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The permeability and elastic moduli of tuff from Campi Flegrei, Italy: implications for ground deformation modelling

M. J. Heap, P. Baud, P. G. Meredith, S. Vinciguerra, and T. Reuschlé

Dear Antonella Longo,

Firstly, thanks for your time and effort spent in dealing with our submission. In general, we are pleased by the positive and constructive nature of the reviewers' comments. The comments of the four reviewers are appended below and our responses are given in bold below each comment (any changes to the manuscript text is highlight in blue). We believe that we have suitably addressed the reviewers' comments and, as a consequence, improved our manuscript. We would now like our improved manuscript to be considered for publication in *Solid Earth*.

Thank you again for your time.

Yours sincerely,

Mike Heap and co-authors

Reviewer #1 (Andrea Manconi)

The manuscript by Heap et al. presents a systematic laboratory study of the influence of pressure and temperature on the permeability and elastic moduli of the two most widespread tuffs from the Campi Flegrei volcanic district, Italy. Their results show that that the water permeability of Neapolitan Yellow Tuff (NYT) and a tuff from the Campanian Ignimbrite (WGI) differ by about two orders of magnitude. In addition, while the NYT properties are systematically affected by temperature, no clear patterns depending on temperatures were revealed for the WGI samples. Moreover, the authors show that the dynamic and static elastic moduli differ significantly.

The results of this study have implications for surface deformation modelling and interpretation at CF caldera and elsewhere. The manuscript may represent a key contribution for a better understanding the influence of rock physical parameters, as well as for a more conscious use of these parameters in models of deformation processes occurring in active volcanic areas. In some cases, the consideration of homogeneous half-space in mechanical models of deformation processes occurring at volcanic areas might be still acceptable, mainly because of lack of information on the material properties. However, in cases as CF caldera where a large dataset of information is already present, the effect of heterogeneities has to be taken carefully into account. Instead, if homogeneous half space is still preferred in modeling attempts, one has to be aware that this might be an oversimplification deeply influencing the modeling results and thus potentially leading to misinterpretations. The methodology and results are clearly presented and thoroughly discussed in the manuscript. Due to the high quality of the results and their important implications, the paper deserves publication in Solid Earth, though some very minor issues have to be clarified before final acceptance. Please find my specific comments/criticism here below.

We are pleased that reviewer #1 considers the manuscript a "key contribution for a better understanding the influence of rock physical parameters, as well as for a more conscious use of these parameters in models of deformation processes occurring in active volcanic areas" and that our results are of a "high quality" with "important implications".

1) Please provide and eventually discuss/comment expected errors in the estimation of rock properties for the considered methodologies of investigation. This might help the reader to better evaluate the results of your analyses.

This is certainly an important consideration in experimental work. However, commonly, the measurement error is insignificant when compared with the natural variability of samples cored from the same block (even for "well-behaved" sandstone or granite samples). We have now added the following paragraph and two new tables, one showing the measurement accuracy and one showing the expected natural sample variability:

"Experimental data are subject to error as a result of the accuracy of the various transducers. Estimations of the accuracy of the measurements of this study are listed in Table 2. The errors are extremely small and lead to error bars that are smaller than the data

points in the figures provided in this study. However, we note that measurement error is dwarfed by the natural sample variability of the tuffs (i.e., the natural variability of samples cored from the same block of material). Estimations of the natural sample variability of the tuffs used this study are provided in Table 3."

Table 2. Summary of the estimated measurement accuracy.

measurement	accuracy
confining pressure [Pa]	± 100 000 (UCL) ± 10 000 (Strasbourg)
pore fluid pressure [Pa]	± 10 000
pore fluid volume [m^3]	± 1.0×10^{-12}
LVDT displacement [m]	± 0.000001
axial stress [Pa]	± 10 000
original sample dimensions [m]	± 0.00001

Table 3. Expected natural variability between tuff samples cored from the same block. Note that these are not "errors" in the measurements. Measurement accuracies (Table 2) are insignificant compared to the natural sample variability, despite efforts to reduce the variability between samples cored from the same block of material (see text for details).

	expected natural variability
Young's modulus [GPa]	± 0.5
Poisson's ratio	± 0.05
shear modulus [GPa]	± 0.5
water permeability [m^2]	± 1.0×10^{-14}
P-wave velocity [kms^{-1}]	± 0.1
S-wave velocity [kms^{-1}]	± 0.1

2) In section 5.3, the authors claim that the NYT and WGI have similar elastic moduli, (thought pressure/depth dependent) supporting the homogeneous half space notion for the CF caldera. However, this statement might be misleading, as these rocks represent only a portion of the caldera infill materials (see e.g. Orsi et al., JVGR 1996).

The reviewer is correct. In fact, those data do not support the notion of a homogenous half space model. We have now completely reworded this paragraph:

"Our data highlight that the elastic moduli of two different tuffs from CF are significantly depth-dependent (Figures 7 and 8). The implication of these data is that the assumption of a homogenous half-space may be an oversimplification, and is exacerbated further when one considers the extent of the variability of the tuffs within the caldera (which are variably lithified, altered, and zeolitized, see the report of Giberti *et al.*, 2006). These data highlight

the need for the development of more complex, multi-layer ground deformation models. In order to assess the extent of the variability in elastic moduli of the rocks within the caldera at CF, a systematic experimental approach involving borehole samples from different depths and locations within the caldera is now required (discussed further at the end of the section). "

3) Fig. 4 is the only one among figs 4-7 where the effective pressure is on the y-axis. Then figs. 8-9 show the differential stress on y-axis. I suggest to make all figures consistent (e.g. pressure/stress on the x-axis for all figures, or vice-versa) to ease their reading and eventual cross-comparison.

The reviewer is correct in the fact that effective pressure is on the y-axis of Figure 4 and is on the x-axes of Figures 5-7; and that differential stress is on the y-axes of Figures 8 and 9. The reason for this is that this is how these data are most commonly portrayed in the wealth of previous literature. While we agree that there is some merit in organising them as the reviewer suggested, we would prefer to keep our figures in the standard format.

4) Please check that abbreviations are systematically defined when used for the first time in the text. I could not find the definition for Pp.

The reviewer is correct. We have now amended this: "Once inside the setup, the confining pressure (Pc) and the pore fluid (distilled water) pressures (Pp) in both the "upstream" (P_{up}) and "downstream" (P_{down}) pore volumometers were increased to 10 and 5 MPa, respectively."

Reviewer #2 (Claudia Cannatelli)

The manuscript by Heap and coauthors presents an experimental study of the effect that pressure and temperature have on permeability and elastic moduli of CI and NYT at Campi Flegrei, Italy. Their results show that the water permeability of Neapolitan Yellow Tuff (NYT) and a tuff from the Campanian Ignimbrite (WGI) differ by about two orders of magnitude, indicating an heterogeneous nature of Campi Flegrei's tuffs. They also point out how the permeability and the elastic moduli of NYT is affected by thermal stressing increase, while the CI appears not to be affected by such stress. The manuscript is well written; the methodology and results are well presented and discussed in the manuscript. The results are very important for the understanding of how the physical parameters of the rock can affect processes such the bradyseism at Campi Flegrei. The bibliography on the Campi Flegrei is outdated, and therefore the presentation of the geological background lacks the most recent published papers (last 10 years!) on the topic. I would recommend publication of this manuscript, but revision of the introduction is NEEDED in order to have an updated description of the volcanic area and its products. In specific, here are my comments:

We are pleased that reviewer #2 deems our results as "very important for the understanding of how the physical parameters of the rock can affect processes such the bradyseism at Campi Flegrei." We have now improved our introduction section, which now boasts a more up-to-date reference list (see our answers to the below comments).

Line 69-70 The Neapolitan area is surrounded by Mt. Somma-Vesuvius to the east and the Campi Flegrei volcanic system to the west. So I will suggest the authors to change Line 69-70 with the following sentence: "The densely populated (about 3 million) Neapolitan area, southern Italy, is in a state of constant threat provided by the proximity of Mt. Somma-Vesuvius and Campi Flegrei (CF) volcanic district."

Agreed. This has now been changed:

"The densely populated (about 3 million) Neapolitan area, southern Italy, is in a state of constant threat provided by the proximity of Mt. Vesuvius and the increasingly-restless Campi Flegrei (CF) volcanic district (Ricci *et al.*, 2013; Figure 1)."

Line 72-73 There are several theories around the activity at Campi Flegrei, which are not taken into account by the authors. Also the bibliography they use is very old (almost 10 years old) and lot of new data has been produced since 1999. As far as the activity in CF, some authors (Rosi and Sbrana, 1987; Orsi et al., 1996) relate the origin of Campi Flegrei either to the eruption of the Campanian Ignimbrite (CI, 39 ka, De Vivo et al., 2001), or to the Neapolitan Yellow Tuff (NYT,15 ka, Deino et al., 2004). Other authors (De Vivo et al., 2001; Rolandi et al., 2003) interpret the eruption of the CI not as a unique event originating in the Campi Flegrei caldera, but as a sequence of eruptive events occurred from fractures activated along the neotectonic Apennine fault system parallel to the Tyrrhenian coastline. These events, of ignimbritic origin, lasted from >300 ka to 19 ka and are not confined to a unique volcanic center in Campi Flegrei. According to Rolandi et al. (2003), only the NYT erupted within Campi Flegrei, whereas the CI has a much wider source area.

Based on these suggestions, we have now significantly improved this paragraph. Notably, we have: (1) included more up-to-date references and, (2) discussed both hypotheses for the eruption of the Campanian Ignimbrite. The text is now as follows:

"The eruptive history of the CF volcanic district can be characterised by two major eruptions: (1) the eruption related to the emplacement of the Campanian Ignimbrite about 39,000 years ago (De Vivo *et al.*, 2001) and, (2) the eruption of the Neapolitan Yellow Tuff (NYT) about 15,000 years ago (Deino *et al.*, 2004); although the area has been volcanically active for more than 300,000 years (Rolandi *et al.*, 2003). Today, the CF volcanic district is dominated by a resurgent, nested caldera (Figure 1) that hosts a large, shallow (< 4 km) hydrothermal system (e.g., De Natale *et al.*, 2006). The CF caldera is considered to have formed due to collapse following (1) both of the major eruptions (e.g., Barberi *et al.*, 1991; Orsi *et al.*, 1996) or, (2) the eruption of the NYT only (see Rolandi *et al.*, 2003 and references therein). In the latter hypothesis, the Campanian Ignimbrite is thought to be the result of eruptive events originating from pre-existing neotectonic faults formed during the Apennine uplift (De Vivo *et al.*, 2001; Rolandi *et al.*, 2003)."

Line 74 It is well established that the Campanian Ignimbrite (CI) is dated at 39ka (De Vivo et al., 2001) and the Neapolitan Yellow Tuff (NYT) at 15ka (Deino et al., 2004).

Agreed. The text now reads:

"The eruptive history of the CF volcanic district can be characterised by two major eruptions: (1) the eruption related to the Campanian Ignimbrite about 39,000 years ago (De Vivo *et al.*, 2001) and, (2) the eruption of the Neapolitan Yellow Tuff (NYT) about 15,000 years ago (Deino *et al.*, 2004); although the area has been volcanically active for more than 300, 000 years (Rolandi *et al.*, 2003)."

Line 84-98 This is just according with one source!! What about the other proposed models? Why the authors choose Chiodini's model over all the others? Why the authors prefer this model to the others published? It seems that the model from Chiodini et al is the one explaining the bradyseisimc events in CF, while the others are only specualtions. I would suggest the authors to rephrase the sentences in lines 84- 98 and to list ALL the proposed models for ground deformation at CF.

Our goal was never to review and critically appraise the various models proposed to explain ground deformation at CF. However, we agree that the paragraph could be improved to better explain the various models, and to remove any hint of unintentional bias. The paragraph now reads:

"However, the interpretation of long-term and short-term ground deformation patterns at CF is a matter of debate (see De Natale *et al.*, 2001 and De Natale *et al.*, 2006 for reviews on the topic). Models to explain the origin of the uplift can be broadly divided into two camps: those that consider solely the input of magma at depth (e.g., Berrino *et al.*, 1984; Bonafede *et al.*, 1986; Bianchi *et al.*, 1987) and those that invoke an interaction between magma and fluids (magmatic-hydrothermal models and thermodynamic models; e.g., Bonafede, 1991; Gaeta *et al.*, 1998; Bonafede and Mazzanti, 1998; De Natale *et al.*, 2001; Lundgren *et al.*, 2001; Troise *et al.*, 2001; Gaeta *et al.*, 2003; Chiodini *et al.*, 2003; Battaglia *et al.*, 2006; Gottsmann *et al.*, 2006; Troise *et al.*, 2007; Bodnar *et al.*, 2007; Lima *et al.*, 2009; Todesco *et al.*, 2010; D'Auria *et al.*, 2011; Troiano *et al.*, 2011; Chiodini *et al.*, 2012). The latter category can be broken down further into models that require the input of fresh magma from depth (e.g., Gaeta *et al.*, 1998) and those that consider magma body cooling and concomitant crystallisation (e.g., Bodnar *et al.*, 2007; Lima *et al.*, 2009). Other models account for the surface deformation by invoking an interaction between the pressure source and caldera boundary fractures (e.g., De Natale and Pingue, 1993; Beauducel *et al.*, 2004) or mechanical heterogeneities (e.g., Manconi *et al.*, 2010). While we note that the goal of this contribution is not to critically review the numerous models invoked to explain the ground deformation at CF, we highlight that the accuracy of all these models relies on accuracy of the rock physical property input parameters. Unfortunately, published laboratory investigations on the physical properties of representative materials from the CF caldera are rare…"

Line 94 Lima et al. (2009) present a quantitative model for subsidence and uplift, based on the linkage between bradyseism and magma body cooling and concomitant crystallization and fluid phase exsolution, coupling long timescale magma crystallization and volatile exsolution from melt and expulsion from magma to shorter timescale hydrothermal system behavior.

We now discuss this in the text:

"The latter category can be broken down further into models that require the input of fresh magma from depth (e.g., Gaeta *et al.*, 1998) and those that consider magma body cooling and concomitant crystallisation (e.g., Bodnar *et al.*, 2007; Lima *et al.*, 2009)."

Line 149 CI and NYT are NOT the two major eruption in CF. The authors are speculating that CI has occurred in the CF, while several authors suggested (in several articles, that the authors are ignoring) that it occurred OUTSIDE the CF. Furthermore, the ages attributed to the eruptions are outdated. Again, CI occurred 39 ka (De Vivo et al., 2001) and NYT occurred 15Ka (Deino et al., 2004).

