9. Grünewald, U. *et al. Ursachen, Verlauf und Folgen des Sommer-Hochwassers 1997 an der Oder sowie Aussagen zu bestehenden Risikopotentialen, Langfassung* (IDNDR, Bonn, 1998).
10. Weikinn, C. *Quellentexte zur Witterungsgeschichte Europas von der Zeitwende bis zum Jahre 1850: Hydrographie*, Parts 1–4 (Akademie, Berlin, 1958–1963); Parts 5–6 (eds Börngen, M. & Tetzlaff, G.) (Gebrüder Borntraeger, Berlin, 2000–2002).
11. Pötzsch, C. G. *Chronologische Geschichte der großen Wasserfluthen des Elbstroms seit tausend und mehr Jahren* (Waltherische Hofbuchhandlung, Dresden, 1784).
12. Schäfer, W. *Chronik der Dresdener Elbbrücke, nebst den Annalen der größten Elbfluthen von der frühesten bis auf die neueste Zeit* (Adler und Dietze, Dresden, 1848).
13. Königliche Elbstrombauverwaltung *Der Elbstrom, sein Stromgebiet und seine wichtigsten Nebenflüsse* Vol. 3.1 (Reimer, Berlin, 1898).
14. Bureau des Ausschusses zur Untersuchung der Wasserverhältnisse in den der Überschwemmungsgefahr besonders ausgesetzten Flußgebieten *Der Oderstrom, sein Stromgebiet und seine wichtigsten Nebenflüsse* Vol. 3.1 (Reimer, Berlin, 1896).
15. Brázdil, R. *et al.* Flood events of selected European rivers in the sixteenth century. *Clim. Change* **43**, 239–285 (1999).
16. Militzer, S. *Klima, Umwelt, Mensch (1500–1800): Studien und Quellen zur Bedeutung von Klima und Witterung in der vorindustriellen Gesellschaft* (Historisches Seminar, Leipzig, 1998).
17. Königliche Elbstrom-Bauverwaltung *Hydrologischer Jahresbericht von der Elbe für 1892* (Baensch, Magdeburg, 1893).
18. Helms, M., Ihringer, J. & Nestmann, F. in *Morphodynamik der Elbe* (eds Nestmann, F. & Büchele, B.) 91–202 (Institut für Wasserwirtschaft und Kulturtechnik TH Karlsruhe, Karlsruhe, 2002).
19. Oderstrombauverwaltung *Mitteilungen der Oderstrombauverwaltung über die Strombauten, die Wasserstände und die Schiffahrtsverhältnisse der Oder, 1905–1906, 1911–1926, 1927–1929, 1930–1932, 1933–1936* (Oderstrombauverwaltung, Breslau, 1907–36).
20. Reiss, R.-D. & Thomas, M. *Statistical Analysis of Extreme Values* (Birkhäuser, Basel, 1997).
21. Cowling, A., Hall, P. & Phillips, M. J. Bootstrap confidence regions for the intensity of a Poisson point process. *J. Am. Statist. Assoc.* **91**, 1516–1524 (1996).
22. Mudelsee, M. XTREND: A computer program for estimating trends in the occurrence rate of extreme weather and climate events. *Sci. Rep. Inst. Meteorol. Univ. Leipzig* **26**, 149–195 (2002).
23. Bundesanstalt für Gewässerkunde, *Untersuchungen zum Abflussregime der Elbe*, (BfG, Berlin, 2000).
24. Bronstert, A., Bismuth, C. & Menzel, L. (eds) *Proc. European Conf. on Advances in Flood Research* (Report No. 65, Potsdam Institute for Climate Impact Research, Potsdam, 2000).
25. Hulme, M., Osborn, T. J. & Johns, T. C. Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations. *Geophys. Res. Lett.* **25**, 3379–3382 (1998).
26. Folland, C. K. *et al.* in *Climate Change 2001: The Scientific Basis* (eds Houghton, J. T. *et al.*) 99–181 (Cambridge Univ. Press, Cambridge, 2001).
27. Luterbacher, J. *et al.* The late Maunder Minimum (1675–1715)—A key period for studying decadal scale climatic change in Europe. *Clim. Change* **49**, 441–462 (2001).
28. Schmidt, M. *Hochwasser und Hochwasserschutz in Deutschland vor 1850* (Oldenbourg, Munich, 2000).
29. Cox, D. R. & Lewis, P. A. W. *The Statistical Analysis of Series of Events* (Methuen, London, 1966).

