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Water fluxes through clay and sandy soils: integration of tracing and soil water data

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Abstract This paper considers infiltration studies in a cracking clay and a sandy loam soil at two sites in the UK. Changes in water potential during infiltration under natural and simulated rain events are determined using tensiometer nests within plots of 9 m^2. An anionic tracer (Br^-) was applied at a controlled rate, following which samples of soil water were collected at regular intervals from porous cup samplers within the two soil profiles. Br^- concentrations were determined using high performance liquid chromatography (HPLC) ion chromatography. The results indicate substantial differences in timing and rate of infiltration and redistribution between the two soil types, and significant internal variability within the same soil. The results are analysed to assess seasonal changes in the nature and magnitude of water movement.

INTRODUCTION

Understanding the mechanisms of water movement through agricultural soils is fundamental to ensuring correct rates of nutrient and water application. Equations of soil water movement traditionally envisage the soil to comprise a homogeneous medium in which water movement conforms to Darcy's law and infiltration can be described by the Richards equation (Richards, 1931). While some of these assumptions may be justified for sandy soils, clay soils are often characterized by low hydraulic conductivity and have been thought to have a low potential for leaching although soil macropores can account for considerable water and solute flow (Flury *et al.*, 1994). The presence of macropores greatly complicates attempts to quantify water and solute flow in clay soils given their seasonal development and decay. These differences in soil properties have implications both for the optimum field technique for studying particular soils, and in the practicality of identifying equations of water and solute flow that may be applied widely. Ideally, a combination of tracing and monitoring of soil moisture provides the information necessary to identify water flow paths. This paper addresses these questions by describing results of water infiltration monitoring and tracer application on two contrasting soil types: a sandy loam and a cracking clay soil.

FIELD SITES

This work was completed at two sites: Woburn Farm and Brimstone Experimental Farm in the UK run jointly by the Institute for Arable Crop Research (IACR),