We have now changed the wording of this paragraph:

"Our experiments were performed on samples of Neapolitan Yellow Tuff (NYT) and grey Campanian Ignimbrite (WGI), sampled from the two most abundant and widespread volcanic deposits in the CF volcanic district."

Line 359 Make reference with figure, example Fig. 6A. Apply to all the properties you discuss: S-wave -Figure 6B, Young modulus -figure 6C and so on.

We have now included references to each specific figure panel in the text.

Line 362 Add A-F. General comment: since you have labeled the figure A through F, you should somehow report the same labeling in the text.

We have now included references to each specific figure panel in the text.

Line 364 Add A-F. See comment for figure 6.

We have now included references to each specific figure panel in the text.

Line 366 Make reference to figure, labeling each property with the appropriate letter.

We have now included references to each specific figure panel in the text.

Line 374 Add A-B

We have now included references to each specific figure panel in the text.

Line 432 Figure 10 is composed by 3 SEM photos, which are not explained at all in the text. In particular what is figure 10A represent? From the figure caption is clear that C is a zoom of B, but what is A?

Figure 10 (now Figure 11) simply shows evidence for pore collapse in NYT. We do not think that the figure warrants a lengthy description. We think that our current description in the text is sufficient:

"Evidence of pore collapse is illustrated in the E-SEM image of a sample of NYT taken beyond P* provided as Figure 11."

However, we agree that we do not explain what is shown in panel A. We have now changed the text in the figure caption to read:

"Figure 11. Scanning electron microscope images of an as-collected sample of Neapolitan Yellow Tuff taken beyond P*. Panel A shows an overview of the post-P* microstructure at a low magnification. Panels B and C show detailed evidence of pore collapse (indicated by the white arrows). Panel C is a zoom of the white box shown in panel B."

Line 452 A-C. Description of figure? Why there are no pictures to compare WGI before and after the heating?

We have now included a new figure (Figure 13, see below) that shows photomicrographs of a sample of WGI heated to 1000 °C, and new text describing both Figures 12 and 13:

"Optical microscope photomicrographs of NYT and WGI thermally stressed to a temperature of 1000 °C are provided as Figures 12 and 13, respectively. Figure 12 shows that the microstructure of NYT is very different to that depicted in Figure 2B for the as-collected material. Many cracks are present (Figure 12A, B and C) and some areas contain 1 mm wide foamed glass (Figure 12A). By contrast, the microstructure of WGI, upon exposure to 1000 °C (Figure 13), is indistinguishable from the as-collected microstructure shown in Figure 2D. These observations have been previously reported in Heap *et al*. (2012)."

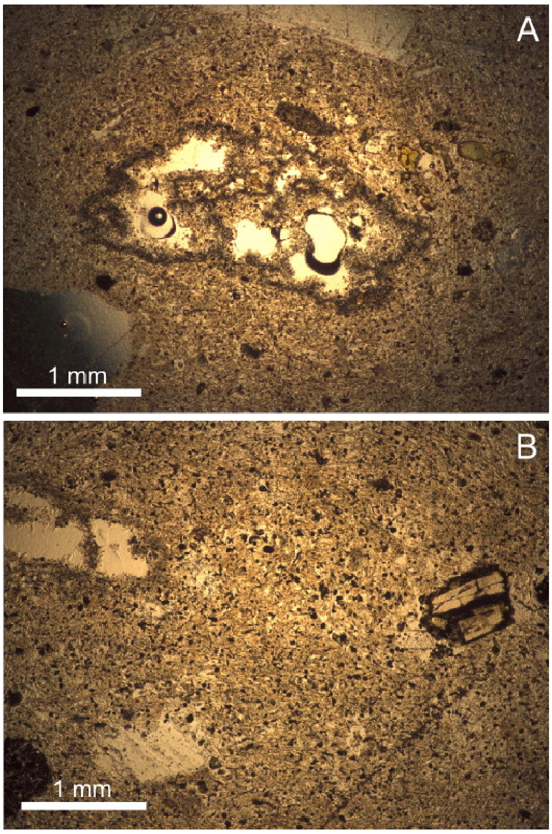

Figure 13. Optical microscope images of grey Campanian Ignimbrite thermally stressed to a temperature of 1000 °C. Both photographs are taken from Heap *et al*. (2012).

Line 456 Which ones? Reference such studies!

We have now included a reference:

"Detailed studies (de Gennaro and Colella, 1989 and references therein) on the thermal decomposition of the zeolites in NYT have highlighted that analcime loses water irreversibly…"

Line 458 "chabazite and phillipsite undergo a partial reversible dehydration at 240 °C". Reference??

See our answer to the above comment.

Line 506-509 Some parentheses are missing. Please check!

This has now been amended.

Line 519-520 why do you use ONLY this model??? There are 4-5 other models for the bradyseismic events at CF. Why assuming that this one is the right one?? Explain why this model is better than the others!!

As stated above, our goal was never to critically appraise the various ground deformation models. We aim to provide values for, and discussion on, experimentally determined values of elastic moduli and permeability (in the sentence in question we are discussing permeability). However, we appreciate that we could word the sentence to sound a little less biased. We have now reworded the sentence to:

"To date, the values of permeability used in the numerous thermodynamical and magmatic-hydrothermal models have spanned many orders of magnitude. For example…"

Line 537-539 What will be the difference between samples collected in boreholes from different parts of the caldera and those available from the AGIP survey? Wouldn't the sample be compacted as well? I do not understand the NEED to have more boreholes in the CF caldera, if the samples are going to be affected by the same "problems" of those from AGIP boreholes. Please explain the reasons why there is the need of collecting both.

The tuffs comprising the caldera are expected to be heterogeneous both vertically and laterally. The AGIP boreholes are a great place to start, but were drilled at the edges of the caldera. While the level of compaction may be comparable, temperatures are likely to be higher in the centre of the caldera, and the rocks exist within the hydrothermal system. Therefore, thermo-metamorphism/alteration is likely to be more prevalent in the centre of the caldera. To best understand the extent of the variation, both AGIP samples and samples from new, more central boreholes would be ideal (although we are aware that is easier said than done!). In an attempt to be clearer, we have changed the wording of this sentence:

"It is clear that systematic measurements on deep scientific borehole samples are now needed from multiple locations and depths within the caldera to assess the extent of the variability in static elastic moduli and permeability of the rocks that form the caldera."

Reviewer #3 (Maurizio de' Gennaro)

I carefully read the paper titled "The permeability and elastic moduli of tuff from Campi Flegrei…" also because I know one of the Authors so, I wanted to deepen the review as much as possible, always within my own specific competencies.

I cannot hide my perplexities on the scientific value of the paper as the objective of the Authors is the drawing of a model that can foresee and interpret the reasons of the soil deformations in Campi Flegrei, by means of laboratory data carried out on outcropping pyroclastic rock samples.

The authors find this comment very strange: we do not present a model in our manuscript. Our aim was to provide new data to improve the accuracy of the various pre-existing models. We are now more explicit about this point:

"…While we note that the goal of this contribution is not to critically review the numerous models invoked to explain the ground deformation at CF, we highlight that the accuracy of all these models relies on accuracy of the rock physical property input parameters…"

As you can note by the comments within the text the Authors evidence a very scarce knowledge of the most recent data (the radiometric data of NYT and WGI are not those from a recent literature). Also, they do not cite a paper from Lima et al. (2009) – Earth Science Reviews, which contain a detailed model of the Campi Flegrei underground as well as a different hypothesis concerning the causes of bradyseism. This aspect could even invalidate their model.

We appreciate that we should have been more up-to-date with our referencing. Thanks to the comments of reviewers #2 and #3, we think we have now suitable addressed this problem (see our answers above). We now also discuss the findings of Lima et al. (2009). However, as outlined above, we do not present a model to explain ground deformation at CF.

The most puzzling aspects are hereafter shortly reported:

1 The authors use the term tuff as a lithological term, but they have to clarify the concept before the first use. They have to point out that they are considering a tuff as a pyroclastic rock lithified owing to post depositional processes. As a matter of fact, the usage they make of the word tuff should be avoided, because the meaning is confusing: better to use a lithified pyroclastic rock.

In our experience, the materials used in this study are well known and well documented in the scientific literature as "tuffs". We note that reviewers #1 and #2, who have both worked on Campi Flegrei, were happy with our use of the word "tuff". However, we now refrain from calling the rocks "tuffs" until our use of the term is defined in the methods section: "In this paper we refer to both lithified pyroclastic rocks as "tuffs"." We have also changed a sentence in the abstract: "…the two most widespread lithified pyroclastic rocks from the Campi Flegrei volcanic district, Italy. Our data…"

2 Laboratory tests carried out on very small specimens of such a high heterogeneous material is a shadow on the reliability of the results. The Authors do not report the number of specimens used for each test. Is that a mean value? Not reported. The amount of lithics, pumice, matrix strongly affects the physical and mechanical behavior of the rock and in such a small specimen as those used by the Author, you can find prevailing matrix vs. pumices and vice versa with values completely different.

We agree that our experimental samples are relatively small when compared with the natural deposit. This is an inherent problem with experimental studies. There is little we can do to circumvent this problem: we cannot measure the permeability/strength of extremely large samples. However, since little is known as to the permeability of these materials, we would argue that our measurements still offer some valuable insight. Further, a report by Giberti et al. (2006) show that 12 and 125 cm^3 samples of a variety of rocks from CF have very similar porosities. We have now added a sentence in the "materials investigated" section to highlight these data:

"We note that, although our samples are small compared to the volume of the natural deposits, a report by Giberti *et al*. (2006) showed that the porosity of 12 cm^3 and 125 cm^3 samples were very similar, for a wide range of material from CF."

We performed one experiment per condition: our permeability data (a total of 130 permeability measurements) do not represent mean values. However, in an attempt to minimise sample variability, all of the samples were cored from the same block and in the same direction. Any anomalous samples (i.e., those containing large crystals, clasts, or pumice lapilli) were removed from the sample set. As a final check, the connected porosity and P-wave velocity of each sample was measured and any outlying samples were removed from the sample set. This rigorous selection method was employed to minimize the variability within the tested samples, allowing us to compare our data with greater confidence. We note that our measurements are in good agreement with previously published data on NYT quarry samples (e.g., Vanario et al., 2002; Vinciguerra et al., 2009). We now report that the permeability values presented in this study are not mean values: "Although one sample was used per thermal-stressing temperature, we note that great care was taken during sample selection to exclude samples that contained large heterogeneities and anomalous connected porosities." We have also included information regarding our sample selection procedure:

"While one of the goals of this contribution is to demonstrate the variability of different tuffs from the CF volcanic district, we strived to minimise the variability between samples cored from the same block by (1) coring many samples and selecting those within a strict porosity range, (2) discarding samples with obvious, large heterogeneities and, (3) discarding samples with anomalous P-wave velocities. Using these sample selection guidelines, our experiments under different conditions (different thermal stressing temperatures and pressures) can be compared with the greatest confidence."

3 One more aspect cannot be disregarded: the Authors hypothesize that the investigated samples undergo to mineralogical and physical modifications as a consequence of the increasing temperature and pressure. This can be modeled for outcropping materials but, if one considers the same pyroclastic materials buried for thousands years at different pressure and temperatures, they experienced a mineralogical evolution leading to the formation of an adularia-like feldspar and analcime. It cannot be excluded that the physical and mechanical features of the rocks are significantly different. This minerogenetic process was demonstrated to occur in the zeolitized phlegraean tuffs as described by de Gennaro et al., (2000) for samples of a deep borehole.

We agree. In fact, we discuss this at the end of the paper:

"Although our experiments were conducted (1) on samples from the two most widespread tuff lithologies that comprise CF, (2) under the relevant pressures or depths, (3) on water-saturated samples and, (4) over a range of thermal stressing temperatures, our samples were collected from an open quarry and may therefore not represent the material at depth (which have had time to compact, lithify, undergo chemical alteration; e.g., see de Gennaro *et al.*, 2000; see also the report by Giberti *et al.*, 2006). However, we highlight that the permeability measurements on borehole samples presented in the report of Giberti *et al.* (2006) suggest that (1) the permeability measurements of this study are not dissimilar to those measured on borehole samples and, (2) there is clearly no simple relationship between porosity and permeability…"

We now also offer comparisons between our data and those measured on borehole samples presented in the report of Giberti et al. (2006):

"This conjecture is confirmed by the reduced porosity of samples taken from borehole samples (see the report by Giberti *et al.*, 2006). Measurements on borehole samples from San Vito 1 (at the periphery of the inferred caldera) showed that the porosity decreases from 40.5 vol.% at the surface to 32.9, 21.9, 21.9, and 15.1 vol.% at depths of 810, 1420, 2130, and 2860 m, respectively. Our data shows that the porosity loss for NYT at 2860 m will be about 9 vol.%. A starting porosity of 44 vol.% yields a porosity, purely due to mechanical compaction, of 35 vol.% at a depth of 2860 m. This would imply a porosity loss due to chemical alteration of about 20 vol.% and suggests that the impact of hot, circulating fluids plays the dominant role in the porosity loss of these pyroclastic deposits at depth. Indeed, the report by Giberti *et al.* (2006) suggests that it is the presence of clay minerals, rather than compaction, that is responsible for the major changes in porosity with depth.

We are certainly aware that our permeability data were collected on rocks from open quarries and, although their properties were measured at the relevant pressures (and under a range of thermal stressing temperatures), may not therefore accurately represent the material at depth (which have had time to compact, lithify, undergo chemical alteration; e.g., see de Gennaro *et al.*, 2000). However, the open access report of Giberti *et al.* (2006) offers some permeability data on borehole samples. Data from borehole samples taken from San

Vito 1 (at the periphery of the inferred caldera) show that, as the porosity is reduced to 32.9, 21.9, 21.9, and 15.1 vol.% at depths of 810, 1420, 2130, and 2860 m, respectively, the permeability (Klinkenberg corrected gas permeabilities) of the samples are 1.1 x 10^{-13}, 2.5 x 10^{-16}, 7.9 x 10^{-16}, and 4.9 x 10^{-16} m^2, respectively. The permeability of the quarry samples of this study are 8.0 x 10^{-17} m^2 at a depth of about 2860 m. From these data it is clear that there is no simple relationship between the mechanical compaction and chemical alteration that afflicted the samples at depth (causing a substantial porosity loss) and their permeability."

4 As far as the paper by Lima et al., the Authors should properly read it as the detailed model of the Campi Flegrei underground and the hypothesis on the causes of bradyseism could strongly invalidate their model.

We now discuss the model presented by Lima et al. (2009) in the text:

"The latter category can be broken down further into models that require the input of fresh magma from depth (e.g., Gaeta *et al.*, 1998) and those that consider magma body cooling and concomitant crystallisation (e.g., Bodnar *et al.*, 2007; Lima *et al.*, 2009)."

