True polar wander (TPW), or planetary reorientation, is well documented for other planets and moons and for Earth at present day with satellites, but testing its prevalence in Earth’s past is complicated by simultaneous motions due to plate tectonics. Debate has surrounded the existence of Late Cretaceous TPW ca. 84 million years ago (Ma). Classic palaeomagnetic data from the Scaglia Rossa limestone of Italy are the primary argument against the existence of ca. 84 Ma TPW. Here we present a new high-resolution palaeomagnetic record from two overlapping stratigraphic sections in Italy that provides evidence for a ~12° TPW oscillation from 86 to 78 Ma. This observation represents the most recent large-scale TPW documented and challenges the notion that the spin axis has been largely stable over the past 100 million years.
True polar wander (TPW) is the reorientation of a planet or moon in order to align the body’s greatest nonhydrostatic principal axis of inertia \( (I_{\text{max}}) \) with the spin axis1–4. On Earth, TPW is achieved by wholesale rotation of the solid, silicate Earth (mantle and crust) around the liquid outer core. As Earth’s magnetic pole is tied primarily to rotationally induced excitations of the outer core, the magnetic poles remain aligned with the rotation axis through a TPW event. Thus, palaeomagnetic data record TPW as the coherent, simultaneous motion of all coeval rocks about a single equatorial Euler pole defined by Earth’s minimum moment of inertia \( (I_{\text{min}}) \). Palaeomagnetic sampling of a continuous sedimentary succession is an effective single-locality test of TPW as it eliminates potential caveats such as differential remagnetization and tectonic structure5,6.

The possibility of Late Cretaceous TPW is hotly debated7–10. One TPW rotation has been proposed to occur between the emplacement of two seamounts with Ar-Ar ages overlapping at ca. 84 Ma and palaeomagnetic poles discordant by 16° ± 3° (refs. 9,10). It has been asserted, however, that classic palaeomagnetic data from the correlative Gubbio and Moria sections of Scaglia Rossa limestone do not permit ca. 84 Ma TPW7. Irrespective of the quality of the original data, an analysis that calculates only three average inclinations from 90 to 75 Ma7 does not constitute a robust test of a comparatively rapid11 process. But the reliability of those old (however seminal) data12,13 is questionable for directional studies8. In particular, the Gubbio and Moria data pre-date least-squares analysis of palaeomagnetic data14, the use of controlled-atmosphere thermal demagnetization, and the measurement by sensitive superconducting magnetometers.

In this work, we present >1000 palaeomagnetic data from the Scaglia Rossa limestone as a rigorous test of the ca. 84 Ma TPW event. Samples were collected from two parallel stratigraphic sections as a test of reproducibility. Modern demagnetization and analytical palaeomagnetic methods were employed, including state-of-the-art rock magnetic experiments that shine new light on the origin of the stable palaeomagnetic remanences of the Scaglia Rossa limestone. Both stratigraphic sections definitively confirm the existence of ca. 84 Ma TPW. Furthermore, our new high-resolution record suggests not only a single TPW shift at this time, but a “roundtrip” TPW oscillation where the pole excurses and then returns back to its original pole position.

Results

Stratigraphic sections. Samples were collected from stratigraphically correlative sections at Apiro and Furlo in Italy (Supplementary Fig. 1) at typical stratigraphic intervals of 5, 10, 25, 50, or 100 cm (Supplementary Fig. 2). At Apiro, the R1 and R2 members of the Scaglia Rossa are devoid of slumps and are lithologically homogenous apart from radiolarian chert beds in the R1 member. Only the homogenous background lithology of pelagic limestone was sampled for palaeomagnetic analysis. At Furlo, sampling was limited to strata in between slumping events known to anomalously rotate declination due to rotation about a local vertical axis15. Furthermore, stylolitic “pseudo-bedding” that characterizes the bedding style of the Scaglia Rossa at Gubbio and elsewhere in the Umbria-Marche basin16 is absent at Apiro, and less pronounced at Furlo (Supplementary Fig. 2), suggesting the sedimentary rocks of our sections are less tectonically modified than others.