Supplementary Information accompanies the paper on **www.nature.com/nature**.

Acknowledgements We thank J. Jacobeit, J. Luterbacher and M. Schulz for comments, and N. Conrads, H. Engel, W. Fröhlich, T. Lüllwitz, J. Munzar, R. Oppermann as well as GRDC (Germany) and NOAA (USA) for data. This work was supported by the Deutsche Forschungsgemeinschaft.

Competing interests statement The authors declare that they have no competing financial interests.

Correspondence and requests for materials should be addressed to M.M. (mudelsee@uni-leipzig.de).

Radiometric dating of the Siloam Tunnel, Jerusalem

Amos Frumkin[1], **Aryeh Shimron**[2] **& Jeff Rosenbaum**[3]

[1] *Department of Geography, The Hebrew University of Jerusalem, 91905, Israel*
[2] *Geological Survey of Israel, 30 Malkhei Israel Street, Jerusalem, 95501, Israel*
[3] *Postgraduate Research Institute for Sedimentology, Reading University, Reading RG6 6AB, UK*

The historical credibility of texts from the Bible is often debated when compared with Iron Age archaeological finds (refs. 1, 2 and references therein). Modern scientific methods may, in principle, be used to independently date structures that seem to be mentioned in the biblical text, to evaluate its historical authenticity. In reality, however, this approach is extremely difficult because of poor archaeological preservation, uncertainty in identification, scarcity of datable materials, and restricted scientific access into well-identified worship sites. Because of these problems, no well-identified Biblical structure has been radiometrically dated until now. Here we report radiocarbon and U–Th dating of the Siloam Tunnel[3–10], proving its Iron Age II date; we conclude that the Biblical text presents an accurate historic record of the Siloam Tunnel's construction. Being one of the longest ancient water tunnels lacking intermediate shafts[11,12], dating the Siloam Tunnel is a key to determining where and when this technological breakthrough took place. Siloam Tunnel dating also refutes a claim[13] that the tunnel was constructed in the second century BC.

The Siloam Tunnel carries water into ancient Jerusalem from the only perennial spring of the region, the Gihon (Fig. 1). This tunnel has attracted the attention of many scholars, who have yet to solve some of its mysteries[3–13]. Most scholars ascribe the Siloam Tunnel to King Hezekiah (727–698 BC), following the biblical verses (2 Kings 20:20, 2 Chronicles 32:3,4) narrating that this Judahite king constructed a waterwork that "brought water into the city". In addition to the biblical record, the Siloam Tunnel's association with Hezekiah also relies on the palaeography and philology of the monumental Siloam inscription found close to the Siloam Tunnel's outlet (refs 14, 15 and references therein). However, the name of King Hezekiah is not mentioned in the inscription, unlike other monumental inscriptions of the Levant, which often praised monarchs for their architectural achievements. If the assumed date of the inscription is correct, it can still be argued that the inscription could be a later copy of a literary narrative, such as the 'Chronicles of the Kings of Judah', so the Siloam Tunnel itself may be older than the inscription. Such a view could be supported by the unique style, differing from most other North-Semitic inscriptions[15]. According to ref. 13, a

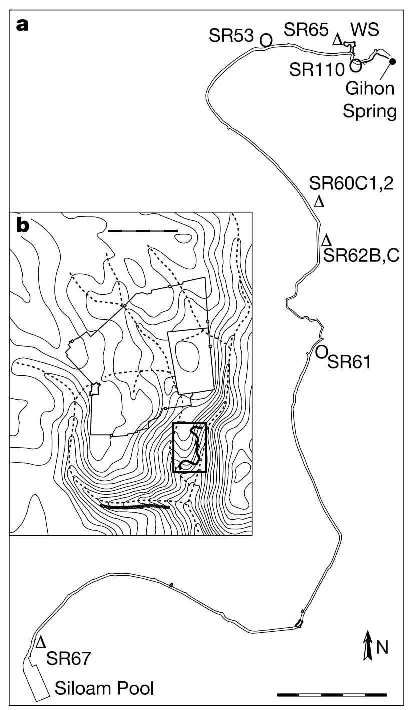

Figure 1 Location map. **a**, Plan of the Siloam Tunnel (Long. 35.17°; Lat. 31.68°) with the location of dated samples. Scale bar, 50 m. Circle, plant fragments within plaster, dated by ^{14}C AMS; triangle, speleothem sample dated by ^{230}Th–^{234}U thermal ionization mass spectrometry. WS, Warren Shaft. **b**, Relation of the Siloam Tunnel (bold line) to the topography of Jerusalem and the present city walls. The Siloam Tunnel conveyed the water of the Gihon Spring into the Siloam Pool within the original core of Jerusalem. Contours are 10 m (vertically) apart. Scale bar, 500 m.