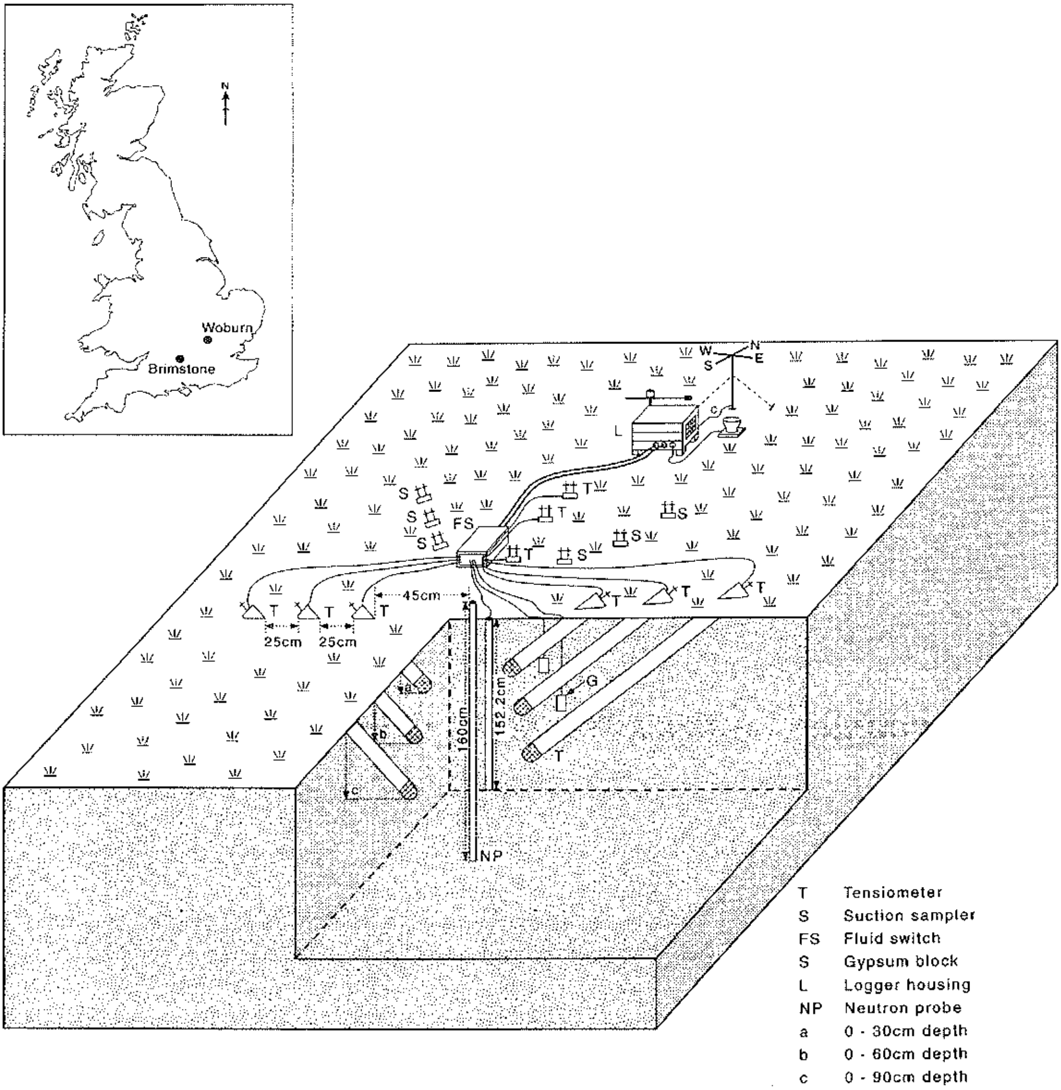

Fig. 1 Location of field sites at Brimstone and Woburn and site instrumentation.

Rothamsted, and the Agricultural Development and Advisory Service (ADAS) (Fig. 1). At both sites, the study plots have been under grass for over two years. The plot at Woburn Farm is located towards the top of a sloping field at 100–105 m a.s.l. The soil is a well-drained loamy sand with low clay content (0–13%) and extremely small amounts of silt. Most sand is between 125 and 250 μm with consistent texture at depth. However, there is a compacted layer at a depth of 30–46 cm with an irregular boundary between upper and lower horizons (Catt *et al.*, 1975). Annual rainfall at the site is 630 mm. In contrast, the soil at Brimstone Farm is a heavy clay (verti-eutric gleysol) characterized by very low hydraulic conductivity ($<0.1 \mathrm{m\,day}^{-1}$) when wet, typical for UK lowland clays. Desiccation cracks often develop to depths of 1.2 m in the summer and autumn (Cannel *et al.*, 1984). Annual rainfall at this site is 680 mm.

INSTRUMENTATION

At both sites, a plot of 9 m^2 area was instrumented from July 1997 (Fig. 1). Four nests of tensiometers were positioned at 30, 60, and 90 cm depths and connected sequentially to a pressure transducer via a Scanivalve switch. The switch was advanced every 180 s and mean millivolt output logged over 150–180 s. These data were corrected for elevation to derive pressure head. A series of 12 porous cup samplers was installed between the tensiometers at the same depths. Precipitation was recorded using a tipping bucket gauge, and data output at 15 minute intervals.

The movement of water through both soils was investigated by tracer application. Choice of tracer reflected the need to combine easily detectable tracer concentrations with minimal adverse effects on plant cover. Given the low background concentration of bromide (Br^-) in both soils, potassium bromide solution in concentrations of 6.3 mM and 11.39 mM was used as tracer at Brimstone and Woburn respectively and was applied at 2 litres m^{-2} to the plot areas. Higher concentrations were applied at Woburn due to higher background Br concentrations.

Values of water potential were low in the two soils before the experiment, and the plots were irrigated with water prior to tracer application. At Brimstone, water was applied for 30 minutes on 20 and 21 May to simulate a 2 mm rain event on each day. Samples were collected at 50–60 minute intervals for the first 6 h, and subsequently at an interval of 1–2 h. At Woburn the soil was considerably drier and 145 litres were applied on 14 July, equivalent to a 16 mm rain event, to ensure collection of sufficient soil water samples. Additional quantities of water were applied hourly (20 litres h^{-1}; 2 mm h^{-1}) to ensure the continued collection of water samples, which were extracted at intervals of 45–50 minutes for 8 h after tracer application. Samples were analysed by high performance liquid chromatography (HPLC) ion chromatography adapting standard anion-gradient procedures.