Magnetic mineralogy. We used traditional palaeomagnetic methods for analysis on an automated system17 and employed a detailed thermal demagnetization scheme (conducted in a controlled nitrogen atmosphere) to facilitate separation of magnetic components (Methods). The reliability and quality of Scaglia Rossa palaeomagnetism is well known12,13,15,16. Previous studies on similar sedimentary rocks generally report stable behavior up to ~750 °C, indicative of magnetite being the predominant remanence carrier despite the red color of the Scaglia Rossa imparted by fine-grained authigenic hematite18. First-order reversal curve (FORC) distributions are dominated by the “central ridge” (Fig. 1c), which indicates negligible magnetostatic interaction among magnetic grains and is interpreted to result from a chain structure of bacterialy formed magnetite19. Additional rock magnetic experiments indicating a similar magnetic mineralogy for all lithologies and magnetization directions are presented in Supplementary Figs. 3 and 4. The presence and dominance of magnetofossils in the Scaglia Rossa limestone can account for its exceptional palaeomagnetic stability (Fig. 1a, b), making it an ideal candidate for testing ca. 84 Ma TPW.

Demagnetization. Virtually all Scaglia Rossa samples carry low-stability magnetic overprints coincident with the present local field, consistently removed after thermal demagnetization to 150 °

Fig. 1 Magnetization of the Scaglia Rossa limestone. a, b Orthogonal vector diagrams of typical demagnetization behavior with low-temperature (LT) components and insets with magnified views of high-temperature (HT) components. NRM natural remanent magnetization, LN2 liquid nitrogen immersion. a Normal polarity sample (FUR2-136) from Furlo section. Steps after significant loss in magnetization >575 °C were excluded from least-squares fit. b Reversed polarity sample (C10AD34) from Apiro section. Steps >590 °C with circular standard deviation (CSD) >10° were excluded from least-squares fit. c First-order reversal curve (FORC) distribution exhibiting a “central ridge” indicating the magnetic mineral assemblage of the Scaglia Rossa limestone is dominated by highly stable, single-domain, biogenic magnetite magnetofossils. San Severino locality, near the main Apiro section. See Methods for experiment details.
C, matching remanence expectations for either secondary goethite or a viscous overprint carried by large magnetite grains (Supplementary Fig. 5 and Supplementary Data 2). After removal of the overprint, the characteristic magnetizations were then typically stable up to 500–580 °C indicative of magnetite. All characteristic remanent magnetizations were determined by linear decay to the origin or stable-end point behavior on orthogonal demagnetization diagrams and exhibit striking palaeomagnetic stability for sedimentary rocks (Fig. 1a, b). The isolation of primary Late Cretaceous remanences is collectively supported by the successful removal of present local field overprints up to 150–180 °C (Fig. 1a, b and Supplementary Fig. 5), magnetostratigraphy matching the geologic time scale (Fig. 2 and Supplementary Figs. 6 and 7), and the success of fold tests conducted in the area.

Palaeomagnetic directions. Exploring the possibility of long-term variations in palaeomagnetic direction, we calculate the average inclination and declination of Italy in one-million-year intervals (Fig. 2) and its associated palaeopole path (Fig. 3). Palaeomagnetic data from Italy must be locally restored relative to the larger African plate, which also must be tectonically reconstructed in order to test the TPW hypothesis (Methods). Contrary to the claim that the Scaglia Rossa limestone does not show significant variations in inclination, our new data show a ~12° oscillation (~24° total) between 86 and 79 Ma (~7 million years [Myr]; Fig. 3) that temporarily both rotated and translated Italy to lower latitudes during C33r, with coeval changes to both declination and inclination, respectively (Fig. 2). Although the excursion broadly overlaps with magnetochron C33r, we note that the peak offset occurs during C34n, arguing against the idea that magnetic polarity contaminates the signal. Furthermore, our demagnetization methods are detailed enough to resolve and remove overprints (Fig. 1a, b and Supplementary Fig. 5) and directional transitions observed across magnetic reversals are smooth instead of sudden (Fig. 2), as would be the case if directional shifts were artifacts of unresolved normal polarity overprints.