However, and we must stress, we are not presenting, or promoting, a model in our paper. Our aim was to provide new data to improve the accuracy of the multitude of pre-existing models. The model of Lima et al. (2009) still requires knowledge of the elastic properties of the rocks within the caldera. They use a Young's modulus of 9 GPa, a shear modulus of 3 GPa, and a Poisson's ratio of 0.29.

5 The Authors refer to Campanian Ignimbrite as a non zeolitized counterpart of NYT. One should remember that a quite large portion of the Campanian Ignimbrite is also zeolitized!

This is a good point. We have now included the following sentence: "Although WGI does not contain any zeolites, we note that portions of the Campanian Ignimbrite are pervasively zeolitized (e.g., see Langella *et al.*, 2013)."

6 The Authors report the porosity of zeolitized pyroclastic rocks from Albani Hill, as documented in Vinciguerra et al. I am very doubtful on the fact that a zeolitized material could have such a low porosity. The same rocks usually provide values of 40-45% of porosity.

This value of porosity is taken from Vinciguerra et al. (2009). In this paper they state: "In contrast to what is commonly observed in outcrops, in the recovered cores the PR displays a very well-lithified facies, resulting from a pervasive zeolitization of the ash matrix." Another paper, dealing with the stratigraphy of the Colli Albani from a scientific borehole, also reports that the rock is zeolitized: "extremely lithified (zeolitized) ash and scoria deposit" (Mariucci et al., 2008). The porosity of this rock was measured using a standard technique (helium pycnometry) in Vinciguerra et al. (2009). We therefore have no reason to challenge their value.

Mariucci, M. T., Pierdominici, S., Pizzino, L. Marra, F., Montone, P., 2008. Looking into a volcanic area: An overview on the 350 m scientific drilling at Colli Albani (Rome, Italy). Journal of Volcanology and Geothermal Research, 176, 225-240.

The above considerations lead me to consider this paper not suitable for publication.

We are confused by the conclusion of "not suitable for publication" by reviewer #3. We feel as though we can suitably address all of his comments. Further, we note that this decision is a far cry from the positive, and relatively "minor", revisions suggested by reviewers #1, #2, and #4.

Line by line comments (on annotated pdf):
Page 1084, line 6: According to the quoted authors, the multiphase caldera formed trough at least two high size eruptions, the CI and NYT. Only the latter is phreatoplinian: the former is a purely magmatic ignimbrite forming event.

Point taken. This sentence, in response to a comment by reviewer #2, has now been changed to respect the hypothesis that the CI could be the result of eruptive events originating from pre-existing neotectonic faults. In fact, we removed the word "phreatoplinian".

Page 1084, line 8: Please, quote the right age of ca. 39 ka, reported in De Vivo et al.,2001; DE VIVO, B., ROLANDI, G., GANS, P.B., CALVERT, A., BOHRSON, W.A., SPERA, F.J., BELKIN, H.E., 2001. New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy). Mineral. Petrol. 73, 47-65. 37 ka, Fedele et al., 2008 FEDELE, L., SCARPATI, C., LANPHERE, M., MELLUSO, L., MORRA, V., PERROTT,A A., RICCI, G., 2008. The Breccia Museo formation, Campi Flegrei, southern Italy: geochronology, chemostratigraphy and relationship with the Campanian Ignimbrite eruption. Bull. Volcanol. 70, 1189-1219.

We agree. We now cite De Vivo et al. (2001): "The eruptive history of the CF volcanic district is characterised by two major eruptions: (1) the eruption related to the Campanian Ignimbrite about 39,000 years ago (De Vivo *et al.*, 2001) and…"

Page 1084, line 9: Please quote the right age of ca 15 ka reported by deino et al. (2004) DEINO, A.L., ORSI, G., DE VITA, S., PIOCHI, M., 2004. The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera Italy) assessed by 40Ar/39Ar dating method. J. Volcanol. Geotherm. Res. 133, 157-170.

We agree. We now cite Deino et al. (2001): "and, (2) the eruption of the Neapolitan Yellow Tuff (NYT) about 15,000 years ago (Deino *et al.*, 2004)…"

Page 1084, line 11: probably you wanted to write a millennium?

Agreed. We have now changed this to: "Although there has not been an eruption for almost

500 years (since the Monte Nuovo eruption of 1538 AD)…"

Page 1084, line 13: In recent times,

Agreed: "…In recent times, two major episodes…"

Page 1084, line 16: forced to evacuate the

We have now changed this sentence: "Surface uplift, on the order of several metres (bradyseism), and accompanying earthquakes in 1984 led to the evacuation of the town of Pozzuoli."

Page 1084, line 19: D'Auria et al. (2011) JGR report the occurrence of an uplift phase starting from 2005. The acme of the phase was reached in the September 2012-January 2013 time span. D'Auria L., Giudicepietro F., Aquino I., Borriello G., Del Gaudio C., Lo Bascio D., Martini M., Ricciardi G.P., Ricciolino P., Ricco C. (2011) - Repeated fluid-transfer episodes as a mechanism for the recent dynamics of Campi Flegrei caldera (1989–2010). Journal of Geophysical Research: Solid Earth, 116.

We have now changed this sentence to:

"Since then, there has been an overall subsidence trend (e.g., see Figure 2 in D'Auria *et al.*, 2011), periodically interrupted by small (cm-scale) and short-lived (months) uplifts in 1989, 1994, 2000-2001 (e.g., Lanari *et al.*, 2004; Bianco *et al.*, 2004; D'Auria *et al.*, 2011), and 2004-2006 (e.g., Saccorotti *et al.*, 2007; Trasatti *et al.*, 2008; D'Auria *et al.*, 2011)."

Page 1085, line 5: Relies

This has now been changed.

Page 1086, line 7: a consequence of

Agreed. We have now changed this sentence: "…This is usually interpreted as a consequence of the formation of new microcracks…"

Page 1086, line 9: owing to

We would rather keep the wording as it is.

Page 1086, line 18: thus confirming what already reported by de Gennaro et al 1983 and 1984 for NYT and zeolitized facies of Campanian Ignimbrite (Industrial Minerals).

Yes. But neither of these papers report strength data.

Page 1087, line 3: see previous note

We have now changed this: "Our experiments were performed on samples of Neapolitan Yellow Tuff (NYT) and grey Campanian Ignimbrite (WGI), sampled from the two most abundant and widespread volcanic deposits in the CF volcanic district."

Page 1087, line 6: It is necessary to report the sampling area (quarries) localization!

We agree. We have now added a new figure (Figure 1 in the revised manuscript, see below) showing a map of the Neapolitan region, and new text in the "materials investigated" section:

"NYT was sourced from an open quarry within the inferred CF caldera at Monte San Severino (i.e., within the red circle in Figure 1), while the WGI was sourced from an open quarry to the north-west of the town of Caserta (the blocks used in this study are the same as those used in Heap *et al.*, 2012)."

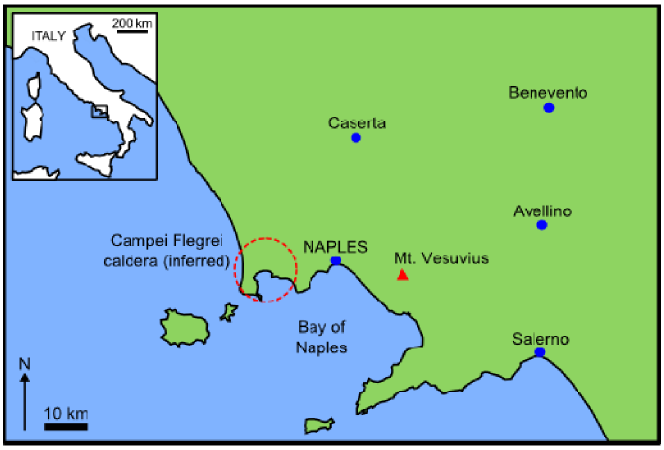

Figure 1. Map showing the location of the inferred Campi Flegrei caldera and the proximity of Naples to both the Campi Flegrei caldera and Mt. Vesuvius. The Neapolitan Yellow Tuff used in this study was sourced from an open quarry within the inferred CF caldera at Monte San Severino (i.e., within the red circle in Figure 1), while the Grey Campanian Ignimbrite was sourced from an open quarry to the north-west of the town of Caserta (the blocks used in this study are the same as those used in Heap *et al.*, 2012).

Page 1087, line 7: Display

We would prefer to keep "contain".

Page 1087, line 15: Pumiceous
Page 1087, line 15: ash mainly made up of glass shards and blocky shaped glass fragments

We have now changed this sentence: "…a matrix of pumiceous lapilli and glassy ash (glass shards and blocky shaped glass fragments)…"

Page 1087, line 22: delete this statement starting from giving

Agreed.

Page 1087, line 24: LANGELLA, A., BISH, D.L., CAPPELLETTI, P., CERRI, G., COLELLA, A., DE GENNARO, R., GRAZIANO, S.F., PERROTTA, A., SCARPATI, C., DE GENNARO, M., 2013. New insights into the mineralogical facies distribution of Campanian Ignimbrite, a relevant Italian industrial material, Applied Clay Science (2013)

We have now included this reference in two sentences: "…WGI (Figure 2C and 2D), feldspathized by authigenic mineralization processes, is made up of reversely-graded black scoriae embedded in an ashy matrix with subordinate lithics and crystals (Cappelletti *et al.*, 2003; Langella *et al.*, 2013)…" and "…Although WGI does not contain any zeolites, we note that portions of the Campanian Ignimbrite are pervasively zeolitized (e.g., see Langella *et al.*, 2013)…"

Page 1088, line 5: Which is the value of ambient humidity?

This sentence refers to the laboratory conditions of Zamora et al. (1994), Vanorio et al. (2005), and Vinciguerra et al. (2006). It is the norm to describe these conditions as "dry". However, rock is never completely dry (especially those that contain hydrated minerals!) and there is still moisture in the atmosphere. Our aim was to use a term that better respects the experimental conditions. We chose "ambient laboratory humidity". However, while we note that laboratory humidity is usually quite low, since these studies did not quote humidity values, we cannot provide a value.

Page 1088, line 8: Specify what kind of fluid phase

We have now included this information: "Since the tuffs of CF are present at depth, and are likely to contain a fluid phase (e.g., a mixture of meteoric water and seawater contaminated by rising magmatic gases, see Valentino *et al.*, 1999), we consider experimental…"

Page 1094, line 3: Does the Authors expect a total range of natural variability for samples cored from the same and unique block? I can say it is much wider, on a scale that considers the whole deposit.

We agree that the range of natural variability within a 30 cm x 30 cm x 30 cm block of material will be much less than the variability of the whole deposit. There is an important distinction here. We were keen to measure the physical properties of very different facies in order to investigate the variability of the deposits at CF, i.e., we welcomed variability

(although we agree that two facies is unlikely to respect the full extent of the variability, something we discuss at the end of the paper). We chose two rocks that (1) are prevalent in the pre-existing literature, (2) are from the two main eruptions that occurred within the CF volcanic district and, (3) contain different mineral constituents (one with zeolites, and one without). In terms of a "first pass" of the variability at CF, we are unsure we could have chosen better. However, within the individual blocks, we were keen to minimise sample variability. If we want to compare experiments on the same material, but at different conditions (i.e., heated to different temperatures to try to understand the influence of thermal stressing on material properties), the variability between samples must be kept at a minimum so that any differences we see in the data can be attributed to the change in condition, and not the natural variability of the rock. The sentence in question: "The different values obtained for the different thermal stressing temperatures are well within the expected range of natural variability between different samples cored from the same block" refers to the small differences between the curves in the figure. Since these differences are small (in fact, the same scatter would be true for a "well-behaved" sandstone), and show no obvious trend, we can conclude that they are unlikely to be the result of the thermal stressing. We have now included a new paragraph explaining our sample selection procedure:

"While one of the goals of this contribution is to demonstrate the variability of different tuffs from the CF volcanic district, we strived to minimise the variability between samples cored from the same block by (1) coring many samples and selecting those within a strict porosity range, (2) discarding samples with obvious, large heterogeneities and, (3) discarding samples with anomalous P-wave velocities. Using these sample selection guidelines, our experiments under different conditions (different thermal stressing temperatures and pressures) can be compared with the greatest confidence."

Page 1096, line 8: I think that the Authors should not disregard how many specimens have been investigated for each test. The sample size is very low, the material is highly heterogeneous. One single data is unacceptable for any kind of consideration. Or the reported data are mean values? In my experience, any new produced data on zeolitized rocks may even more stress the heterogeneity of these rocks.

We performed one experiment per condition: our permeability data (a total of 130 permeability measurements) do not represent mean values. However, in an attempt to minimise sample variability, all of the samples were cored from the same block and in the same direction. Any anomalous samples (i.e., those containing large crystals, clasts, or pumice lapilli) were removed from the sample set. As a final check, the connected porosity of each sample was measured and any outlying samples were removed from the sample set. This rigorous selection method was employed to minimize the variability within the tested samples, allowing us to compare our data with greater confidence. We now report that the permeability values presented in this study are not mean values: "Although one sample was used per thermal-stressing temperature, we note that great care was taken during sample

selection to exclude samples that contained large heterogeneities and anomalous connected porosities/P-wave velocities."

We would certainly expect that any new permeability data would stress the variability of zeolitized rocks (although, any new data would also be measured on "small" samples). We would welcome these data; in fact, one of the conclusions of our paper is that more experiments on the full range of materials are now needed to assess the extent of the variability at Campi Flegrei.

Page 1096, line 14: Not surprising at all! The problem is not the slight difference in porosity. If you consider the specific surface area of the two materials there is an order of magnitude difference. A zeolitized tuff with about 50% of zeolite has a 8-9% of water (wt.%) content at ambient temperature vs 0% for WGI.

While we are inclined to agree that the specific surface area of these materials are probably quite different, the link between permeability and specific surface area is not as simple as depicted by reviewer #3. For example, Bentheim sandstone, which has a porosity of 23 vol.% and a permeability of about 1.0 x 10^{-12} m^2 has the same specific surface area as Lanhelin granite, which has a porosity of about 1 vol.% and a permeability of about 1.0 x 10^{-19} m^2. We suspect that the difference in permeability is more related to the difference in microstructure (i.e., the connectivity of the porosity). We have changed the text to emphasise our stance on this matter:

"This difference in permeability could be considered surprising if one were to solely consider their connected porosities (44 and 49 vol.% for NYT and WGI, respectively). The difference in permeability is likely due to differences in pore space connectivity, perhaps related to the extent of zeolitization and lithification. A similar conclusion was drawn by Vinciguerra *et al.* (2009)."