RESULTS

Soil water response to rainfall events

Patterns of soil water response to rainfall are given in Fig. 2. Tensiometer responses in two profiles (3 and 4) at Woburn between 24 August and 8 September are shown in Fig. 2(a). The results indicate a slow response to rainfall, evident in a delayed increase of roughly 200 cm in potential at 30 cm depth over a period of 2 days in response to the first rain event. Steady-state conditions develop after 24 h as illustrated by increasing soil water potential on 26 August when no rain was observed. Potentials at 90 cm depth are similar for both profiles with a delayed increase over the four days following rainfall. At 60 cm, potential remained constant over the period changing little after rain events; however, a higher water potential was observed at this depth in profile 3, following infiltration from rain events on 24 and 25 August (Fig. 2(a)). These wetter antecedent conditions and the rain event of 27 August increased water potential on 27 August. A marked response is absent at 60 cm in profile 4, where water potential was much lower even after the initial rain events of 24 and 25 August, indicating the role of antecedent moisture conditions on infiltration and redistribution of water in this sandy soil.

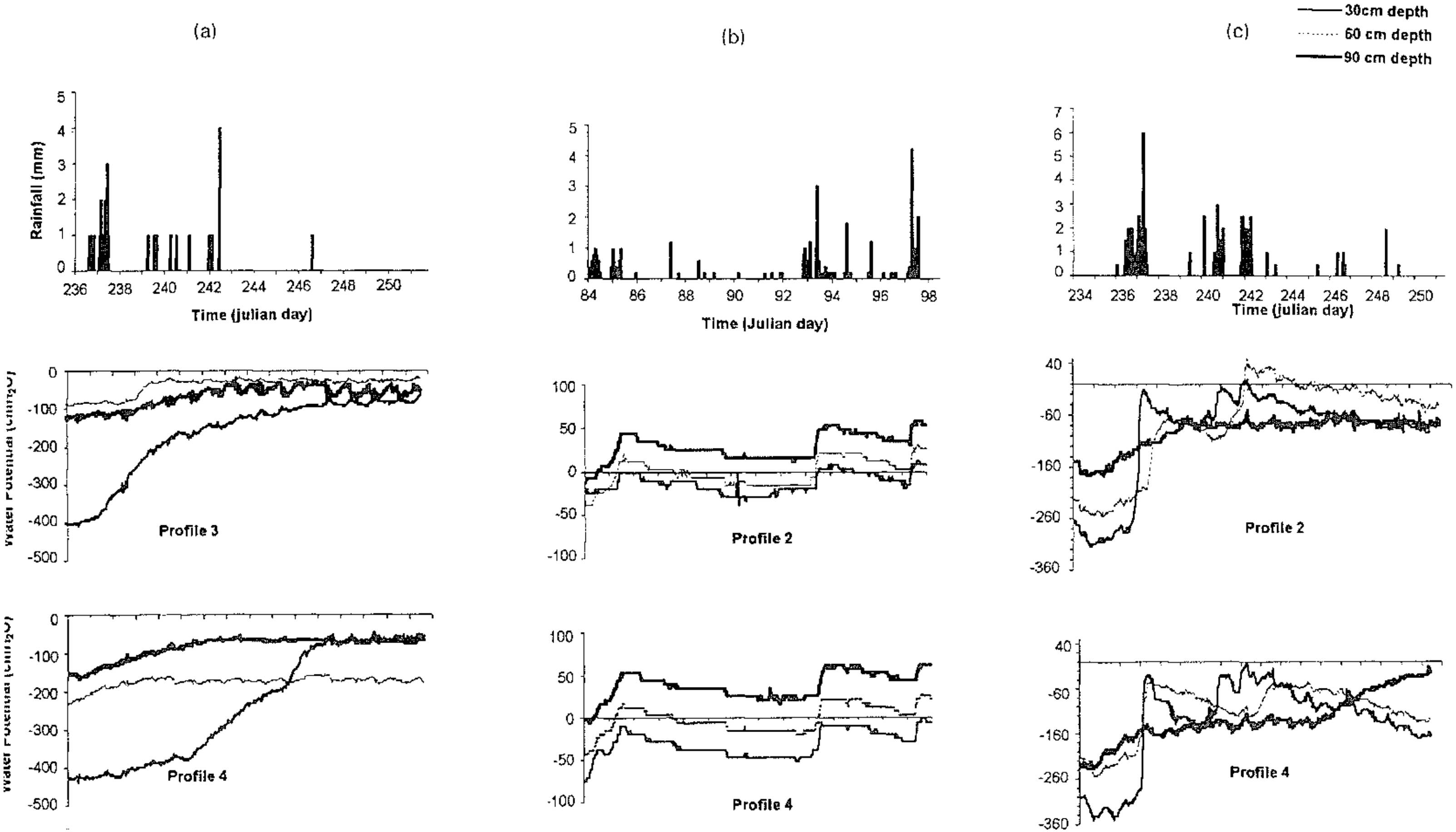

Fig. 2 Relationship between soil water tension and hourly rainfall: (a) Woburn Farm 21 August–8 September 1997 (Julian days 236 to 251); (b) Brimstone Farm "winter" 23 March–8 April 1998 (Julian days 82 to 98); (c) Brimstone Farm "summer" 22 August–11 September 1997 (Julian days 234 to 254).

Table 1 Estimated unsaturated hydraulic conductivity of the Woburn soil.

	Δ soil water potential	Δ height	K_{unsat} (cm day^{-1})
Profile 3			
30–60 cm	124.1	30	0.218
60–90 cm	31.9	30	0.845
Profile 4			
30–60 cm	132.9	30	0.203
60–90 cm	102.1	30	0.264