Inclination shallowing. Inclination shallowing due to sediment compaction is a common problem in sedimentary palaeomagnetism that must be considered to explain the temporary lowering of inclination. Inclination shallowing usually stems from the electrostatic attraction of small magnetite lathes to clay flocs or hematite platelets having a preferred flow-regime or gravity-induced directionality. But with the Scaglia Rossa, we are not relying on nanoscale magnetite laths or on hematite platelets for our magnetization, rather, single-domain biogenic magnetite grains (Fig. 1c). The Scaglia Rossa magnetofossils may well be independent of the clay associated or grain shape anisotropic effects that commonly cause inclination shallowing. Nonetheless, to test for burial compaction, we conducted anisotropy of
magnetic susceptibility (AMS) experiments. Previous AMS data at Apiro and Furlo reveal a minor clustering of $k_{\text{min}}$ axes and girdle of $k_{\text{max}}$ and $k_{\text{int}}$ axes, implying a mildly oblate compaction fabric in the plane of bedding\textsuperscript{21}. Our new data from the same sections confirm a minor oblate flattening in the plane of bedding generally for all samples. However, no correlation between AMS and inclination is found when the data are cross-plotted (Supplementary Fig. 8), suggesting inclination shallowing is unlikely to explain the inclination variation within a section. Finally, the distinct data groupings through time (Fig. 2) differ substantially in declination, not just inclination, so inclination shallowing cannot entirely account for the systematic dispersion of the Scaglia Rossa data.

Discussion
As predicted by the ca. 84 Ma TPW hypothesis\textsuperscript{9}, the largest polar excursion observed in Italy occurs between 84 and 82 Ma (Fig. 3). Our Italy data thus do not refute the ca. 84 Ma TPW hypothesis\textsuperscript{9}. The amplitude of the $\sim12^\circ \pm 3^\circ$ excursion of Italy palaeopoles (Fig. 3) furthermore overlaps within uncertainty the $16^\circ \pm 3^\circ$ dispersion of Pacific Plate palaeopoles\textsuperscript{9,10}. TPW is able to explain the coincident excursions in both inclination and declination observed in Italy (Fig. 2). Due to the palaeogeographic position of Italy relative to the TPW axis near Africa\textsuperscript{22}, Italy should have experienced both latitude change (inclination) as well as rotation (declination) during the TPW excursion, as is observed. The TPW axis ($I_{\text{min}}$) is defined by the triaxial or nearly prolate shape of the nonhydrostatic Earth due to long-wavelength mantle convection\textsuperscript{23,24}, which is thought to be stable over the past 300 Myr during the Pangaea supercontinent cycle\textsuperscript{22}. The east-west longitudinal orientation of the polar motion observed in the Late Cretaceous in Italy is similar to that of earlier Mesozoic TPW\textsuperscript{22} as well as the present-day TPW axis\textsuperscript{4,25}, as expected (Fig. 3). Also, as observed elsewhere\textsuperscript{5} and in high-resolution detail here (Figs. 2 and 3), TPW is typically modeled as a back-and-forth “roundtrip” oscillation where the pole shifts away, but then snaps back to the original pole position\textsuperscript{33}. Whether the “figure 8” path exhibited by both Mesozoic TPW oscillations (Fig. 3) is significant remains to be tested with modeling.

A cumulative “roundtrip” amplitude of $\sim24^\circ$ for the TPW oscillation observed in Italy over $\sim8$ Myr (86–78 Ma) implies a TPW rate of $\sim3.0^\circ$ Myr$^{-1}$. The present viscosity of the lower mantle sets a $\sim2.4^\circ$ Myr$^{-1}$ “speed limit” for TPW as the solid Earth must conform to the migrating hydrostatic bulge for reorientation to proceed\textsuperscript{11}. Our data are thus broadly compatible with this theoretical speed limit, but may suggest that the
Cretaceous mantle was different than today. As detectable secular mantle cooling has occurred since Late Cretaceous time[26], the TPW speed limit is determined11 renders the implication for a hotter mantle at this time as constrained by TPW rate ambiguous at best. Instead, older, and potentially faster TPW events24, should be used to constrain such a problem. The slightly above average speed of ca. 84 Ma TPW could rather be explained by a larger mantle convective forcing than normal.

