magma supplied to Hawaii varies over time