Water flow apparently follows Darcian principles which enables unsaturated hydraulic conductivity to be estimated from the steady water flux from rainfall, and the hydraulic gradient between adjacent tensiometers. The results are summarized in Table 1 which indicates that K_{unsat} is higher at 90 cm than at 60 cm depths in both profiles, reflecting the effects of the compacted soil layer between 30 and 46 cm referred to above. Although K_{unsat} is dependent upon the moisture status of the soil, the data provide a comparative measure of the infiltration rate.

Soil water responses for the clay soil at Brimstone are given in Fig. 2(b) and (c). Figure 2(b) shows tensiometer response to precipitation under "winter" conditions with no significant macropore development. The two profiles indicate a similar response to rainfall: the water table lies near 60 cm, indicated by alternating positive and negative pressure here, while the ground was consistently unsaturated at 30 cm. There was little variation in potential gradient within and between profiles following rain events (Fig. 2(b)), demonstrating uniform rates of water transmission through the saturated soil.

The data shown in Fig. 2(c) for "summer" conditions indicate much drier moisture conditions with large variations in potential at 30 and 60 cm and rapid increases in potential following rain events. Both profiles in Fig. 2(c) have periods when higher tensions are recorded at 60 cm as vertical drainage occurs at lower rates than rainfall infiltration. At 90 cm, the tensiometer has a much delayed response to rainfall, with a slow adjustment over 48 hours, possibly showing the effects of changing soil water pressure during infiltration.

Tracing results

Woburn Results from Br^- application on 14 July at Woburn are presented in Fig. 3. The dense soil layer between 30 and 46 cm made it difficult to collect soil water samples at the lower depths in two profiles. However, the figure illustrates that for profile 3, where a complete set of data was obtained, measurements indicated a gradual response to water and tracer application. Peak concentrations at 30 cm were 22.2 ppm and 40.2 ppm in profiles 3 and 4 respectively when measurements ceased, indicating a lag of over 8 h after tracer was applied. Br^- concentration also varied significantly between profiles at this depth indicating near-surface variations in permeability.