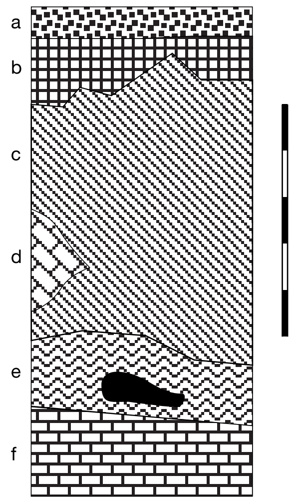

Figure 2 Typical layering in a core drilled at the bottom of the Siloam Tunnel. Scale bar, 5 cm. Layer a, silty tufa; layer b, young black plaster; layer c, intermediate coarse plaster; d, limestone clast; layer e, the lowest plaster termed 'ancient plaster', in which a piece of wood is shown (black); layer f, limestone bedrock. Note that no deposit exists between the ancient plaster and the bedrock.

much later date should be assigned to the inscription and the Siloam Tunnel: about the second century BC, and the Siloam inscription cannot serve as a cornerstone for dating other inscriptions, because it was never dated independently. "Attempts to reconstruct the history of Hebrew scripts can only be based upon texts whose dating can be established other than by palaeography"[13]. Other scholars[16] discredited the proposed late age of the Siloam Tunnel, but both sides of the debate relied on the inscription text itself, failing to produce any independent dating. Most scholars believe that independent dating of the Siloam Tunnel is impossible because the tunnel was cleared of debris during the early twentieth century[3], so it does not contain any artefacts that can be dated by classic archaeological methods.

We overcome this difficulty by dating artificial and natural materials incorporated within the tunnel walls, ceiling and floor, which constrain the age of the Siloam Tunnel. During our geological mapping of the tunnel some of our work focused on an important feature (previously documented in ref. 3) that the Siloam Tunnel was originally cemented with plaster covering its floor, walls and occasionally ceiling. This material had been applied to the rock-cut limestone and dolomite surface of the Siloam Tunnel to seal it and to avoid the loss of water through fissures. Such fissures in the bedrock above and within the Siloam Tunnel allow dripwater to enter the tunnel and deposit calcite speleothems (flowstone and stalactites). We have drilled and obtained core samples from these materials, and classified them according to field relations as well as petrographic, geochemical, scanning electron microscopy (SEM), X-ray diffraction (XRD) and isotopic analyses, performed at the Geological Survey of Israel laboratories[17].

The plaster of the Siloam Tunnel varies in thickness from about 1 to 20 cm. In a typical core we distinguish a silty tufa veneer covering three varieties of plaster (Fig. 2). We refer to the stratigraphically oldest variety as the 'ancient plaster' (AP)[17]. The ancient plaster is a very fine hydraulic lime plaster, composed of a recarbonated lime (CaO) binder with a filler of soil, chips of marl, organic materials and bone fragments, as well as rare charcoal and ash. Shrinkage cracks and oval vugs are abundant and are now filled with acicular crystals of aragonite. XRD and SEM also reveal the presence of bone apatite, traces of the rare carbonate vaterite and zoned isotropic peloids containing amorphous varieties of CaAl-silicates with fibres of ettringite. The low firing temperature, absence of pottery shards and the relatively high content of clays and phosphorus clearly distinguish the ancient plaster from younger plasters in the waterworks. The chemical and petrographic characteristics of the ancient plaster indicate that the source rock for lime manufacture was probably the phosphorus-rich marly chalk occurring in Senonian formations on the hills east of Jerusalem. The marly and organic-rich nature of this chalk imparted upon the plaster its natural hydraulic characteristics. This plaster is generally covered by younger plasters or by a lamina, about 2–4 cm thick, of silty tufa and siltstone deposited from the spring waters flowing along the Siloam Tunnel. The siltstone is quartzose with some feldspar and abundant heavy minerals (magnetite, ilmenite, amphibole, garnet and zircon). It is derived by the erosion of a sandy unit intercalated with the local carbonate rock.