Page 1096, line 20: I made a lot of porosity measurements on the zeolitized tuff from Albani Hill and I never found such a low porosity value.

This value of porosity is taken from Vinciguerra et al. (2009). In this paper they state: "In contrast to what is commonly observed in outcrops, in the recovered cores the PR displays a very well-lithified facies, resulting from a pervasive zeolitization of the ash matrix." Another paper, dealing with the stratigraphy of the Colli Albani from a scientific borehole, also reports that the rock is zeolitized: "extremely lithified (zeolitized) ash and scoria deposit" (Mariucci et al., 2008). The porosity of this rock was measured using a standard technique (helium pycnometry) in Vinciguerra et al. (2009). We therefore have no reason to challenge their value.

Mariucci, M. T., Pierdominici, S., Pizzino, L. Marra, F., Montone, P., 2008. Looking into a volcanic area: An overview on the 350 m scientific drilling at Colli Albani (Rome, Italy). Journal of Volcanology and Geothermal Research, 176, 225-240.

Page 1097, line 19: They are NYT and WGI only from a volcanological point of view. From a mineralogical and petrophysical point of they are something else.

This is a rather cryptic comment. NYT is not NYT from a mineralogical or petrophysical point of view?

Page 1098, line 3: That is exactly the percent of water bound to zeolites and smectites always occurring in NYT! You can easily achieve this value by a simple LOI

Yes. The reported number, from Heap et al. (2012), was determined by simple loss-on-ignition (thermo-gravimetric) analysis. The NYT used in this study is from the same blocks used in Heap et al. (2012). We have now reworded this sentence to make this more explicit: "Heap *et al*. (2012) showed, using a combination of thermo-gravimetric analysis, optical microscopy, and X-ray diffraction, that NYT lost 18% of its initial mass…"

Page 1098, line 15: Wrong citation. The paper is de Gennaro et al., 1987.

De Gennaro and Colella (1989) summarise the findings of the key papers on the influence of temperature on hydrated tuff from Campi Flegrei. We would prefer to keep this reference (that also cites de Gennaro et al., 1987). However, we are aware that not all of the data in de Gennaro and Colella (1989) are unique to this study. We have now changed this sentence to: "Phillipsite breaks down during dehydration and chabazite undergoes reversible hydration at 350 °C, and, by 900 °C, the structure of the zeolites will be so damaged that no further water molecules can be stored (see de Gennaro and Colella, 1989 and references therein)."

Page 1098, line 17: These two phenomena are strongly interconnected as the framework collapse of zeolites defines a shrinkage of the specimen and the consequent cracks.

Agreed. We have now altered the wording of this sentence: "Therefore, the reported changes in NYT physical properties are due to a combination of thermal cracking and the cracks formed as a result of the disintegration of the material through the loss of zeolites."

Page 1102, line 6: ....that whoever studies NYT and Campanian Ignimbrite well knows.......

Yes. But we show, for the first time, the heterogeneity in permeability and elastic moduli of different tuffs from Campi Flegrei.

A e B sono ad ingrandimenti diversi e quindi non confrontabili. Ovviamente anche in questo caso vale la considerazione sulla eterogeneità del materiale.

All of the SEM pictures in Figure 10 (now Figure 11) were taken under different magnifications. Our aim with panel A was to show an overview of the post-P* microstructure, whilst panels B and C focus on evidence for pore collapse. It was never our intention to compare panels A and B. However, we appreciate that we do not clearly explain this in either the text or the figure caption. We have now changed the figure caption to:

"Figure 11. Scanning electron microscope images of an as-collected sample of Neapolitan Yellow Tuff taken beyond P*. Panel A shows an overview of the post-P* microstructure at a low magnification. Panels B and C show detailed evidence of pore collapse (indicated by the white arrows). Panel C is a zoom of the white box shown in panel B."

Reviewer #4 (anonymous)

The paper "The permeability and elastic moduli of tuff from Campi Flegrei, Italy: implications for ground deformation modelling" concerns estimation of parameters which are critical in the evaluation of the Campi Flegrei caldera deformation due to injection of both magma or magmatic fluids. The argument is of great interest, as acquisition of data on deformation of the caldera is in progress as number and quality, and it would deserves the publication.

We are pleased that reviewer #4 deems our work "critical", "of great interest", and that it "deserves the publication".

Some critical question arise:

1) the samples used by author, if I understood, seams (line 7, section material investigated) relative to one block of material for type (NYT and WGI) and collected in open quarries, and the estimated porosity is 44 and 49 vol.% respectively. The Phlegrean Field show a very high variability in porosity and permeability (see for examples http://www.fedoa.unina.it/398/1/Campi_Flegrei.pdf where core samples by AGIP oil company are analyzed) even at the same sampling depth (different wells) showing that not only temperature and pressure act on these parameters but evidently these depend on lithotypes and alteration degree; moreover if we consider even the dependence on depth, values of porosity range from some % to about 60% while permeability change up to 3 magnitude order and more. This mean, in general, extrapolation of the analysis performed in the paper are difficult to sustain and extend to the whole caldera sediments, and it as it stand seems applicable only to that open quarry samples.

We agree that the rocks of Campi Flegrei span a wide range of porosity and permeability. For example, in the report (which is not peer reviewed) highlighted by the reviewer, the porosity of the rocks in the San Vito 1 well are 40.5% near the surface and 15.1% at a depth of 2860 m. Low porosity (6-8%) lavas were encountered in some of the other wells. The permeability of the aforementioned borehole tuff samples ranges from 10^{-13} to 10^{-16} m^2. The permeabilities of our open quarry samples also span a similar range (from 10^{-13} to 10^{-15} m^2 at Peff = 5 MPa). While we understand that our samples may not accurately represent the rock at depth (due to compaction, lithification, alteration), we would contend that (1) measurements on tuffs from Campi Flegrei are actually extremely rare, adding interest to our open quarry rock data (further, we feel that we are very open about the limitations of our data), (2) that our data still highlight that the physical properties of the tuffs of Campi Flegrei can be very variable. We agree that, using our data, it is difficult to "extend to the whole caldera sediments", but, and as we conclude in the paper, we envisage that our data simply highlight that consideration should be afforded to the input parameters in ground deformation modelling and the need for more experimental studies, using our study as a stepping stone. We have now added several paragraphs discussing the difference between our data and data from borehole samples:

“This conjecture is confirmed by the reduced porosity of samples taken from borehole samples (see the report by Giberti *et al.*, 2006). Measurements on borehole samples from San Vito 1 (at the periphery of the inferred caldera) showed that the porosity decreases from 40.5 vol.% at the surface to 32.9, 21.9, 21.9, and 15.1 vol.% at depths of 810, 1420, 2130, and 2860 m, respectively. Our data shows that the porosity loss for NYT at 2860 m will be about 9 vol.%. A starting porosity of 44 vol.% yields a porosity, purely due to mechanical compaction, of 35 vol.% at a depth of 2860 m. This would imply a porosity loss due to chemical alteration of about 20 vol.% and suggests that the impact of hot, circulating fluids plays the dominant role in the porosity loss of these pyroclastic deposits at depth. Indeed, the report by Giberti *et al*. (2006) suggests that it is the presence of clay minerals, rather than compaction, that is responsible for the major changes in porosity with depth.

We are certainly aware that our permeability data were collected on rocks from open quarries and, although their properties were measured at the relevant pressures (and under a range of thermal stressing temperatures), may not therefore accurately represent the material at depth (which have had time to compact, lithify, undergo chemical alteration; e.g., see de Gennaro *et al*., 2000). However, the open access report of Giberti *et al*. (2006) offers some permeability data on borehole samples. Data from borehole samples taken from San Vito 1 (at the periphery of the inferred caldera) show that, as the porosity is reduced to 32.9, 21.9, 21.9, and 15.1 vol.% at depths of 810, 1420, 2130, and 2860 m, respectively, the permeability (Klinkenberg corrected gas permeabilities) of the samples are 1.1 x 10^{-13}, 2.5 x 10^{-16}, 7.9 x 10^{-16}, and 4.9 x 10^{-16} m^2, respectively. The permeability of the quarry samples of this study are 8.0 x 10^{-17} m^2 at a depth of about 2860 m. From these data it is clear that there is no simple relationship between the mechanical compaction and chemical alteration that afflicted the samples at depth (causing a substantial porosity loss) and their permeability.”

2) A second question arise relative to the usefulness of the relation found by authors about permeability and porosity and showed in the figure 3 and 4. The sample analyzed by authors has been subject to a different history from the NYT and WGI sediments which fill the caldera at different depth and different time; pressure, time and temperature contribute heavily to the alteration of the materials. It should be performed analysis, by the authors, to some sample collected at different depths to contribute in a substantial improving of our knowledge on the caldera. Papers relative to the physical parameters of the caldera use widely measurements on cored samples. These are, for example, analysis of permeability and porosity on cored samples for which suddenly decrease both pressure and temperature as they are extracted from the wells. The question touched by the authors is critical and it would be very interesting if they could measure hysteresis curves; the curves in fig 4 beyond the P* point clearly shows irreversible processes, as stated in the paper. If authors could show some curves with hysteresis cycles it could contribute to the extrapolation of the measured parameters to the original state before the extraction of the sample from the wells.

We agree that the history of our samples (heating them to different temperatures and pressurising them in a pressure vessel) differs from the natural case. We discuss this at

length in the discussion section (and we have included new discussion, see our answers above). In fact, we conclude by stating that measurements on borehole samples are more representative and that future studies should focus in this direction. However, and we would still argue the case, there are extremely few papers that contain such data. The report "Geophysical Exploration of the Campi Flegrei (Southern Italy) Caldera' Interiors: Data, Methods and Results" highlighted by the reviewer certainly contains some interesting data, but this document was not peer-reviewed. For instance, there is extremely little information on how the permeability values were measured (confining pressure? pore fluid pressure? pressure gradient?...). Unfortunately, we did not measure permeability while we were reducing the confining pressure on the sample. We do understand the interest of this. However, in the scenario described by the reviewer, perhaps this is best done on samples taken from boreholes.

3) page 1092 row 1-5. Authors stated that they estimate the values of the young modulus in the linear zone at effective pressure of 5 Mbar, but in order to render usefulness the static modules, to apply static elasticity modelisation at episodes of deformation, they would estimate the static moduli at different pressure and temperature or show that they do not depend on these variables or in negligible way.

Our goal was to simply demonstrate the difference between static and dynamic moduli under the same pressure conditions. We completely agree that the static (and dynamic, see Figures 7 and 8) moduli will change with increasing pressure or temperature. Rock will be stiffer at higher pressures. For example, we measured the Young's modulus for an unpublished "wet" uniaxial experiment on NYT and found a value of 1.6 GPa (lower than the 2.1 GPa found at 5 MPa). However, our high porosity quarry samples are already ductile at 5 MPa: at higher pressures the "elastic window" may well be negligible. Further, P* is at about 15 MPa. To satisfy the reviewer's request, static elastic moduli should be measured on borehole samples (that contain a lower porosity). However, no such data exists (and we do not have borehole samples). We have now added a sentence to this effect in the paper:

"We note that, while values of the shear modulus of borehole samples provided in the report of Giberti *et al*. (2006) show that the dynamic shear modulus can reach values of 10.9 GPa at a depth of 2860 m, no complementary static values exist. Future research should focus on the determination of the static elastic moduli of borehole samples."

Minor comments

In all the relations showed in figures and in tables it lack the error bars, making it difficult to evaluate the grapes.

In fact, the error bars are very small. The natural sample variability – something we tried to minimise – is much larger. We now include tables showing the expected measurement

accuracies and sample variability, and discussion on our method to reduce the variability between samples cored from the same block (see our answers above).

page 1101 row 11-12. I would not say that data analyzed emphasized the heterogeneous nature of the tuffs of the caldera, they are only 2 types of tuffs
page 1102 row 5-6. Hold the same comment as the previous.

Perhaps our data do not respect the full extent of the variability. But, our tuffs still display a difference in permeability of two orders of magnitude. We have now expanded the sentence in our conclusions to emphasise the fact that we do not capture the full extent of the variability at CF:

"While we urge that these new laboratory data should be considered in routine ground deformation modelling, our study highlights that the physical properties of just two rocks that comprise the caldera at Campi Flegrei can be extremely heterogeneous (we also anticipate that future measurements will further expand our knowledge of such heterogeneity)."

page 1117 figure 5 B. There is a strange intersection of the permeability/pressure curves at different temperature around 12-30 MPa, it deserve probably some explanation, or error bars could include it?

We discuss this in the text. It is due to the natural variability between samples cored from the same block (not measurement error). However, we did our best to avoid variability between samples cored from the same block, and we now provide our transducer accuracies and the expected natural variability as Tables 2 and 3 (see our answers above).

The permeability and elastic moduli of tuff from Campi Flegrei, Italy: Implications for ground deformation modelling

M. J. Heap[1], P. Baud[1], P. G. Meredith[2], S. Vinciguerra[3,4], and T. Reuschlé[1]

[1]Laboratoire de Déformation des Roches, Équipe de Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France.

[2]Rock & Ice Physics Laboratory, Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK.

[3]Department of Geology, University of Leicester, University Road, Leicester, LE1 7RH, UK.

[4]British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, UK.

Abstract

The accuracy of ground deformation modelling at active volcanoes is a principal requirement in volcanic hazard mitigation. However, the reliability of such models relies on the accuracy of the rock physical property (permeability and elastic moduli) input parameters. Unfortunately, laboratory-derived values on representative rocks are usually rare. To this end we have performed a systematic laboratory study on the influence of pressure and temperature on the permeability and elastic moduli of samples from the two most widespread lithified pyroclastic deposits at the Campi Flegrei volcanic district, Italy. Our data show that the water permeability of Neapolitan Yellow Tuff and a tuff from the Campanian Ignimbrite differ by about 1.5 orders of magnitude. As pressure (depth) increases beyond the critical point for inelastic pore collapse (at an effective pressure of 10-15 MPa, or a depth of about 750 m), permeability and porosity decrease significantly, and ultrasonic wave velocities and dynamic elastic moduli increase significantly. Increasing the thermal stressing temperature increases the permeability and decreases the ultrasonic wave velocities and dynamic elastic moduli of the Neapolitan Yellow Tuff; whereas the tuff from the Campanian Ignimbrite remains unaffected. This difference is due to the presence of thermally unstable zeolites within the Neapolitan Yellow Tuff. For both rocks we also find, under the same pressure conditions, that the dynamic (calculated from ultrasonic wave velocities) and static (calculated from triaxial stress-strain data) elastic moduli differ significantly. The choice of elastic moduli in ground deformation modelling is therefore an important consideration. While we urge that these new laboratory data should be considered in routine ground deformation modelling, we highlight the challenges for ground deformation modelling based on the heterogeneous nature (vertically and laterally) of the rocks that comprise the caldera at Campi Flegrei.