Throughout the sampling period at Woburn, there was no appreciable change in Br^- concentration at the lower depths in the two profiles. It seems that the effect of the compacted layer is to limit water seepage below 30 cm depth. This interpretation is consistent with the water potential response to wetting under natural precipitation

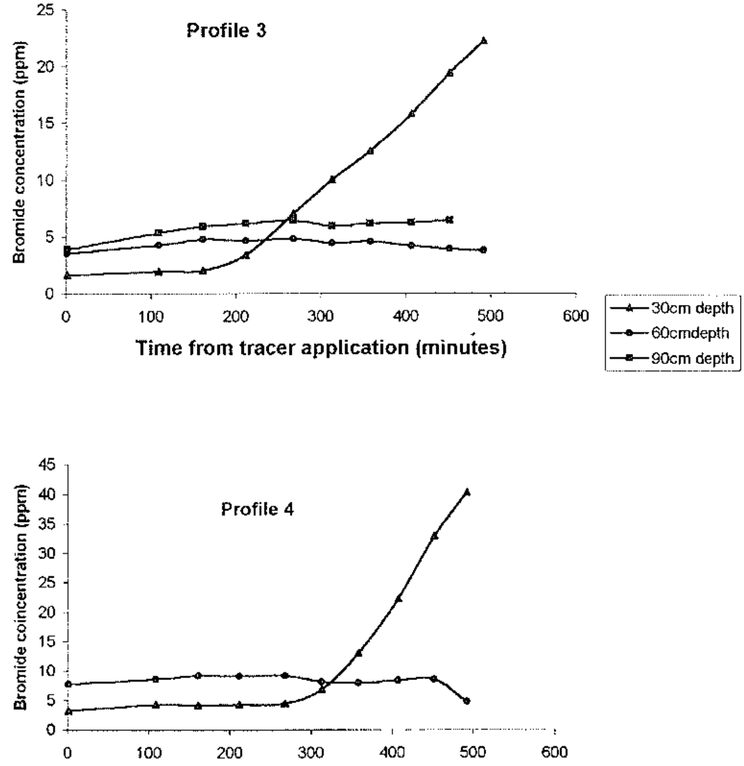

Fig. 3 Br⁻ concentrations for tracer application at Woburn, 14 July 1998.

described above and in Fig. 2(a). The absence of sharp peaks in Br⁻ concentration, and in previously observed water potential responses to wetting, even at 30 cm depth, confirms the lack of influence of drainage pores on fluxes in this sandy soil.

Brimstone The results from the tracing experiment completed at Brimstone on 21 May 1998 are given in Fig. 4. The graphs show soil water potential at three depths for profiles 1 and 3, with Br⁻ concentrations derived from adjacent cup samplers. Preliminary irrigation accounts for the large increase in potential in both profiles, particularly at 30 cm. The tracer was applied at 13:00 on 21 May resulting in Br⁻ breakthrough curves that reflect closely the trend in infiltration and moisture redistribution. Typical curves show a rapid increase in Br⁻, followed by a fast recession that stabilizes gently. However, the breakthrough curves indicate greater variability within depths than shown by water potential values alone, particularly at the 30 and 60 cm depths (Table 2). Peak Br⁻ concentrations of 12 ppm and 4 ppm, 0.7 ppm and 14 ppm, and 0.5 and 0.96 ppm were obtained at 30, 60 and 90 cm depths respectively. The lag between peak water potential and peak Br⁻ concentration ranged from 5–8 h at 30 and 60 cm, to 8–10 h at 90 cm depth. This seems to imply the absence of bypass flow despite indications that macropores were present during the measurement period. However, the breakthrough of Br⁻ at 60 cm nearly 1 h earlier than at 30 cm, suggests bypass flow, which may have been diminished by swelling following initial soil wetting.