We drilled 15 holes through the Siloam Tunnel's floor, evenly distributed along the entire length of the tunnel. None of them encountered evidence of a sedimentary layer between the ancient plaster and bedrock. Because clastic and chemical sediments were, and are to this day, deposited from waters of the spring, their absence beneath the ancient plaster indicates that a natural water conduit was not present along the bottom of the Siloam Tunnel before the application of the ancient plaster. It also indicates that plastering took place soon after construction of the tunnel. Plastering of ancient waterworks has been a well-known technological practice in the region[12,18].

We have recovered from the ancient plaster fine plant fragments that are extraordinarily well preserved. Two samples were radiocarbon dated at the Oxford University accelerator mass spectrometry (AMS) facility by its standard procedure[19]. After correction for isotopic fractionation with the use of measured $\delta^{13}C$, and based on the ^{14}C half-life of 5,568 yr, the conventional dates for the ancient plaster organic materials are 2,620 ± 35 yr BP

Table 1 **Radiogenic isotopic data and ages of Siloam Tunnel (ST) and the bottom of Warren Shaft (WS)**

Field no.	Laboratory no.	Sample description	$\delta^{13}C$	^{14}C date (yr BP)	Calibrated age, 1σ range
SR53*	OxA-8522	Piece of wood, ST	−26.0	2,620 ± 35	822–796 BC
SR61*	OxA-8523	Short-lived plant, ST	−25.0	2,505 ± 35	790–760; 690–540 BC
SR110*	OxA-8990	Piece of wood, ST	−27.5	605 ± 65	AD 1300–1405

Field no.	Sample description	U conc. (p.p.m.)	$^{230}Th/^{234}U$	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$ age (yr)
SR67†	Stalactite from ceiling, ST	0.617	0.02237 ± 0.00016	1.0403 ± 0.0031	27.15	2,317 ± 18
SR65†	Flowstone in natural void, WS	0.386	0.9899 ± 0.0054	1.0918 ± 0.0052	920.5	>400,000
SR62B†	Flowstone on plaster, ST	0.911	0.01942 ± 0.00020	1.2253 ± 0.0053	2.446	<1,000
SR62C†	Flowstone on plaster, ST	0.615	0.05892 ± 0.00056	1.2185 ± 0.0035	1.604	<500
SR60C1†	Flowstone on plaster, ST	0.664	0.05082 ± 0.00083	1.3765 ± 0.0027	2.619	<2,500
SR60C2†	Flowstone on plaster, ST	0.625	0.03101 ± 0.00014	1.3956 ± 0.0048	2.067	<2,000

*Radiocarbon AMS dates calibrated with OxCal[20,21].
† ^{230}Th–^{234}U dates of speleothems corrected for detrital content assuming that initial $^{230}Th/^{232}Th = 1.6$ (ref. 22).
Isotope ratios are given as activity ratios.

for a piece of wood (SR53; Table 1), and 2,505 ± 35 yr BP for a short-lived plant (SR61). Calibrated with the OxCal program[20] using the INTCAL 98 calibration curve[21], these correspond within 1σ uncertainty to calendar age ranges of 822–796 BC for the wood sample, and a multiple range of 790–760 and 690–540 BC for the short-lived plant. Within an uncertainty margin of 2σ, the short-lived plant age range is 800–510 BC.

To test these dates against the observed stratigraphic order of plasters, we also dated a small fragment of charred wood recovered from a layer of coarse slag-bearing plaster overlying the ancient plaster between the Gihon Spring and Warren Shaft. The conventional ^{14}C age of this sample (SR110; Table 1) is 605 ± 65 yr BP, which is in agreement with the field relations and indicates previously undocumented Mamluk period (AD 1260–1516) activity in the Siloam Tunnel.

The chronology of the Siloam Tunnel speleothems is based on ^{230}Th–^{234}U dating by thermal ionization mass spectrometry performed at the Open University, Milton Keynes (Table 1). Laboratory errors are reported with 2σ uncertainty. After conventional chemical preparation, mass abundances of natural U and Th isotopes were measured[22]. For precise dating we used only reliable samples in which ^{230}Th/^{232}Th > 20, indicating that radiogenic ^{230}Th predominated and detrital contamination was negligible[23]. We calculated the dates and corrected for detrital content assuming an initial ^{230}Th/^{232}Th ratio of 1.6 (ref. 22).