Our observed TPW oscillation of ~12° amplitude at this age can be used to parameterize models to better assess Earth’s nonhydrostatic figure and the relative effects of sinking slabs and rising mantle plumes on Earth’s rotational stability. Using the well-constrained history of recently subducted slabs, the modeled effect on Earth’s nonhydrostatic geoid that controls the location of the spin axis (and thus TPW) predicts a large and rapid TPW event between 80 and 90 Ma27, precisely when our observations indicate that TPW in fact occurred (Figs. 2 and 3). This general agreement thus begins to reconcile the apparent discrepancy between TPW observations and the model predictions at this age27. Nonetheless, despite the striking consistency in suggesting palaeomagnetic study would suggest that one cannot rule out the possibility of rapid TPW shifts of small amplitude (<20°) in the most recent past.

Methods
Geologic setting and sampling. The Umbria–Marche pelagic succession of central Italy is the classic locality for the Cretaceous-Palaeogene (K/Pg) extinction[30] and several of the oceanic anoxic events, where they occur within rhythmically bedded limestones, marls, and cherts[22,23]. This study focuses on a ~15-Myr interval between these dramatic Late Cretaceous events. Much previous work has been done to date the Umbria–Marche succession. The Gubbio section (Supplementary Fig. 1) spans 10 Myr of Late Cretaceous time and serves as a standard for magnetostratigraphic sampling15. Although relatively stratigraphically condensed, a subsequence of samples was collected for magnetostratigraphy at Moria (Supplementary Fig. 1) confirms the magnetic reversal pattern observed at Gubbio and on the sea floor, as well as serving as a positive palaeomagnetic test validating the Scaglia Rossa palaeopoles11.

Both the classic Gubbio and Moria sections, unfortunately, are tectonically disturbed with faults and slumps, often causing crustal block rotations vital to avoid[15,16,40], at the base of the R2 Member of the Scaglia Rossa Formation, our target interval. We sampled two correlative stratigraphic sections in distinct thrust blocks (Supplementary Figs. 1, 2). The Apiro section (Supplementary Fig. 2) spans the entire ~10-Myr-long magnetostratigraphic sample is exposed on the western flank of a large anticline and was previously sampled for magnetostratigraphy12. By correlation, the Furlo record is within a ~2-Myr gap in record. The Furlo record during Santonian–Cenomanian time throughout the basin. U/Pb constraints from across the Umbria–Marche Apennines allows correlation from the basin (e.g., Gubbio) to the southern platform44.

The Scaglia Rossa is composed of three principal lithologies (light pink pelagic limestone, nodular or tabular chert of assorted colors, and dark pink marl), sometimes deposited in cycles that are striking at the outcrop scale. Only the Scaglia Rossa has never been studied within a stratigraphic context. Red chert layers near the base of the exposure can be lithologically identifiable as the top of the R2 Member of the Scaglia Rossa. Apiro contains all of the Scaglia Rossa Formation, with exception of a ~30-m-thick covered interval near the base of C33r. Apiro is stratigraphically expanded and devoid of stylolitic "pseudo-bedding," which
characterizes the bedding style of the Scaglia Rossa elsewhere in the Umbria–Marche basin9. Correlation to the relatively constant thin beds of the Furlo reveals much thicker beds and faster sediment accumulation. Turbidites and evidence for reworked sediments are not found at Apiro as in Furlo. Data from Furlo can be imported into the Apiro record in an attempt to help unblock larger multi-domain magnetite grains by Furlo can be imported into the Apiro record in an attempt to help unblock larger multi-domain magnetite grains by