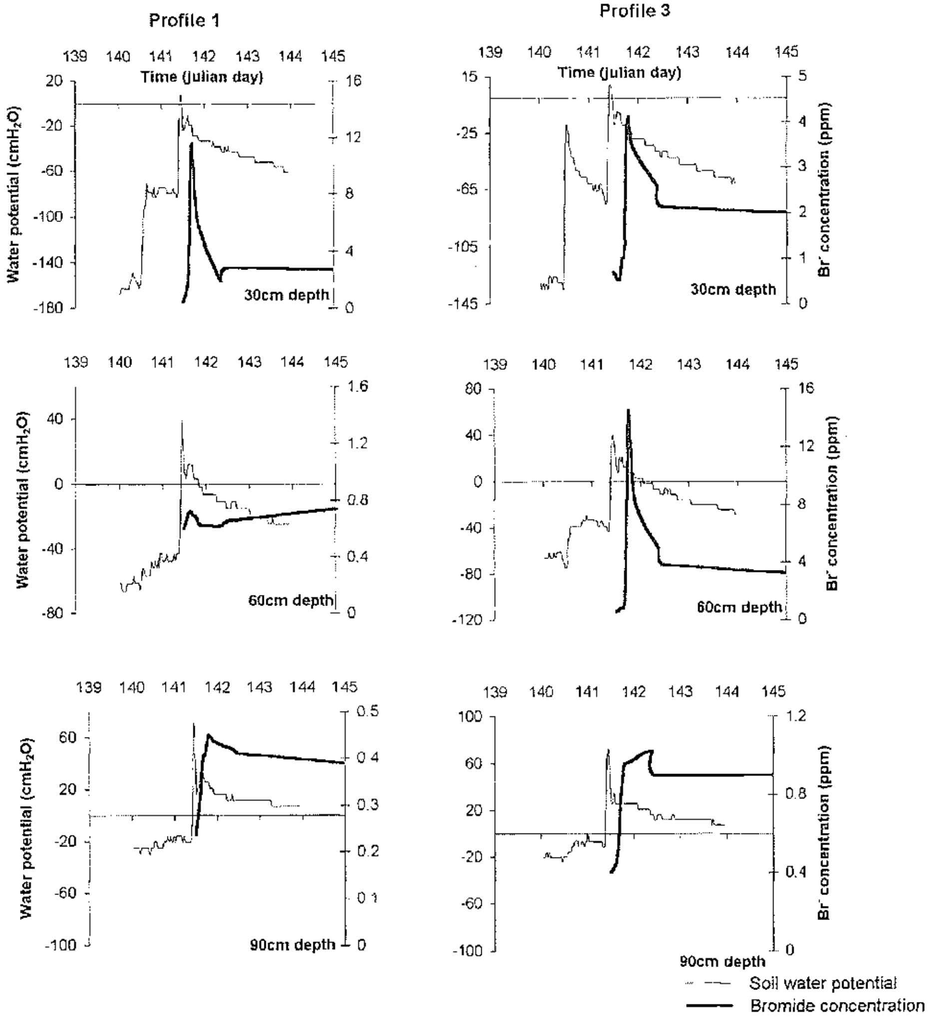

Fig. 4 Combined series of soil water potential and Br$^-$ concentration for Brimstone on 21 May 1998.

DISCUSSION

The results described above demonstrate the value of adopting an experiment approach combining soil physics (recording tensiometers) and tracers. Although the manner of water flow and redistribution differ considerably for the two soils described at Woburn

Table 2 Values of peak soil water potential and Br$^-$ concentration (Brimstone).

Depth (cm)	Peak potential (cmH$_2$O):		Peak Br$^-$ concentration (ppm):	
	Profile 1	Profile 3	Profile 1	Profile 3
30	8.16	8.16	11.54	4.12
60	39.95	39.95	0.72	14.30
90	71.74	71.74	0.45	0.97

and Brimstone, the same techniques are equally applicable to both and clarify the respective modes of water flow. Inevitably the biggest problem with both soil systems lies in representing the temporal variation of soil water pressures and tracer concentrations, given constraints on sampling frequency and a discrete set of sample points. In both soil types, there is some evidence of heterogeneous flow systems whether reflecting macropores within the clay soil, the existence of unstable wetting, or fingers in the sandy soil (Selker *et al.*, 1992). In the clay soil, flow processes are dominated by the seasonal development of desiccation cracks that evidently influences soil water movement significantly (Messing & Jarvis, 1990). However, in the free-draining sandy soil, water movement is limited by the low unsaturated hydraulic conductivity and the presence of dense lower soil horizons which produced an incomplete recovery of soil water samples. Such interpretations would be difficult to justify without having available a combination of tensiometer and tracer results.

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