Stalactite SR67, taken from the ceiling of the Siloam Tunnel about 4 m above the flowing water, was sufficiently distal from detrital contamination, as also indicated by its low ^{230}Th/^{232}Th ratio. The stalactite is not active today, so its deposition must have occurred closer to the Siloam Tunnel's construction than to the present. Its thorium age (measured on AD 2000) is 2,317 ± 18 yr, representing the mean deposition age of the bulk sample. This indicates that the Siloam Tunnel was constructed before 2,300 yr ago, ruling out the 'late date proposal'[13]. Samples SR60C1 to SR62C, taken from still active flowstone covering ancient plaster, are all <2,500 yr old, in agreement with the proposed age of the tunnel.

The historic-period dates of all Siloam Tunnel speleothems are compatible with our field observation that the Siloam Tunnel is human-made and did not follow a pre-existing karstic conduit[17,24]. For comparison, we collected one flowstone sample (SR65) in the proximal Warren Shaft, which is a natural karstic shaft[25,26]. Not surprisingly, this sample is older than the dating method limit (400 kyr), thus predating human construction of the waterworks by a considerable time span.

We have shown above that the ancient plaster was applied immediately after the Siloam Tunnel's construction. The material for plaster manufacture, including the dated organic matter, must have been readily available for the construction team. The piece of wood from 822–796 BC (SR53) retrieved from the ancient plaster had been originally taken from a tree that grew for some time before it was cut. Therefore it determines the maximum possible age of the Siloam Tunnel. Trees which reach a biological age of several hundreds years are rare in this region. Consequently, the Siloam Tunnel was probably constructed not later than ~100 yr after the 822–796 BC range of SR53, yielding a probable age for the Siloam Tunnel of about 700 BC or slightly earlier.

The age of a short-lived plant should be closer to the true archaeological date of construction. Indeed, the conventional ^{14}C age of the short-lived plant SR61 is 2,505 ± 35 yr, 115 yr younger than the age of SR53 (2,620 ± 35 yr). The calendar age of SR61 is, with 95% probability, between 800 and 510 BC (the ^{14}C calibration curve is relatively flat at about 2,500 yr BP (ref. 21)). Within this range, the true age is most probably about 700 BC, as indicated by SR53 (see above).

On the basis of the ^{14}C dates it can be concluded that the Siloam Tunnel was most probably constructed in about 700 BC. This agrees well with the *terminus post quem* thorium age of the speleothems deposited after the Siloam Tunnel's construction (see above).

The independent dating of both speleothem and plaster show that the Siloam Tunnel is hundreds of years older than the second century BC[13]. The radiometric Siloam Tunnel age of about 700 BC agrees well with the palaeographic age suggested for the Siloam Inscription[14,15]. Our dating agrees well also with the date commonly assigned to King Hezekiah, whom the biblical text describes as having constructed the Siloam Tunnel. The three independent lines of evidence—radiometric dating, palaeography and the historical record—all converge on about 700 BC, rendering the Siloam Tunnel the best-dated Iron-Age biblical structure thus far known. □

Received 27 April; accepted 30 June 2003; doi:10.1038/nature01875.