1. Introduction

Monitoring ground deformation, the surface expression of deeper magmatic and/or hydrothermal activity, at active volcanoes is an important tool in volcanic hazard forecasting and mitigation. Ground deformation at a volcano [measured by global positioning system (GPS) satellites, interferometric synthetic aperture radar (InSAR), tiltmeters, or electronic distance metres

(EDM)] are typically analysed using inverse problem models that consider a source (e.g., a magma chamber, a zone of overpressurised fluids, or a combination of the two) embedded within a homogenous elastic or viscoelastic half-space (e.g., Mogi, 1958; Dzurisin, 2006; Hurwitz *et al.*, 2007). These models yield important information regarding the location, shape, and volume/pressure changes of the source. The accuracy of such modelling relies on the accuracy of the rock physical property input parameters (typically elastic moduli and permeability, depending on the type of model). Even small changes in the values of key controlling parameters can lead to large differences in the rate, magnitude, and geometry of ground surface deformation (e.g., Hurwitz *et al.*, 2007). For instance, a recent contribution using viscoelastic modelling to better understand flank motion and summit subsidence at Kīlauea (Hawai'i) showed that deformation rates are enhanced when the elastic moduli input parameters are lowered (Plattner *et al.*, 2013). Furthermore, homogenous half-space models, by definition, assume that all the rocks that comprise the volcano have identical physical properties. However, volcanoes are built from successive eruptive episodes and thus the physical properties of the rock strata that form the edifice are likely to span a wide range. For this reason, conventional homogenous half-space modelling at volcanoes has recently been considered an oversimplification that could lead to misinterpretation of the derived source parameters (Manconi *et al.*, 2007; Manconi *et al.*, 2010). For instance, Manconi *et al*. (2010) showed that this "standard" approach can lead to inaccurate values for the source volume changes. Therefore, models that consider mechanical heterogeneities (e.g., Manconi *et al.*, 2007; Manconi *et al*., 2010) require a good knowledge of the breadth of elastic moduli that can be expected for representative rocks, and thermodynamic and magmatic-hydrothermal models (e.g., Hurwitz *et al.*, 2007; Todesco *et al*., 2010) require accurate values of their permeability and elastic moduli. However, such laboratory data are commonly scarce or absent.

The densely populated (about 3 million) Neapolitan area, southern Italy, is in a state of constant threat provided by the proximity of Mt. Vesuvius and the increasingly-restless Campi Flegrei (CF) volcanic district (Ricci *et al.*, 2013; Figure 1). The eruptive history of the CF volcanic district can be characterised by two major eruptions: (1) the eruption related to the emplacement of the Campanian Ignimbrite about 39,000 years ago (De Vivo *et al.*, 2001) and, (2) the eruption of the Neapolitan Yellow Tuff (NYT) about 15,000 years ago (Deino *et al.*, 2004); although the area has been volcanically active for more than 300,000 years (Rolandi *et al.*, 2003).

Today, the CF volcanic district is dominated by a resurgent, nested caldera (Figure 1) that hosts a large, shallow (< 4 km) hydrothermal system (e.g., De Natale *et al.*, 2006). The CF caldera is considered to have formed due to collapse following (1) both of the major eruptions (e.g., Barberi *et al.*, 1991; Orsi *et al.*, 1996) or, (2) the eruption of the NYT only (see Rolandi *et al.*, 2003 and references therein). In the latter hypothesis, the Campanian Ignimbrite is thought to be the result of eruptive events originating from pre-existing neotectonic faults formed during the Apennine uplift (De Vivo *et al.*, 2001; Rolandi *et al.*, 2003). Although there has not been an eruption for almost 500 years (since the Monte Nuovo eruption of 1538 AD), CF has become increasingly restless and is densely monitored by permanent seismic and ground deformation networks. In recent times, two major episodes of unrest have occurred, between 1969-1972 and 1982-1984 (Bianchi *et al.*, 1987; Bonafede, 1991). Surface uplift, on the order of several metres (bradyseism), and accompanying earthquakes in 1984 led to the evacuation of the town of

Pozzuoli. Since then, there has been an overall subsidence trend (e.g., see Figure 2 in D'Auria *et al.*, 2011), periodically interrupted by small (cm-scale) and short-lived (months) uplifts in 1989, 1994, 2000-2001 (e.g., Lanari *et al.*, 2004; Bianco *et al.*, 2004; D'Auria *et al.*, 2011), and 2004-2006 (e.g., Saccorotti *et al.*, 2007; Trasatti *et al.*, 2008; D'Auria *et al.*, 2011). However, the interpretation of long-term and short-term ground deformation patterns at CF is a matter of debate (see De Natale *et al.*, 2001 and De Natale *et al.*, 2006 for reviews on the topic). Models to explain the origin of the uplift can be broadly divided into two camps: those that consider solely the input of magma at depth (e.g., Berrino *et al.*, 1984; Bonafede *et al.*, 1986; Bianchi *et al.*, 1987) and those that invoke an interaction between magma and fluids (magmatic-hydrothermal models and thermodynamic models; e.g., Bonafede, 1991; Gaeta *et al.*, 1998; Bonafede and Mazzanti, 1998; De Natale *et al.*, 2001; Lundgren *et al.*, 2001; Troise *et al.*, 2001; Gaeta *et al.*, 2003; Chiodini *et al.*, 2003; Battaglia *et al.*, 2006; Gottsmann *et al.*, 2006; Troise *et al.*, 2007; Bodnar *et al.*, 2007; Lima *et al.*, 2009; Todesco *et al.*, 2010; D'Auria *et al.*, 2011; Troiano *et al.*, 2011; Chiodini *et al.*, 2012). The latter category can be broken down further into models that require the input of fresh magma from depth (e.g., Gaeta *et al.*, 1998) and those that consider magma body cooling and concomitant crystallisation (e.g., Bodnar *et al.*, 2007; Lima *et al.*, 2009). Other models account for the surface deformation by invoking an interaction between the pressure source and caldera boundary fractures (e.g., De Natale and Pingue, 1993; Beauducel *et al.*, 2004) or mechanical heterogeneities (e.g., Manconi *et al.*, 2010).

While we note that the goal of this contribution is not to critically review the numerous models invoked to explain the ground deformation at CF, we highlight that the accuracy of all these models relies on accuracy of the rock physical property input parameters. Unfortunately, published laboratory investigations on the physical properties of representative materials from the CF caldera are rare. Values of permeability have, thus far, either been inferred from *in-situ* observations (Rosi and Sbrana, 1987) or have been taken from experiments conducted on NYT under ambient pressure conditions (Ascolese *et al.*, 1993a; Ascolese *et al.*, 1993b; Peluso and Arienzo, 2007). In the most recent study, Peluso and Arienzo (2007) measured the permeability of NYT at ambient pressure to be between 2.0 x 10^{-15} and 6.3 x 10^{-17} m^2 (the range of porosity was between 48 and 52 vol.%). However, not only are the deposits within the CF caldera present at depth (which is likely to severely influence their permeability), but it is known that the permeability of lithified pyroclastic deposits can be highly variable (a variety of representative materials should therefore be measured), depending on their degree of lithification (Vinciguerra *et al.*, 2009). We also highlight that permeability data of borehole samples are presented in an open access report (Giberti *et al*., 2006). For example, this report shows, for the San Vito 1 borehole, that the permeability can range from 10^{-13} m^2 at the surface to 10^{-16} m^2 at a depth of almost 3000 m.

Elastic moduli are generally assumed, or extrapolated from seismic tomography studies (e.g., Chiarabba and Moretti, 2006; Vinciguerra *et al*., 2006). Typically, Poisson's ratio is taken as 0.3 and shear modulus as 5 GPa (e.g., De Natale *et al*., 1991). However, dynamically-determined elastic moduli (i.e., those calculated from ultrasonic wave velocities) may not represent the most appropriate values to use in volcano ground deformation modelling. Deformation caused by a volcanic source proceeds quasi-statically rather than dynamically and therefore static elastic moduli are likely to be the most appropriate input parameters (Heap *et al*., 2009; Manconi *et al*., 2010). It is well known that dynamic and static moduli differ as a result of the large differences in the frequency at which they were measured (Simmons and Brace, 1965; Cheng and Johnston, 1981; Eissa and Kazi, 1989; Ciccotti and Mulargia, 2004; Ciccotti *et al*., 2004). Static elastic moduli for representative materials from CF are not yet available (see Manconi *et al.*, 2010).

The pyroclastic deposits that comprise the caldera at CF are exposed to elevated temperatures, as evidenced by two-dimensional conductive/convective numerical modelling (Wohletz *et al.*, 1999), seismic attenuation tomography (de Lorenzo *et al.*, 2001), and infrared imaging (Chiodini *et al.*, 2007). Surface geothermal gradients of about 150-200 °C/km are estimated (for the first 1.5 km) and, at the edge of the hydrothermal system, a temperature of 420 °C was measured at a depth of 3 km (AGIP borehole San Vito 1, de Lorenzo *et al*., 2001). It has been shown previously that thermal stresses can increase the permeability (e.g., Homand-Etienne and Troalen, 1984; Jones *et al.*, 1997; David *et al.*, 1999; Nara *et al.*, 2011) and decrease the Young's modulus (e.g., Keshavarz *et al.*, 2010) of rock. This is usually interpreted as being a consequence of the formation of new microcracks due to the build-up of internal thermal stresses. Volcanic rocks are persistently challenged by elevated temperatures due to their proximity to large permanent heat sources, and the fluctuations in temperature caused by the movement of magma, are therefore especially prone to thermal microcracking. Furthermore, many fine-grained pyroclastic deposits can be further jeopardised by thermal stresses due to the presence of thermally unstable zeolites (Heap *et al.*, 2012). Since zeolitization promoted lithification, the loss of zeolites can impose dramatic consequences on rock physical properties. Recent data has shown that NYT becomes structurally unstable upon exposure to high (100-750 °C) temperatures, resulting in a severe decrease in both tensile and compressive strength (Heap *et al.*, 2012). A recent contribution by Manconi *et al*. (2010) highlighted the need for the evaluation of the temperature-dependence of the material properties of the rocks at CF.

For the reasons outlined above we have conducted a systematic study of the influence of pressure and temperature on the physical properties (permeability, porosity, ultrasonic velocities, and elastic moduli) of two lithified pyroclastic deposits (one zeolitized) from CF. We first present the investigated materials and methods. We then present our experimental results before discussing our data in terms of ground deformation modelling at CF.

2. Materials investigated

Our experiments were performed on samples of Neapolitan Yellow Tuff (NYT) and grey Campanian Ignimbrite (WGI), sampled from the two most abundant and widespread volcanic deposits in the CF volcanic district. NYT was sourced from an open quarry within the inferred CF caldera at Monte San Severino (i.e., within the red circle in Figure 1), while the WGI was sourced from an open quarry to the north-west of the town of Caserta (the blocks used in this study are the same as those used in Heap *et al.*, 2012). In this paper we refer to both lithified pyroclastic rocks as "tuffs".

NYT and WGI contain average connected porosities of 44 and 49 vol.%, respectively (measured using the triple weight water saturation technique; Guéguen and Palciauskas, 1994). We note that, although our samples are small compared to the volume of the natural deposits, a report by Giberti *et al*. (2006) showed that the porosity of 12 cm^3 and 125 cm^3 samples were very similar, for a wide range of material from CF. Photographs and optical microscopy photomicrographs of the samples are provided as Figure 2 and their ambient pressure, "as-collected" (i.e., "natural" samples that have undergone no heating or deformation) physical properties are listed in Table 1. NYT (Figure 2A and 2B), a trachytic pyroclastic deposit characterized by both pyrogenic and authigenic phases (de Gennaro *et al.*, 2000), contains phenocrysts of sanidine, plagioclase, clinopyroxene, biotite, and minor amounts of Ti-magnetite and apatite within a matrix of pumiceous lapilli and glassy ash (glass shards and blocky shaped glass fragments). X-ray diffraction pattern analysis has indicated the presence of phillipsite, chabazite, and analcime (Heap *et al.*, 2012). The mean content of these zeolites in NYT can exceed 50 wt. % (e.g., de Gennaro *et al.*, 1990; de Gennaro *et al.*, 2000). WGI (Figure 1C and 1D), feldspathized by authigenic mineralization processes, is made up of reversely-graded black scoriae embedded in an ashy matrix with subordinate lithics and crystals (Cappelletti *et al.*, 2003; Langella *et al.*, 2013). WGI contains hypidiomorphic phenocrysts of alkali-feldspars with minor amounts of clinopyroxene, as well as microlites of alkali-feldspar, Ti-magnetite and apatite. The matrix comprises well-sorted glass shards with occasional accretionary ash clots and porous lapilli fragments (Heap *et al.*, 2012 and references therein). Although WGI does not contain any zeolites, we note that portions of the Campanian Ignimbrite are pervasively zeolitized (e.g., see Langella *et al.*, 2013).

3. Experimental methods

The caldera at CF hosts a large, shallow (< 4 km) hydrothermal system (e.g., De Natale *et al.*, 2006). Indeed, laboratory studies have demonstrated that water-saturated ultrasonic velocities on tuffs from CF are more representative of the *in-situ* values than “dry” (measurements conducted on oven dried samples at ambient laboratory humidity) ultrasonic velocities (Zamora *et al.*, 1994;

Vanorio *et al.*, 2005; Vinciguerra *et al.*, 2006). Since the tuffs of CF are present at depth, and are likely to contain a fluid phase (e.g., a mixture of meteoric water and seawater contaminated by rising magmatic gases, see Valentino *et al.*, 1999), we consider experimental values on pressurised, water-saturated samples as the most representative. Our experimental program was twofold. (1) Hydrostatic (i.e., $\sigma_1 = \sigma_2 = \sigma_3$) experiments to measure changes in permeability, porosity, ultrasonic wave velocities, and dynamic elastic moduli with increasing effective pressure (Peff, from 5 MPa to 50 MPa) on samples that had been thermally stressed to a range of temperatures (from as-collected to 1000 °C). (2) Constant strain rate conventional triaxial (i.e., $\sigma_1 > \sigma_2 = \sigma_3$) deformation experiments at a Peff of 5 MPa to measure static elastic moduli. Importantly, we measure both static and dynamic elastic moduli at the same Peff (= 5 MPa) so that the values can be easily compared. All our experiments were performed at room temperature (while this may not accurately represent the natural case, we note that, to explore the influence of temperature on the physical properties of the tuffs, we conducted experiments on samples thermally stressed to a range of temperatures).

