Interactions between electrons and the topology of their energy bands can create unusual quantum phases of matter. Most topological electronic phases appear in systems with weak electron–electron interactions. The instances in which topological phases emerge only as a result of strong interactions are rare and mostly limited to those realized in intense magnetic fields. The discovery of flat electronic bands with topological character in magic-angle twisted bilayer graphene (MATBG) has created a unique opportunity to search for strongly correlated topological phases. Here we introduce a local spectroscopic technique using a scanning tunnelling microscope to detect a sequence of topological insulators in MATBG with Chern numbers $C = \pm 1$, $\pm 2$ and $\pm 3$, which form near filling factors of $\pm 3$, $\pm 2$ and $\pm 1$ electrons per moiré unit cell, respectively, and are stabilized by modest magnetic fields. One of the phases detected here ($C = +1$) was previously observed when the sublattice symmetry of MATBG was intentionally broken by a hexagonal boron nitride substrate, with interactions having a secondary role. We demonstrate that strong electron–electron interactions alone can produce not only the previously observed phase, but also other unexpected Chern insulating phases in MATBG. The full sequence of phases that we observe can be understood by postulating that strong correlations favour breaking time-reversal symmetry to form Chern insulators that are stabilized by weak magnetic fields. Our findings illustrate that many-body correlations can create topological phases in moiré systems beyond those anticipated from weakly interacting models.

The role of topology in the electronic properties of moiré flat-band systems has been revealed experimentally by the discovery of a quantized anomalous Hall conductance $\sigma_{xy} = \frac{C \hbar}{e^2}$, with various integer Chern numbers $C$ in different graphene-based heterostructures ($e$, electron charge; $\hbar$, Planck constant). Thus far, these topological phases have been mostly reported for device geometries that purposely break a spatial symmetry of the graphene system. For MATBG, alignment with its hexagonal boron nitride (hBN) substrate breaks $C_3$ symmetry, gapping the Dirac points that connect the conduction and valence flat bands of this system to form degenerate flat single-particle valley Chern bands. Electron–electron interactions can favour lifting the degeneracy of these bands, resulting in spin- and/or valley-polarized insulators with Chern numbers consistent with those observed in experiments. This weakly interacting picture can not only explain reports of a $C = +1$ insulating phase near filling $\nu = +3$ ($\nu$ labels the number of filled moiré bands away from charge neutrality) observed in samples with hBN alignment, but even Chern states with $C = -3$ and $C = -2$ at $\nu = -2$ reported in samples in which hBN alignment was not suspected. By contrast, the presence of strong correlations in MATBG opens up the possibility for interactions to create topological states unanticipated by weakly interacting theories, as in ABC (rhombohedral) trilayer graphene/hBN.

Here we introduce an experimental approach for detecting topological insulating phases and their associated Chern numbers by using density-tuned scanning tunnelling spectroscopy (DT-STS) in the presence of a magnetic field. Our approach enables us to identify the many-body origin of a gapped phase using local spectroscopy while simultaneously analysing its magnetic-field response to quantify its characteristic topological invariant. Our results show that strong correlations, as opposed to single-particle symmetry-breaking effects, can intrinsically produce topological phases in MATBG. Our sequence of strongly correlated Chern insulator (SCCI) phases remarkably includes not only those previously induced by hBN alignment, but also new $C = \pm 3$ phases near $\nu = \pm 1$. This sequence of SCCI states is incompatible with the weakly interacting theories proposed thus far. However, it can be understood by postulating that interactions induce a Haldane mass term, which breaks time-reversal (T) symmetry and modifies the single-particle picture of MATBG by gapping its Dirac points. This mechanism produces the Chern bands necessary to explain the observed sequence of SCCI states and can be further corroborated by our spectroscopic measurements. Our results demonstrate that strong correlations in moiré flat-band systems can produce correlated topological phases of matter.
**Topological gapped phases in DT-STS**