1. Finkelstein, I. & Silberman, N. *The Bible Unearthed: Archaeology's New Vision of Ancient Israel and the Origin of Sacred Texts* (Simon & Schuster, New York, 2001).
2. Montgomery, J. A. *A Critical and Exegetical Commentary on The Book of Kings* (Scribner, New York, 1951).
3. Vincent, L. H. *Underground Jerusalem: Discoveries on the Hill of Ophel (1909–11)* (Horace Cox, London, 1911).
4. Amiran, R. in *Jerusalem Revealed* (ed. Yadin, Y.) 75–78 (Israel Exploration Society, Jerusalem, 1976).
5. Ussishkin, D. The original length of the Siloam Tunnel in Jerusalem. *Levant* **8,** 82–95 (1976).
6. Shaheen, N. The sinous shape of Hezekiah's Tunnel. *Palestine Exploration Fund Quarterly Statement*, January–June, 103–108 (1979).
7. Gill, D. Subterranean waterworks of Biblical Jerusalem: Adaptation of a karst system. *Science* **254,** 1467–1471 (1991).
8. Abells, Z. & Arbit, A. *The City of David Water Systems* (Hadassah College, Jerusalem, 1995).
9. Mazar, A. Jerusalem's water supply in the First Temple Period. in *The history of Jerusalem* (eds Ahituv, S. & Mazar, A.) 195–232 (Yad Izhak Ben-Zvi, Jerusalem, 2000).
10. Reich, R. & Shukron, E. Reconsidering the karstic theory as an explanation to the cutting of Hezekiah's Tunnel in Jerusalem. *Bull. Am. Sch. Orient. Res.* **325,** 75–80 (2002).
11. Issar, A. S. The evolution of the ancient water supply system in the region of Jerusalem. *Israel Explor. J.* **26,** 130–136 (1976).
12. Tsuk, T. *Ancient Water Systems in Settlements in Eretz-Israel* (Tel Aviv Univ., 2000).
13. Rogerson, J. & Davies, P. R. Was the Siloam Tunnel built by Hezekiah? *Bibl. Archaeologist* **59,** 138–149 (1996).
14. Sasson, V. The Siloam Tunnel inscription. *Palestine Exploration Fund Quarterly Statement* **114,** 111–117 (1982).
15. Della-Vida, G. L. in *In Memoriam Paul Kahle (BZAW103)* (eds Black, M. & Fohrer, G.) 162–166 (Topelmann, Berlin, 1968).
16. Hackett, J. A. *et al.* Defusing pseudo-scholarship: The Siloam inscription ain't Hasmonean. *Bibl. Archaeol. Rev.*, March–April, 41–50 (1997).
17. Shimron, A., Frumkin, A., Rosenbaum, J., Deutch, Y. & Dvoracek, M. The significance of geological structures, cave sediments and hydraulic lime in the interpretation of the subterranean waterworks beneath ancient Jerusalem. *Geol. Surv. Israel Curr. Res.* **12,** 247–256 (2000).
18. Amit, D., Patrich, J. & Hirschfeld, Y. The aqueducts of Israel. *J. Roman Archaeol. Suppl. Ser.* no. 46, (*Journal of Roman Archaeology*, Portsmouth, Rhode Island, 2002).
19. Hedges, R. E. M., Law, I. A., Bronk Ramsey, C. & Housley, R. A. The Oxford accelerator mass spectrometry facility: Technical developments in routine dating. *Radiocarbon* **31,** 99–113 (1989).
20. Bronk Ramsey, C. Radiocarbon calibration and analysis of stratigraphy: The OxCal program. *Radiocarbon* **37,** 425–430 (1995).
21. Stuiver, M. *et al.* INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon* **40,** 1041–1083 (1998).
22. Kaufman, A. *et al.* U–Th isotope systematics from the Soreq Cave, Israel and climatic correlations. *Earth Planet. Sci. Lett.* **156,** 141–155 (1998).
23. Frumkin, A., Ford, D. C. & Schwarcz, H. P. Continental oxygen isotopic record of the last 170,000 years in Jerusalem. *Quat. Res.* **51,** 317–327 (1999).
24. Frumkin, A. & Shimron, A. in *11th International Conference on Water in Antiquity* (eds Fahlbusch, H., Meshel, Z., Peleg, Y., Porath, Y. & Tsuk, T.) 4, (Tel Aviv University, 2001).
25. Frumkin, A. *9th Congreso International de Espeleologia* 264–267 (Union Internacional de Espeliogia, Barcelona, 1986).
26. Gill, D. in *Excavations at the city of David 1978–1985 (Qedem 35)* (eds Ariel, D. T. & de Groot, A.) 1–28 (Institute of Archaeology, Hebrew University, Jerusalem, 1996).

Acknowledgements We thank U. Piner (Israel Cave Research Center) for assistance during the initial survey; S. Ashkenazi and Y. Peled (Geological Survey of Israel) for performing the drilling programme; the Research Laboratory for Archaeology and History of Art, Oxford University, for radiocarbon dating; the Open University, Milton Keynes, for ^{230}Th/^{234}U dating; C. Doherty (plaster and mortar) and P. Pettitt (radiocarbon) and Y. Elitzur for discussions, and K. Allred for surveying a new map of the Siloam Tunnel. The National Center for Cooperation Between Science and Archaeology provided financial assistance. Israel Antiquities Authority and Nature and Parks Authority permitted the study.

Competing interests statement The authors declare that they have no competing financial interests.

Correspondence and requests for materials should be addressed to A.F. (msamos@mscc.huji.ac.il).