Palaeomagnetism. Oriented palaeomagnetic cores 2.54 cm in diameter were drilled on site using a portable, gasoline-powered, diamond-tipped coring drill with both air- and water-cooled functionality. All 1090 samples were hand-drilled cores except for 24 block samples. Sun-compass observations were made whenever possible to check the magnetic compass, and to independently measure the local magnetic declination which, at ~ 1°E, is indistinguishable from the International Geomagnetic Reference Field model for the sites. Remanent magnetization measurements were made with a 2G Enterprises DC-SQuID magnetometer with background noise sensitivity of 5 × 10⁻¹² Am² per axis at both the California Institute of Technology and Yale University. The magnetometers are equipped with computer-controlled, automated vacuum pick-and-put-sample-changing arrays. Samples and instruments are housed in a magnetically shielded room with residual fields <100 nT throughout the demagnetization procedure and <5 nT in the sense region. After measurement of natural remanent magnetization (NRM), all samples were demagnetized chemically in a low-stress liquid hydrogen bath in an attempt to help unblock larger multi-domain magnetite grains by “zero-field” cycling through the Verwey transition near 77 °K (ref. 48), and typically this step was repeated a second time. Next, all samples were thermally demagnetized in steps of 4–25 °C, starting at 50 °C and going up to 590 °C (or until thoroughly demagnetized or unstable, usually 20–30 °C thermal steps per sample) in a magnetically shielded furnace (±2 °C relative error) in a flowing nitrogen atmosphere. After each demagnetization step, automated three-axis measurements were made in both sample-up and sample-down orientations, and samples with circular standard deviation >10° were rerun manually.

Magnetic component measurements were computed for each sample using principal component analysis6 as implemented in PaleOMag OS X® (Fig. 1a, b). See main text for discussion of results. Palaeomagnetic poles from various previous works are compiled and compared using the software programs GPlates (www.gplates.org) (Fig. 3) and Paleomac60 (Supplementary Fig. 9). To first order, the records between Apiro and Furlo are consistent with each other and demonstrated Apiro. Nonetheless, due to appreciable uncertainties in the different local tectonic restorations and degrees of inclination shallowing in the two sections (see below), we do not combine the data from the two sections when calculating palaeopoles.

Instead, we use exclusively poles from Apiro with the exception of the 85 and 84 Ma poles from Furlo that fill the temporal gap at Apiro (Supplementary Fig. 2 and Supplementary Data 1).

Rock magnetism. Non-destructive rock magnetic experiments were performed on seven samples of the Scaglia Rossa limestone (six samples from Apiro and one sample from Furlo) using a 2G Enterprises SQuID magnetometer following the RAPID protocols, and analyzed using the RAPID Matlab scripts57 (https://sourceforge.net/projects/paleomag/). Our protocol includes measurements of AF demagnetization to 10 mT, the acquisition and demagnetization, and irreversible cooling curve with strong field increase in susceptibility and a slight shift in Curie temperature. No Verwey transition is seen in the sample, but even a few weight percent titanium can cause the transition to be irreversible and shifted to lower temperatures beyond the range of the KappaBridge, although the substitution of titanium would be surprising in biogenic magnetite. The FORC distributions are mainly dominated by “Pomeroy” (Fig. 1c), which indicates that magnetofossils are the main constituent of the magnetic mineral assemblage. Biogenic magnetite, then, may be the answer to age-old mystery of what accounts for the remarkable stability of Scaglia Rossa remanent magnetization.

Biotrastigraphy. Aliquots of palaeomagnetic samples from both Apiro and Furlo sections were prepared for biotrastigraphic foraminifera identification. First occurrences and last occurrences were identified following a new age-calibrated biotrastigraphic zonation55. Planktonic foraminifera were studied in washed residue. Preparation included gentle crushing, cold acetolysis with acetic acid (80%) following the method of Linse66 sieving through a 63 μm mesh, 1–2 h cleaning in an ultrasonic cleaner, and drying at 60 °C. The cold acetolysis method enables extraction of generally well-identifiable foraminifera even from indurated limestone. This offers the possibility of accurate taxonomic determination and detailed analysis of foraminiferal assemblages.