Figure 1a shows a schematic of our experiment, in which we combine scanning tunnelling microscope (STM) imaging of MATBG together with DT-STS measurements of the differential conductance $\frac{dI}{dV}(V_s, V_g)$ between the tip and sample as a function of sample bias $V_s$ and back-gate voltage $V_g$ (Fig. 1b–e; see Methods). DT-STS characterizes the local density of states (LDOS) as a function of energy and carrier concentration, which provides a powerful approach for studying density-dependent phases in two-dimensional (2D) materials. The experiments were carried out in a homebuilt millikelvin STM and in the presence of a perpendicular magnetic field $B$. Topographic images of the moiré superlattice confirm that our samples are near the magic angle (Fig. 1a) and are not aligned with the hBN flake underneath (see Supplementary Information section A for high-resolution images). Figure 1b shows representative spectra measured at the centre of an AA-stacked region of the moiré superlattice (bright spots in Fig. 1a), which appear as two sharp peaks in the LDOS when the fourfold-degenerate conduction and valence flat bands of MATBG are either full (red; $v = +4$) or empty (blue; $v = -4$), respectively. At partial fillings of the flat bands ($-4 < v < +4$), previous DT-STS studies have shown that the sharp peaks of the flat bands in the LDOS, which identify Van Hove singularities, develop substantial broadening and are energetically split into a cascade of sub-band features, both of which are caused by strong electron–electron interactions. These studies demonstrate that the strength of interactions exceeds the non-interacting bandwidth in MATBG—an important property that probably drives the formation of the topological phases uncovered in this study.

At millikelvin temperatures, DT-STS measurements of MATBG reveal features similar to those found at higher temperatures, but here we focus on gaps detected at the Fermi level ($E_F$). Figure 1c–e shows a rich array of gaps that sequentially open and close at $E_F$ and develop with increasing magnetic field at partial flat-band fillings. The most prominent gaps are accompanied by sharp changes in the energies of spectroscopic features observed away from $E_F$, signalling sudden changes in the chemical potential at those fillings. In this study, we focus only on gaps that occur at densities that systematically shift with the magnetic-field strength. Specifically, we observe nine gaps (for example, $-15 < V_s < 10$ in Fig. 1d; purple triangles) about the charge-neutrality point (CNP; $V_s = 1.5$ V) and six gaps away from the CNP (for example, $V_s = -3.23$ V, $-23.6$ V, $-15.6$ V, $18.1$ V, $26.2$ V and $34.4$ V in Fig. 1d; red and blue triangles), all of which shift along the $V_s$ axis as we vary the field. Gaps that do not shift in density systematically as we vary the magnetic field (identified in Supplementary Information section B) will be discussed elsewhere.

First, we consider the nine gaps near the CNP (Fig. 2a). Each gap is centred at a gate voltage corresponding to a carrier density of $n_{\text{LL}}/B/\Phi_0$, where $\Phi_0 = \hbar/e$ is the magnetic flux quantum and $n_{\text{LL}}$ is an integer between $-4$ and 4, indicating that the gaps separate eight Landau levels (LLs). These eight LLs (labelled 2LL, zeroth Landau level, in Fig. 2a) appear as peaks in the $dI/dV$ spectra (Fig. 2b). Because we observe two peaks when the LLs are fully filled ($V_s = 9.9$ V) or emptied ($V_s = -6.6$ V), we conclude that the eight LLs are grouped into two sets of four. Each fourfold-degenerate LL peak splits as it is partially filled, producing the gaps at $n_{\text{LL}}/B/\Phi_0$. 

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**Figure 1** Magnetic-field-dependent spectroscopic gaps in MATBG at 200 mK. a. Schematic diagram of the experimental setup. Inset, STM topographic image of the magic angle region ($\phi = -95$ mV, $I = 200$ pA, scale bar, 5 nm). b. $dI/dV(V_s, V_g)$ spectra measured at the centre of an AA site at zero magnetic field. The red, blue and purple spectra were obtained with the chemical potential tuned to lie above, between and below the two flat bands of MATBG, respectively. Initial tunnelling parameters: $V_s = -100$ mV, $I = 500$ pA. 4.121 kHz sinusoidal modulation with root-mean-square voltage $V_{\text{rms}} = 1$ mV. c. $dI/dV(V_s, V_g)$ measured at the centre of an AA site at $B = 1$ T (c), $B = 6$ T (d) and $B = 9$ T (e). Initial tunnelling parameters: $V_s = -80$ mV (e), $-70$ mV (d); $I = 1.5$ nA (c), $1$ nA (d); $4.121$ kHz sinusoidal modulation of $V_{\text{rms}} = 0.2$ mV.
These eight LLs form the ZLLs\(^2\) that originate from the eight (spin, valley, and moiré Brillouin zone corner) Dirac cones expected in the band structure of MATBG (see Supplementary Information section C for spectroscopy of higher-index LLs, which are energetically well separated from the ZLLs). This eightfold degeneracy is separated into two fourfold-degenerate manifolds by single-particle effects, which could include strain\(^2\), interlayer bias\(^3\) and orbital Zeeman effects\(^4\), consistent with magnetotransport measurements that show a fourfold-degenerate Landau fan near the CNP\(^5\) (see Supplementary Information section D for the magnetic-field dependence of ZLL spacing). Finally, the remaining fourfold degeneracy is spontaneously broken by exchange interactions to form quantum Hall ferromagnetic (QHF) states as the ZLLs are gated to \(E_F\) (Fig. 2a, b).\(^5,\)\(^6\)\(^7\)\(^8\) Similar spectroscopic signatures of QHF states have been observed in other material systems\(^9\)\(^10\)\(^11\)\(^12\)\(^13\)\(^14\).