Experimental data are subject to error as a result of the accuracy of the various transducers. Estimations of the accuracy of the measurements of this study are listed in Table 2. The errors are extremely small and lead to error bars that are smaller than the data points in the figures provided in this study. However, we note that measurement errors are dwarfed by the natural sample variability of the tuffs (i.e., the natural variability of samples cored from the same block of material). Estimations of the natural sample variability of the tuffs used this study are provided in Table 3. While one of the goals of this contribution is to demonstrate the variability of different tuffs from the CF volcanic district, we strived to minimise the variability between samples cored from the same block by (1) coring many samples and selecting those within a strict porosity range, (2) discarding samples with obvious, large heterogeneities and, (3) discarding samples with anomalous P-wave velocities. Using these sample selection guidelines, our experiments under different conditions (different thermal stressing temperatures and pressures) can be compared with the greatest confidence.

3.1 Hydrostatic experiments

Hydrostatic experiments were performed in the Rock & Ice Physics Laboratory (RIPL) at University College London (UCL) using a 300 MPa hydrostatic pressure vessel equipped with two 70 MPa servo-controlled pore fluid intensifiers or volumometers (Figure 3, see also Kolzenburg *et al.*, 2012). The apparatus is designed to measure permeability, porosity, and ultrasonic wave velocities contemporaneously. In our experiments we chose an experimental pressure range of 5-50 MPa (i.e., up to a depth of about 3.5 km).

Cylindrical samples, 25 mm in diameter and nominally 40 mm in length, were all cored from the same set of blocks and in the same orientation. Samples were precision ground so that their end faces were flat and parallel. Prior to experimentation, samples were either: (1) held at ambient temperature (as-collected) or, (2) thermally stressed to pre-determined temperatures of 100, 200, 300, 500, 750, or 1000 °C (note: NYT could not be tested after exposure to 1000 °C due to a severe volume reduction). Thermal stressing was achieved by heating the sample to the target temperature at a rate of 1 °C/min, holding the temperature constant for 60 minutes, and then cooling at the same rate. Once at room temperature, all samples were vacuum-saturated in distilled water prior to experimentation. The measured sample was then inserted into a nitrile rubber jacket and fixed between the two endcaps. The sample assembly was then lowered into the pressure vessel. Once inside the setup, the confining pressure (Pc) and the pore fluid (distilled water) pressures (Pp) in both the “upstream” (P_{up}) and “downstream” (P_{down}) pore volumometers were increased to 10 and 5 MPa, respectively. The confining and pore pressures were increased slowly to avoid damaging the sample, and care was taken to ensure the sample was not pressurised beyond the maximum effective pressure targeted for the experiments (5 MPa). For the purpose of this study we apply the simple effective pressure law of Peff = Pc – αPp, assuming that poroelastic constant α = 1 (Guéguen and Palciauskas, 1994). The sample was left for 30 minutes at an effective pressure of 5 MPa to ensure microstructural equilibration and complete saturation.

Once equilibration at Peff = 5 MPa was complete, the first ultrasonic measurements were taken. Ultrasonic waves velocities were measured via PZT piezoelectric P- and S-wave transducer crystals housed in the sample endcaps (Figure 3) using an Agilent Technologies 1.5GHz “Infiniium” digital storage oscilloscope and a JSR DPR300 35MHz ultrasonic pulser/receiver. All ultrasonic wave arrival times were individually picked as the first deviation from the baseline signal. Dynamic elastic moduli were calculated from the resultant ultrasonic wave velocities using the following formulae (Guéguen and Palciauskas, 1994):

$$E_d = \rho \frac{V_s^2(3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \quad (1)$$

$$\upsilon_d = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad (2)$$

$$\mu_d = \frac{E_d}{2(1 + \upsilon_d)} \quad (3)$$

Where E_d is the Young's modulus, υ_d is the Poisson's ratio, μ_d is the shear modulus, ρ is the bulk sample density and Vp and Vs are the P- and S-wave velocities, respectively.

Water permeability measurements were made by imposing a 1 MPa pressure difference across the jacketed sample. To achieve this, P_{up} and P_{down} were set at 4.5 and 5.5 MPa, respectively. The volumometers were then allowed to move full stroke (10 cm^3) and steady-state flow was only assumed when the flow rate was constant over a protracted period. Water permeability (κ_{water}) was then calculated directly from Darcy's law:

$$\frac{Q}{A} = \frac{\kappa_{water}}{\eta L}\left(P_{up} - P_{down}\right) \quad (4)$$

where Q is the fluid volume flux, A is the cross-sectional area of the sample, η is the viscosity of the pore fluid (taken as 8.94 x 10^{-4} Pa.s), L is the length of the sample, and P_{up} and P_{down} are the pore pressures at the "upstream" and "downstream" ends of the sample, respectively.

Once the permeability measurement was complete, the "downstream" volumometer was isolated and the "upstream" volumometer was set back at 5 MPa. The Pc was then slowly increased to 15 MPa. By monitoring the movement of the "upstream" volumometer the porosity change from

Peff = 5 MPa to Peff = 10 MPa could be accurately calculated. The sample was then left for 30 minutes at the new pressure to ensure microstructural equilibration. Once equilibration was complete, the ultrasonic measurements for Peff = 10 MPa were taken. This procedure was repeated for every 5 MPa Peff increment up to 50 MPa.

During our experiments, the length of the sample *L* and the cross-sectional area *A* will change due to the compaction of the sample at elevated pressure. We have corrected for this (in our calculations of permeability and ultrasonic wave velocities) using the volume reduction of our sample (as measured by the water expelled from the sample) at each pressure interval, assuming isotropic compaction. Although one sample was used per thermal-stressing temperature, we reiterate that great care was taken during sample selection to exclude samples that contained large heterogeneities or anomalous connected porosities/P-wave velocities.

3.2 Triaxial deformation experiments

Constant strain rate (1.0 x 10^{-5} s^{-1}) conventional (i.e., $\sigma_1 > \sigma_2 = \sigma_3$) triaxial experiments were performed on as-collected cylindrical samples of the two tuffs (20 mm in diameter and nominally 40 mm in length). Samples were cored from the same blocks and in the same direction as for the hydrostatic experiments described in the previous section. The samples were precision ground so that their end faces were flat and parallel. Both experiments were performed in the conventional triaxial deformation apparatus (Figure 4) at the Laboratoire de Déformation des Roches (Université de Strasbourg) at a Peff of 5 MPa (Pp of 5 MPa and a Pc of 10 MPa). Axial stress and strain were monitored continuously using a load cell and an LVDT displacement transducer, respectively. Pore volume change (used as a proxy for volumetric strain, ε_v) was monitored using a pore pressure intensifier, and the output of acoustic emissions (AEs) by a piezoelectric transducer crystal (located on the top of the piston) using a Physical Acoustics USB AE Node. AEs are high frequency elastic wave packets generated by the rapid release of strain energy such as during brittle microfracturing (see Lockner, 1993 for a review). During experimentation, an AE hit was recorded if a signal exceeded the set threshold of 40 dB. The AE "energy" (the area under the received AE waveform envelope) of each received AE signal was provided by the AEwin software. In this study we will adopt the convention that compressive stresses and compactive strains are positive.

Static Young's moduli (E_s) and Poisson's ratio (v_s) were then calculated from the resultant stress-strain data, following the method of Heap and Faulkner (2008). We take both from the quasi-linear elastic regions of our tangent modulus curves (i.e., those regions where the moduli did not change). Static Poisson's ratio is given by:

$$v_s = -\frac{\varepsilon_r}{\varepsilon_a} \quad (5)$$

where

$$\varepsilon_r = \frac{\varepsilon_v - \varepsilon_a}{2} \quad (6)$$

Where ε_r and ε_a are the radial and axial strain, respectively. Static shear modulus (μ_s) was then calculated using the following formula (Guéguen and Palciauskas, 1994):

$$\mu_s = \frac{E_s}{2(1 + v_s)} \quad (7)$$

3.3 Microstructural analyses

Microstructural analyses were performed using (1) the Hitachi S-3600N Environmental Scanning Electron Microscope (E-SEM) at the University of Leicester using a working distance of 14.3 mm and an accelerating voltage of 15 kV and, (2) a Leica DM2500 (equipped for both transmitted and reflected light) microscope with a mounted 5 megapixel Leica DFC425 digital camera (at the Laboratoire de Déformation des Roches, Université de Strasbourg). The E-SEM was used to look for evidence of pore collapse in samples of NYT taken beyond P*. Optical microscopy was used to investigate the influence of high temperatures (1000 °C) on the microstructure of NYT and WGI.

4. Results

4.1 The evolution of porosity with increasing pressure and temperature

Plots of the evolution of porosity with increasing Peff (commonly called “hydrostats”) for both NYT and WGI at each thermal stressing temperature are displayed in Figure 5. For porous rock, an increase in hydrostatic pressure results in a volume and porosity decrease. Initially, this compaction is elastic (i.e., recoverable) but, at some critical pressure (assuming the rock is porous enough), pore collapse and grain crushing (now non-recoverable damage) ensues and the rate of compaction accelerates. This critical pressure is denoted P* (Wong and Baud, 2012). The Peff required to reach P* varies from rock to rock, but depends largely on the initial rock porosity and grain size (generally, the higher the porosity, the lower the Peff for P*). The stress at which P* occurs can therefore provide important information on the physical and microstructural state of rock at depth. In our experiments, the position of P* is about 10 MPa for NYT (Figure 5A) and about 10-15 MPa for WGI (Figure 5B). Prior to P*, during elastic compaction, we note that the porosity change is linear (i.e., there is no concave portion that is usually attributed to the closure of microcracks; however this may be a result of the large steps in Peff between measurements). We note that there is no microstructural evidence for microcracks in the as-collected materials (see Figure 2). Immediately following P*, during inelastic compaction, there is a dramatic increase in the rate of porosity reduction, as inelastic compaction proceeds. However, the porosity reduction rate then gradually decreases (especially above about 20 MPa). This represents the hardening of the rock due to compaction. Over the entire pressure range (up to 50 MPa) the porosity change for the as-collected sample is about the same for NYT and WGI (between 9 and 10 vol%). Figure 5B also shows that the porosity evolution for WGI with increasing Peff is unaffected by thermal stressing. By contrast, in the case of NYT, the porosity change decreases significantly as thermal stressing temperature increases (Figure 5A). It can also be seen that, for both tuffs, thermal stressing does not appear to influence the position of P* (Figure 5).

4.2 The evolution of permeability with increasing pressure and temperature

The evolution of permeability with increasing Peff for NYT and WGI at each thermal stressing temperature is displayed in Figure 6 (the values are reported in Tables 4 and 5). Firstly, we notice that the as-collected permeabilities of the two samples are very different. For instance, at a Peff of 5 MPa, the permeabilities are about 1.0 x 10^{-15} and 1.0 x 10^{-13} m^2 for NYT (Figure 6A) and WGI (Figure 6B), respectively.

For WGI, the permeability curves show little change between 5 and 15 MPa (Figure 6B). However, above 15 MPa, the permeability starts to decrease rapidly before reaching an apparent plateau above about 30 MPa. We note that this rapid decrease starts at the same pressure as the onset of inelastic compaction (P*). Overall, the permeability is reduced by about an order of magnitude from 1.0 x 10^{-13} m^2 at 5 MPa to 1.0 x 10^{-14} m^2 at 50 MPa. The permeability curves for WGI show no clear trend with increasing thermal stressing temperature (Figure 6B). The different values obtained for the different thermal stressing temperatures are within the expected range of natural variability between different samples cored from the same block.

However, there is a clear influence of the thermal stressing temperature on the permeability of NYT (Figure 6A). At a Peff of 5 MPa, the permeability increases from 1.0 x 10^{-15} m^2 for the as-collected sample to 1.1 x 10^{-14} m^2 for the sample thermally stressed to 750 °C, an increase of an order of magnitude. As for the WGI, the permeability curves show little change between 5 and 10 MPa, after which permeability decreases more rapidly. We again note that this rapid decrease starts at the same pressure as the onset of inelastic compaction (P*). Over the entire pressure range, the permeability is reduced by about an order of magnitude for the as-collected sample and by about three orders of magnitude for the sample thermally stressed to 750 °C. Further, the total decrease in permeability increases with increasing thermal stressing temperature (Figure 6A). The permeability curves all converge at about 40 MPa (at a permeability of about 4.0 x 10^{-17} m^2). Therefore, at Peffs of 40 MPa and above, there is no longer any influence of thermal stressing on the permeability of NYT.

4.3 The evolution of ultrasonic velocities and dynamic elastic moduli with increasing pressure and temperature

The evolution of the tuff physical properties (ultrasonic wave velocities, dynamic elastic moduli, and Vp/Vs ratio) for NYT and WGI are shown in Figures 7 and 8, respectively. Firstly, it can be remarked that the as-collected physical properties of the two tuffs are similar (see also Table 1). For both tuffs, P- and S-wave velocity (Figures 7A, B and Figures 8A, B), dynamic Young's modulus (Figures 7C and 8C), dynamic Poisson's ratio (Figures 7D and 8D), dynamic shear modulus (Figures 7E and 8E) and Vp/Vs ratio (Figures 7F and 8F) all increase with increasing Peff, and in a similar manner. For example, for the as-collected NYT sample, P-wave velocity increases by 40% (Figure 7A), S-wave velocity by 21% (Figure 7B), Young’s modulus by 53% (Figure 7C), Poisson’s ratio by 19% (Figure 7D), shear modulus by 47% (Figure 7E), and Vp/Vs ratio by 15% (Figure 7F) over the entire pressure range (5 to 50 MPa). The relative increases are similar for both tuffs. However, whereas the results for NYT (Figure 7) show a systematic decrease in all the physical properties with increasing thermal stressing temperature, no systematic pattern can be discerned in the WGI results (Figure 8). At a constant Peff, thermal stressing decreases P- and S-wave velocity, dynamic Young's modulus, dynamic Poisson's ratio, and Vp/Vs ratio in NYT. For example, for NYT at a Peff of 5 MPa, P-wave velocity decreases by 21% (Figure 7A), S-wave velocity by 4% (Figure 7B), Young's modulus by 18% (Figure 7C), Poisson's ratio by 56% (Figure 7D), shear modulus by 8% (Figure 7E), and Vp/Vs ratio by 17% (Figure 7F) over the entire temperature range (as-collected to 750 °C).