Age models. Age modeling of the sampled sections using dated magnetic reversal boundaries provides both time scales for each section and new biotrastigraphic ages for global chronostratigraphic correlation (Supplementary Fig. 6). The Apiro and Furlo sections both span the C34n-C33r-C33n interval, where C34n-C33r is preserved at Furlo, C33r-C33n is present at both sections, and the top of C33n is identified at Apiro. At Apiro, we identify the C33r-C33n reversal within less than a half of a meter (Supplementary Fig. 7), but a substantial covered interval (from 50 to 83 mT) masks the C34n-C33r reversal (Supplementary Figs. 2 and 7). At Furlo, the C34n-C33r reversal is documented within less than a meter (Supplementary Fig. 7). Following convention, ages for stratigraphic heights occurring between two dated levels are determined by linear interpolation, whereas ages of strata above and below the dated levels are determined by linear extrapolation. The assumption of constant sediment accumulation rates is applied for each bracketed time segment. Updated ages are used for the top and bottom of C33r, requiring recalculation of foraminiferal zonal boundaries within chron 33. A refined age of 80.32 Ma for the C33r-C33n reversal boundary from U/Pb ages on zircon in benthonites in the Pliensbachian in the Furlo section, the end of the normal superchron, is radiometrically unconstrained62, but cyclostratigraphy provides an astronomical calibration63. Ages of biotrastigraphic boundaries are updated in Petrizzo et al.55, ages of those zonal boundaries that are calibrated by our work are provided in Supplementary Fig. 6. Clayton and Brown68 showed that the standard error shown in Supplementary Fig. 6. A rather uniform sediment accumulation rate of ~10 m Myr⁻¹ is thought to characterize much of the pelagic Umbria–Marche basin59. Dating of our sections generally supports this classic interpretation. Compared with Gubbio, or any other section for that matter, Apiro is stratigraphically expanded. Increased sediment accumulation rates may indicate an eastern thrust that is exposed (Supplementary Fig. 1) represented an intrabasinal depocenter that sourced turbidite events recorded elsewhere (e.g., Furlo64).
Local tectonic restoration of northern Umbria. The Umbrian path of palaeo-poles has traditionally been regarded to have an “African” character; once relative rotation during Neogene time is restored, the two APW paths are nearly identical. Northern Umbria is thought to have rotated counterclockwise relative to southern Umbria (and stable Africa) since Mesozoic time. Umbrian tectonic deformation is attributable to orocinal bending and/or local or regional tectonic rotation about a sub-vertical axis in the Apennines, which proposed a 25° clockwise restoration of Northern Umbria into an African reference frame. Independently, Channell et al. proposed a slightly smaller restoration of 22° clockwise, and subsequently rounded that estimate to 20° (ref. 65). Most recently, van Hinsbergen et al. developed a kinematic model for Mediterranean tectonic evolution using Euler rotations guided by palaeomagnetic and other datasets. For 80 Ma, northern Umbria (their plate #3980) restores to Africa with these Euler parameters: 64.75°N, 9.89°E, 4.01°CW. Within the northern Umbrian plate, local rotations are additionally possible. By comparing our declination means to the predicted values from van Hinsbergen et al. and the global APW path of Torsvik et al., we find minimal offset within our sections. Relative rotation during Neogene time is restored, the two APW paths are nearly identical. Linear drift and periodic variations observed in Rock magnetic data were analyzed using the RAPID Matlab scripts available at https://sourceforge.net/projects/paleomag/.

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Data availability
The palaeomagnetic data from this study are available in the online content of this paper and from the Open Science Framework (https://osid.io/8qdhpyd/; view only: 2c-5a8f4569d8428ab76788b8d1a27d4d). Magnetometer measurements are available from the corresponding author upon reasonable request.

Code availability
Rock magnetic data were analyzed using the RAPID Matlab scripts available at https://sourceforge.net/projects/paleomag/.

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Author contributions
R.N.M., C.J.T., D.A.E., and J.L.K. designed the study. R.N.M., C.J.T., S.P.S., R.C., and J.L.K. conducted the field work. R.C. conducted the biostatigraphy. S.P.S. conducted the rock magnetic experiments. T.Y. conducted the FORC experiment. R.N.M., C.J.T., D.A.E., and S.P.S. conducted the paleomagnetic and paleogeographic analysis. R.N.M. wrote the manuscript with input from all authors.

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