4.4 Static elastic moduli under triaxial conditions

The differential stress-axial strain curves and associated AE energy output curves for the triaxial experiments are shown in Figure 9, and the differential stress-porosity reduction curves are shown in Figure 10. Even at a Peff as low as 5 MPa, the deformation behaviour of the two tuffs can be described as macroscopically ductile (i.e., their ability to resist load did not decrease, see Rutter, 1986). For both rocks, a critical pressure, termed C* (Wong and Baud, 2012), is reached which marks the point where there is an acceleration in axial strain (Figure 9) and porosity reduction (or volumetric strain, Figure 10) for a given stress increment. This phenomenon is called "shear-enhanced compaction", and beyond C* the rocks are deforming in the compactive, cataclastic flow regime which, in this case, is associated with strain hardening. In our experiments, C* occurs at differential stresses of about 4.5 and 9 MPa for NYT (Figures 9A and 10A) and WGI (Figures 9B and 10B), respectively. This contrasts with the values for P* of 10 and 15 MPa, respectively, and demonstrates how the application of shear stresses enhances compactive deformation. Although this mode of failure differs greatly from the brittle failure seen in the uniaxial experiments of Heap *et al*. (2012) on the same rocks, both deformation mechanisms involve the same micromechanical process: microcracking (as evidenced by the output of AE energy; a proxy for microcracking). However, whereas strain localisation is seen in the brittle field, cataclastic flow involves distributed microcracking (i.e., localisation does not occur). Indeed, we see no evidence for strain localisation in the post-experimental samples. The output of AE energy is seen to increase in a somewhat stepwise manner for both rocks (Figure 9), reflecting bursts of microcracking events during deformation, we note that the average rate of AE energy output for WGI is some 20 times higher than for NYT. The difference in AE energy output during deformation is likely to be the result of the compositional differences between the two tuffs.

Values for the static Young's modulus, static Poisson's ratio, and static shear modulus were calculated from the elastic portions of the stress-strain curves and are given in Table 6, together with dynamic values determined at the same pressure (Peff = 5 MPa) for comparison. We note that both the static Young's modulus and the static shear modulus are significantly lower than the corresponding dynamic values.

5. Discussion

5.1 Fluid flow and physical property evolution with depth

Our experimental data show that the water permeability of different as-collected tuff samples from Campi Flegrei can vary by multiple orders of magnitude (at a Peff of 5 MPa, permeabilities are 1.0 x 10^{-15} and 1.0 x 10^{-13} m^2 for NYT and WGI, respectively). This difference in permeability could be considered surprising if one were to solely consider their connected porosities (44 and 49 vol% for NYT and WGI, respectively). The difference in permeability is likely due to differences in pore space connectivity, perhaps related to the extent of zeolitization and lithification. A similar conclusion was drawn by Vinciguerra *et al*. (2009). Vinciguerra *et al*. (2009) measured the permeability of two different tuffs from the Alban Hills (Italy) and found that, at a Peff of 5 MPa, the permeabilities of the two tuffs were significantly different. While the first (well-lithified, zeolitized facies with an average porosity of 14 vol.%) was found to have a permeability of about 10^{-18} m^2, which decreased by about an order of magnitude upon the application of a Peff of 70 MPa, the second (fine-grained, matrix-supported facies with frequent cm-sized accretionary lapilli and an average porosity of 18 vol.%) had a much higher permeability (about 10^{-15} m^2) that decreased by about two orders of magnitude over the same pressure range. Further, considering the high porosities of NYT and WGI, their permeabilities are actually surprisingly low; considered to be a consequence of their complex pore structure. By contrast, Boise sandstone (porosity of 35 vol.%), a rock with a much simpler microstructure, has a permeability of 1.8×10^{-12} m^2 at a Peff of 5 MPa (Zhu and Wong, 1997).

Our experimental data also show that the permeability of the two tuffs is reduced by about an order of magnitude over the pressure range from 5 MPa to 50 MPa. In detail, the reduction in permeability with increasing Peff is modest up to a Peff of about 10-15 MPa, and accelerates at pressures above 10-15 MPa. This can be explained by the position of P* (Figure 5), the onset of inelastic pore collapse and grain crushing. As pores collapse and grains crushed, the pathways for fluid flow are obstructed. This inelastic compaction also has a significant influence on other physical properties of the tuffs (ultrasonic wave velocities, dynamic elastic moduli, and the Vp/Vs ratio all increase), in agreement with similar studies on NYT (Vanorio *et al*., 2002; Vinciguerra *et al*., 2006). Evidence of pore collapse is illustrated in the E-SEM image of a sample of NYT taken beyond P* provided as Figure 11. Pore collapse above P* has previously been observed in a tuff from the Alban Hills, Italy (Zhu *et al.*, 2011). A pressure of about 10-15 MPa roughly equates to a depth of about 750 m. Geological cross sections of CF (e.g., Orsi *et al.*, 1996) suggest therefore that a large volume of the NYT and WGI tuffs are located at depths where the pressure will be above P*. This conjecture is confirmed by the reduced porosity of samples taken from borehole samples (see the report by Giberti *et al.*, 2006). Measurements on borehole samples from San Vito 1 (at the periphery of the inferred caldera) showed that the porosity decreases from 40.5 vol.% at the surface to 32.9, 21.9, 21.9, and 15.1 vol.% at depths of 810, 1420, 2130, and 2860 m, respectively. Our data show that the porosity loss for NYT at 2860 m will be about 9 vol.%. A starting porosity of 44 vol.% yields a porosity, purely due to mechanical compaction, of 35 vol.% at a depth of 2860 m. This would imply a porosity loss due to chemical alteration of about 20 vol.% and suggests that the impact of hot, circulating fluids plays the dominant role in the porosity loss of these pyroclastic deposits at depth. Indeed, the report by Giberti *et al*. (2006) suggests that it is the presence of clay minerals, rather than compaction, that is responsible for the major changes in porosity with depth.

We are certainly aware that our permeability data were collected on rocks from open quarries and, although their properties were measured at the relevant pressures (and under a range of thermal stressing temperatures), may not therefore accurately represent the material at depth (which have had time to compact, lithify, undergo chemical alteration; e.g., see de Gennaro *et al*., 2000). However, the open access report of Giberti *et al*. (2006) offers some permeability data on borehole samples. Data from borehole samples taken from San Vito 1 (at the periphery of the inferred caldera) show that, as the porosity is reduced to 32.9, 21.9, 21.9, and 15.1 vol.% at depths of 810, 1420, 2130, and 2860 m, respectively, the permeability (Klinkenberg corrected gas permeabilities) of the samples are 1.1 x 10^{-13}, 2.5 x 10^{-16}, 7.9 x 10^{-16}, and 4.9 x 10^{-16} m^2, respectively. The permeability of the quarry samples of this study are 8.0 x 10^{-17} m^2 at a depth of about 2860 m. From these data it is clear that there is no simple relationship between the mechanical compaction and chemical alteration that afflicted the samples at depth (causing a substantial porosity loss) and their permeability.

5.2 The influence of temperature on fluid flow and physical properties

Our experimental data show that thermal stressing has a strong influence on the physical properties of NYT, whereas those for WGI are unaffected. The fluid flow properties of NYT are enhanced (especially at shallow depths) upon exposure to high temperatures, and the ultrasonic wave velocities, dynamic elastic moduli, and the Vp/Vs ratio decrease. Thermal stressing has previously shown to decrease ultrasonic wave velocities in a zeolitized tuff from CF (Vinciguerra *et al.*, 2006). The marked difference in the temperature-dependence of the physical properties between the two tuffs is likely due to the presence of significant quantities of thermally unstable zeolites in NYT, namely phillipsite and chabazite, which are not present in WGI (Heap *et al.*, 2012). Heap *et al.* (2012) showed, using a combination of thermo-gravimetric analysis, optical microscopy, and X-ray diffraction, that NYT lost 18% of its initial mass, contained large numbers of macrocracks, and no longer contained any zeolites after exposure to 1000 °C. By contrast, no changes in mass, microstructure, or chemistry were seen in WGI heated to the same temperature (Heap *et al.*, 2012). Optical microscope photomicrographs of NYT and WGI thermally stressed to a temperature of 1000 °C are provided as Figures 12 and 13, respectively. Figure 12 shows that the microstructure of NYT is very different to that depicted in

Figure 2B for the as-collected material. Many cracks are present (Figure 12A, B and C) and some areas contain 1 mm wide foamed glass (Figure 12A). By contrast, the microstructure of WGI, upon exposure to 1000 °C (Figure 13), is indistinguishable from the as-collected microstructure shown in Figure 2D. These observations have been previously reported in Heap *et al*. (2012). Since, phillipsite and chabazite represent the “cement” that promoted the lithification of the originally incoherent pozzolanic material constituting NYT (de Gennaro *et al*., 2000), the structural integrity of NYT deteriorates significantly upon their loss (Heap *et al.*, 2012). Detailed studies (de Gennaro and Colella, 1989 and references therein) on the thermal decomposition of the zeolites in NYT have highlighted that analcime loses water irreversibly, and that chabazite and phillipsite undergo a partial reversible dehydration at 240 °C. Phillipsite breaks down during dehydration and chabazite undergoes reversible hydration at 350 °C, and, by 900 °C, the structure of the zeolites will be so damaged that no further water molecules can be stored (see de Gennaro and Colella, 1989 and references therein). Therefore, the reported changes in NYT physical properties are due to a combination of thermal cracking and the cracks formed as a result of the disintegration of the material through the loss of zeolites.

If we consider NYT at a depth of 1 km, the geothermal gradients provided by the AGIP (1987) exploration boreholes show that temperatures of 200-250 °C are not unreasonable (Wohletz *et al.*, 1999; de Lorenzo *et al*., 2001). The data of this study reveal that the zeolitized NYT are prone to undesirable thermal alteration at these temperatures. At temperatures of 200-250 °C , permeability increases by a factor of 2.5, ultrasonic wave velocities, dynamic elastic moduli, and Vp/Vs ratio decrease by roughly 10%; and uniaxial compressive strength and indirect tensile strength are reduced by more than a factor of 2 (Heap *et al.*, 2012). A reduction in tensile strength may further promote physical property changes by encouraging fluid pressure driven fracturing. An internal pore fluid pressure of 22-23 MPa (under a confining pressure of 6-7 MPa) was sufficient to fracture a sandstone of 13 vol.% porosity (Vinciguerra *et al.*, 2004). It is therefore likely that the estimated overpressures needed to explain the ground deformation at CF (e.g., 10 MPa, Gaeta *et al.*, 1998) are sufficient to fracture the tuffs and cause further changes in rock physical properties. Although it has been shown that the porosity of borehole samples can be much less than those collected from the surface (see the report of Giberti *et al.*, 2006) perhaps, given their complex microstructure, it is unwise to assume that these rocks are stronger. To understand whether fluid driven fracturing is prevalent at CF, measurements of the tensile strength of samples taken from boreholes is required.

5.3 Application of these data to ground deformation modelling at CF

Our data highlight that the elastic moduli of two different tuffs from CF are significantly depth-dependent (Figures 7 and 8). The implication of these data is that the assumption of a homogenous half-space may be an oversimplification, and is exacerbated further when one considers the extent of the variability of the tuffs within the caldera (which are variably lithified, altered, and zeolitized, see the report of Giberti *et al.*, 2006). These data highlight the need for the development of more complex, multi-layer ground deformation models. In order to assess the extent of the variability in elastic moduli of the rocks within the caldera at CF, a systematic experimental approach involving borehole samples from different depths and locations within the caldera is now required (discussed further at the end of the section).

We also find that static and dynamic moduli for the same tuff differ substantially. Although it is not uncommon for static and dynamic elastic moduli to be different, due to their frequency-dependence (Simmons and Brace, 1965; Cheng and Johnston, 1981; Eissa and Kazi, 1989; Ciccotti and Mulargia, 2004; Ciccotti *et al.*, 2004), it raises an important question regarding which values are more appropriate in modelling. Manconi *et al*. (2010) highlighted that, while dynamic elastic constants (those derived from seismic velocities) are representative for rock subject to a dynamic stress, perhaps static values are more appropriate in the analysis of deformation caused by volcanic sources. A similar conclusion was drawn by Heap *et al*. (2009). However, static elastic moduli for representative rocks at CF have not been available until now. Thus far, elastic moduli have been generally assumed, or extrapolated from seismic tomography studies (e.g., Chiarabba and Moretti, 2006). Typically, Poisson's ratio is taken as 0.3 and shear modulus as 5 GPa (e.g., De Natale *et al*., 1991). However, while our data show that static and dynamic Poisson's ratio is similar for the measured tuffs (and equal to about 0.3; measurements on borehole samples are also consistently about 0.3, see the report by Giberti *et al*., 2006), we also observe that the static shear modulus is about a factor of four lower than the dynamic value (Table 6). If one were to assume that our static values are representative, then a more suitable shear modulus would be 0.5 GPa, an order of magnitude lower than the values typically used in ground deformation modelling at CF. We note that, while values of the shear modulus of borehole samples provided in the report of Giberti *et al*. (2006) show that the dynamic shear modulus can reach values of 10.9 GPa at a depth of 2860 m, no complementary static values exist. Future research should focus on the determination of the static elastic moduli of borehole samples.

To date, the values of permeability used in the numerous thermodynamical and magmatic-hydrothermal models have spanned many orders of magnitude. For example, Gaeta *et al*. (1998) use a value of 10^{-11} m^2, inferred from the measurements of Ascolese *et al*. (1993a,b) and De Natale *et al*. (2001) use the same value, but inferred from the *in-situ* observations of Rosi and Sbrana (1987). By contrast, Gaeta *et al*. (2003) use a much lower value of 10^{-15} m^2, taken from the ambient pressure measurements of Peluso and Arienzo (2007). The experimental data of this study has shown that (1) the permeability of tuffs at CF can differ by about 1.5 orders of magnitude (from 2.0×10^{-15} to 6.3×10^{-17} m^2, due to the extent of zeolitization and lithification, see Tables 4 and 5), (2) effective pressure (depth) can significantly alter the permeability of tuff (by up to two orders of magnitude, see Figure 6) and, (3) if the tuff is zeolitized, permeability can be increased by thermal stressing episodes (Figure 6A). While we note that the permeability of different tuffs at CF can differ greatly (we expect the extent of the variation to greatly exceed the 1.5 orders of magnitude quoted here), the same will also to true for tuff from the same eruptive episode. The NYT and the Campanian Ignimbrite – both thick and widespread pyroclastic deposits – are well-known to be variably lithified and zeolitized (de Gennaro *et al.*, 2000; Langella *et al*., 2013). The highly variable nature of tuffs at CF (both laterally and vertically, see the report by Giberti *et al*., 2006), coupled with the depth-dependence of permeability, is likely to produce highly variable permeabilities within the caldera.

Unfortunately, the implication of this conclusion is that, to accurately model ground deformation using a model that requires an estimation of the permeability of the materials within the caldera, we now require (1) permeability measurements on borehole samples (from different depths and different locations within the caldera) to assess the extent of the variability in permeability within the caldera and, (2) the development of more complex models that can account for such variations in permeability.

To conclude, while we advise that our laboratory-derived values should be considered for routine ground deformation modelling at CF, we also urge caution. Firstly, our measurements on laboratory-sized samples do not account for large faults or fractures, which, for example, would serve to lower the Young's modulus. Secondly, an important question arises: what constitutes "representative" materials for the caldera at CF? Although our experiments were conducted (1) on samples from the two most widespread tuff lithologies that comprise CF, (2) under the relevant pressures or depths, (3) on water-saturated samples and, (4) over a range of thermal stressing temperatures, our samples were collected from an open quarry and may therefore not represent the material at depth (which have had time to compact, lithify, undergo chemical alteration; e.g., see de Gennaro *et al*., 2000; see also the report by Giberti *et al.*, 2006). However, we highlight that the permeability measurements on borehole samples presented in the report of Giberti *et al*. (2006) suggest that (1) the permeability measurements of this study are not dissimilar to those measured on borehole samples and, (2) there is clearly no simple relationship between porosity and permeability. Further, the tuffs of CF are likely to be extremely variable (due to variable lithification, zeolitization, interaction with fluids and temperatures) laterally (i.e., within the same lithological unit) and therefore their physical properties at a constant depth are also likely to span a wide range. It is clear that systematic measurements on deep scientific borehole samples are now needed from multiple locations and depths within the caldera to assess the extent of the variability in static elastic moduli and permeability of the rocks that form the caldera. To conclude, we anticipate that no unique values of permeability or elastic moduli exist for the materials within CF, highlighting the need for the development of more complex ground deformation models.

6. Conclusions

1. Our experimental data show that the permeabilities of tuffs from Campi Flegrei (the Neapolitan Yellow Tuff and a tuff from the Campanian Ignimbrite) can vary by multiple orders of magnitude. Despite this, our data also show that their elastic moduli are similar; however, we note that dynamic and static moduli differ greatly. These data emphasize the heterogeneous nature of the tuffs that comprise the caldera at Campi Flegrei.
2. Increasing the effective pressure from 5 MPa to 50 MPa results in a permeability reduction of about an order of magnitude and a porosity reduction between 5 and 10 vol.% for both tuffs. As effective pressure increases we also observe an increase in ultrasonic wave velocities, dynamic elastic moduli, and Vp/Vs ratio. These changes all accelerate after the onset inelastic pore collapse (P*), which exists between effective pressures of 10-15 MPa.
3. Thermal stressing increases the permeability and decreases the ultrasonic wave velocities, dynamic elastic moduli, and Vp/Vs ratio of the Neapolitan Yellow Tuff. However, the tuff from the Campanian Ignimbrite is unaffected by thermal stressing. This is the result of the loss of thermally unstable zeolites, namely phillipsite and chabazite, in Neapolitan Yellow Tuff. For example, for the sample thermally stressed to 750 °C, the permeability at an effective pressure of 5 MPa increases by an order of magnitude relative to the as-collected material.

4. While we urge that these new laboratory data should be considered in routine ground deformation modelling, our study highlights that the physical properties of just two rocks that comprise the caldera at Campi Flegrei can be extremely heterogeneous (we also anticipate that future measurements will further expand our knowledge of such heterogeneity). These data underline the challenges for accurate ground deformation modelling at Campi Flegrei. We anticipate that no unique values of permeability or elastic moduli exist for the materials within Campi Flegrei, highlighting the need for the development of more complex ground deformation models.

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Table 1. Summary of the ambient pressure, as-collected physical properties of Neapolitan Yellow Tuff (NYT) and Grey Campanian Ignimbrite (WGI). “Dry” indicates measurements on samples that were dried in a vacuum oven for at least 24 hours; the measurements were then performed under ambient laboratory humidity. “Wet” indicates measurements on samples that were vacuum-saturated with distilled water.

	Neapolitan Yellow Tuff (NYT)	**Grey Campanian Ignimbrite (WGI)**
connected porosity [vol.%]	43.8	48.5
dry bulk sample density [kg/m^3]	1270	1330
dry P-wave velocity [kms^{-1}]	2.29	2.31
wet P-wave velocity [kms^{-1}]	2.60	2.56
dry S-wave velocity [kms^{-1}]	1.25	1.28
wet S-wave velocity [kms^{-1}]	1.30	1.33
dry Vp/Vs	1.84	1.80
wet Vp/Vs	2.00	1.93
dry dynamic Young’s modulus [GPa]	5.07	5.58
wet dynamic Young’s modulus [GPa]	7.68	8.42
dry dynamic Poisson’s ratio	0.28	0.28
wet dynamic Poisson’s ratio	0.33	0.31
dry dynamic shear modulus [GPa]	1.97	2.19
wet dynamic shear modulus [GPa]	2.88	3.20
dry unconfined compressive strength [MPa] (from Heap et al., 2012)	3.47	9.23

Table 2. Summary of the estimated measurement accuracy.

measurement	accuracy
confining pressure [Pa]	± 100 000 (UCL) ± 10 000 (Strasbourg)
pore fluid pressure [Pa]	± 10 000
pore fluid volume [m^3]	± 1.0 x 10^{-12}
LVDT displacement [m]	± 0.000001
axial stress [Pa]	± 10 000
original sample dimensions [m]	± 0.00001

Table 3. Expected natural variability between tuff samples cored from the same block. Note that these are not “errors” in the measurements. Measurement accuracies (Table 2) are insignificant compared to the natural sample variability, despite efforts to reduce the variability between samples cored from the same block of material (see text for details).

	expected natural variability
Young’s modulus [GPa]	± 0.5
Poisson’s ratio	± 0.05
shear modulus [GPa]	± 0.5
water permeability [m^2]	± 1.0 x 10^{-14}
P-wave velocity [kms^{-1}]	± 0.1
S-wave velocity [kms^{-1}]	± 0.1

Table 4. Water permeability of Neapolitan Yellow Tuff (NYT) as a function of effective pressure and thermal stressing temperature.

Neapolitan Yellow Tuff (NYT)						
effective pressure [MPa]	"as-collected" permeability [m^2]	100 °C permeability [m^2]	200 °C permeability [m^2]	300 °C permeability [m^2]	500 °C permeability [m^2]	750 °C permeability [m^2]
5	1.2×10^{-15}	1.7×10^{-15}	1.9×10^{-15}	2.7×10^{-15}	4.1×10^{-15}	1.1×10^{-14}
10	8.5×10^{-16}	1.7×10^{-15}	2.0×10^{-15}	2.7×10^{-15}	3.6×10^{-15}	1.1×10^{-14}
15	6.3×10^{-16}	1.6×10^{-15}	1.6×10^{-15}	2.4×10^{-15}	2.5×10^{-15}	8.5×10^{-15}
20	4.9×10^{-16}	1.1×10^{-15}	8.2×10^{-16}	1.6×10^{-15}	1.5×10^{-15}	6.1×10^{-15}
25	2.5×10^{-16}	7.6×10^{-16}	4.5×10^{-16}	1.2×10^{-15}	8.0×10^{-16}	4.4×10^{-15}
30	1.7×10^{-16}	5.3×10^{-16}	2.5×10^{-16}	8.6×10^{-16}	4.8×10^{-16}	3.2×10^{-15}
35	8.0×10^{-17}	5.3×10^{-16}	1.4×10^{-16}	6.4×10^{-16}	3.0×10^{-16}	1.8×10^{-15}
40	4.7×10^{-17}	3.1×10^{-16}	9.6×10^{-17}	5.3×10^{-16}	2.7×10^{-16}	3.1×10^{-16}
45	3.5×10^{-17}	2.3×10^{-16}	6.0×10^{-17}	4.1×10^{-16}	1.5×10^{-16}	5.4×10^{-17}
50	2.4×10^{-17}	1.7×10^{-16}	4.0×10^{-17}	3.2×10^{-16}	1.0×10^{-16}	3.3×10^{-17}

Table 5. Water permeability of grey Campanian Ignimbrite (WGI) as a function of effective pressure and thermal stressing temperature.

Grey Campanian Ignimbrite (WGI)							
effective pressure [MPa]	"as-collected" permeability [m^2]	100 °C permeability [m^2]	200 °C permeability [m^2]	300 °C permeability [m^2]	500 °C permeability [m^2]	750 °C permeability [m^2]	1000 °C permeability [m^2]
5	1.0×10^{-13}	7.8×10^{-14}	1.1×10^{-13}	1.0×10^{-13}	1.0×10^{-13}	1.0×10^{-13}	9.9×10^{-14}
10	9.7×10^{-14}	7.8×10^{-14}	1.1×10^{-13}	1.0×10^{-13}	9.7×10^{-14}	1.0×10^{-13}	9.4×10^{-14}
15	8.9×10^{-14}	6.8×10^{-14}	9.2×10^{-14}	9.5×10^{-14}	7.8×10^{-14}	9.8×10^{-14}	8.2×10^{-14}
20	7.4×10^{-14}	3.8×10^{-14}	6.7×10^{-14}	8.4×10^{-14}	4.9×10^{-14}	8.4×10^{-14}	6.2×10^{-14}
25	5.3×10^{-14}	2.4×10^{-14}	2.4×10^{-14}	6.3×10^{-14}	2.7×10^{-14}	4.0×10^{-14}	4.4×10^{-14}
30	2.5×10^{-14}	1.5×10^{-14}	8.6×10^{-15}	4.8×10^{-14}	1.4×10^{-14}	2.0×10^{-14}	3.2×10^{-14}
35	1.3×10^{-14}	1.2×10^{-14}	5.7×10^{-15}	3.7×10^{-14}	8.0×10^{-15}	1.2×10^{-14}	2.4×10^{-14}
40	7.9×10^{-15}	8.6×10^{-15}	4.6×10^{-15}	2.4×10^{-14}	5.5×10^{-15}	8.7×10^{-15}	1.9×10^{-14}
45	4.5×10^{-15}	6.0×10^{-15}	4.0×10^{-15}	1.9×10^{-14}	4.0×10^{-15}	6.6×10^{-15}	1.4×10^{-14}
50	2.2×10^{-15}	4.2×10^{-15}	3.5×10^{-15}	1.3×10^{-14}	3.0×10^{-15}	5.5×10^{-15}	1.1×10^{-14}

Table 6. The static and dynamic elastic moduli of Neapolitan Yellow Tuff (NYT) and Grey Campanian Ignimbrite (WGI) measured under an effective pressure of 5 MPa.

	Neapolitan Yellow Tuff (NYT)		**Grey Campanian Ignimbrite (WGI)**	
	static	**dynamic**	**static**	**dynamic**
Young's modulus [GPa]	2.1	6.0	1.7	4.9
Poisson's ratio	0.30	0.31	0.29	0.24
shear modulus [GPa]	0.81	3.1	0.66	2.7

Figure captions

Figure 1. Map showing the location of the inferred Campi Flegrei caldera and the proximity of Naples to both the Campi Flegrei caldera and Mt. Vesuvius. The Neapolitan Yellow Tuff used in this study was sourced from an open quarry within the inferred CF caldera at Monte San Severino (i.e., within the red circle in Figure 1), while the Grey Campanian Ignimbrite was sourced from an open quarry to the north-west of the town of Caserta (the blocks used in this study are the same as those used in Heap *et al.*, 2012).

Figure 2. Photographs and optical microscopy images of the as-collected Neapolitan Yellow Tuff (A and B) and Grey Campanian Ignimbrite (C and D). The photomicrographs are taken from Heap *et al*. (2012).

Figure 3. Schematic diagram of the permeameter at the Rock & Ice Physics Laboratory (RIPL), University College London. Schematic is not to scale.

Figure 4. Schematic diagram of the triaxial deformation apparatus at the Laboratoire de Déformation des Roches, Université de Strasbourg. Schematic is not to scale.

Figure 5. The evolution of porosity change with increasing effective pressure for Neapolitan Yellow Tuff (A) and Grey Campanian Ignimbrite (B). The temperatures in the legend refer to the thermal stressing temperature (see text for details).

Figure 6. The evolution of water permeability with increasing effective pressure for Neapolitan Yellow Tuff (A) and Grey Campanian Ignimbrite (B). The temperatures in the legend refer to the thermal stressing temperature (see text for details).

Figure 7. The evolution of P-wave velocity (A), S-wave velocity (B), dynamic Young's modulus (C), dynamic Poisson's ratio (D), dynamic shear modulus (E), and Vp/Vs ratio (F) with increasing effective pressure for Neapolitan Yellow Tuff The temperatures in the legend refer to the thermal stressing temperature (see text for details).

Figure 8. The evolution of P-wave velocity (A), S-wave velocity (B), dynamic Young's modulus (C), dynamic Poisson's ratio (D), dynamic shear modulus (E), and Vp/Vs ratio (F) with increasing effective pressure for Grey Campanian Ignimbrite. The temperatures in the legend refer to the thermal stressing temperature (see text for details).

Figure 9. Constant strain rate stress-strain curves, together with the cumulative output of acoustic emission (AE) "energy" (the area under the received AE waveform envelope) for as-collected Neapolitan Yellow Tuff (A) and Grey Campanian Ignimbrite (B). The experimental conditions are provided on each panel and the positions of C* are indicated by the arrows. The steps in the data are due to the stepwise nature of the pumps.

Figure 10. Constant strain rate stress-porosity reduction curves for as-collected Neapolitan Yellow Tuff (A) and Grey Campanian Ignimbrite (B). The experiments shown here are the same

as those in Figure 9. The experimental conditions are provided on each panel and the positions of C* are indicated by the arrows. The steps in the data are due to the stepwise nature of the pumps.

Figure 11. Scanning electron microscope images of an as-collected sample of Neapolitan Yellow Tuff taken beyond P*. Panel A shows an overview of the post-P* microstructure at a low magnification. Panels B and C show detailed evidence of pore collapse (indicated by the white arrows). Panel C is a zoom of the white box shown in panel B.

Figure 12. Optical microscope images of Neapolitan Yellow Tuff thermally stressed to a temperature of 1000 °C showing macrocracks. The photomicrograph in panel A, showing foaming, is taken from Heap *et al*. (2012).

Figure 13. Optical microscope images of grey Campanian Ignimbrite thermally stressed to a temperature of 1000 °C. Both photographs are taken from Heap *et al*. (2012).

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