Fig. 2 | Spectroscopic gap morphology of strongly correlated Chern insulating gaps and ZLLs. a. \(\frac{d}{dV}(V_g, V_s)\) measured at the centre of an AA site at \(B_\perp = 6\) T, showing the ZLL crossing \(E_\perp\) (same data as in Fig. 1d). b. \(\frac{d}{dV}\) line cuts of data in a for \(V_g = 9.9\) V, 9.0 V, 7.2 V, 5.4 V, 2.0 V, 0.2 V, −2.3 V, −4.1 V, −6.6 V (vertical offset of 20–40 nS). Highlighted numbers correspond to the degeneracy of \(d_{sg}\) line cuts of data in c from \(V_g = 20.6\) V to 13.6 V (vertical offset of 32 nS). Triangles mark the edges of the spectroscopic gap. c. \(\frac{d}{dV}(V_g, V_s)\) measured at the centre of an AA site at \(B_\perp = 6\) T in a saturated colour scale highlighting a field-stabilized spectroscopic gap at \(E_\perp\) between \(v = 2\) and \(v = 1\). d. \(\frac{d}{dV}\) line cuts of data in e from \(V_g = 20.6\) V to 13.6 V (vertical offset of 32 nS). e. \(\frac{d}{dV}(V_g, V_s)\) measured at the centre of an AA site at \(B_\perp = 6\) T in a saturated colour scale highlighting a field-stabilized gap between \(v = −1\) and \(v = −2\). f. \(\frac{d}{dV}\) line cuts of data in f from \(V_g = −13\) V to −18.6 V (vertical offset of 32 nS). VHS, Van Hove singularity.

Quantized magnetic-field response
A topological gap and its associated Chern number can be identified in DT-STS measurements by studying its magnetic-field dependence. The charge density of a Chern insulating phase changes with magnetic field at a rate equal to its quantized Hall conductance\(^3\)\(^5\)\(^6\)\(^7\), \(\frac{dn}{dB} = \frac{\sigma_{xy}}{e^2/\hbar} = C/\Phi_0\). Therefore, tuning both the density and the magnetic field in DT-STS measurements allows us to identify topological gaps and their associated Chern numbers using this local spectroscopic technique. Figure 3a shows that the gaps display this expected linear dependence in a magnetic field, all measured within Device A (see Supplementary Information sections F–G for devices B and C). In Fig. 3b, we aggregate the results of such measurements from three devices, all of which show similar behaviour. This information has been reparameterized as a function of flat-band filling \(\nu\) and magnetic-flux quanta per superlattice unit cell \(\Phi_0\) (see Supplementary Information sections H, I). The error bars represent the entire density range over which each gap is observed, with markers placed at the centre of each range (see Supplementary Information section J for the method). Each shaded region (Fig. 3a) and line (Fig. 3b) identifies a possible quantized Chern number for each gap. This figure illustrates the power of applying this straightforward analysis to high-quality DT-STS data, which we use to uncover the rich array of correlation-driven topological phases in MATBG.

As expected, the QHF and higher-index LL gaps observed in spectroscopy all emanate from \(\nu = 0\) as a function of magnetic field, with Chern
measurements on one device

\[ C = -8,9 \]

This created isolated flat sub-bands \( \nu = +3 \) with sub-bands. Previous studies discovered a Chern insulating phase near \( F \) bands with Chern number \( \pm 1 \). This lowers the Landau free energy \( T \)-symmetry-breaking mass term, producing degenerate, flat Chern sub-band consistent with the experimentally observed \( C = +1 \) state, equivalent to quantum Hall ferromagnetism. At first glance, our observation of a \( C = +1 \) state near \( \nu = +3 \) in the absence of hBN alignment may suggest that strong interactions spontaneously generate a \( C_2 \)-breaking mass, inducing a band topology similar to that of the hBN-aligned samples. However, this mechanism is expected to produce \( C = \pm 1 \) states near \( \nu = \pm 1 \) because time-reversed partner sub-bands in the K and K′ valleys would have opposite Chern numbers (Fig. 4b), inconsistent with the \( C = \pm 3 \) states that we have observed near these fillings (Supplementary Information section K).

Alternatively, we postulate that the Dirac points are gapped by interactions in the form of a T-symmetry-breaking mean-field mass term. Because the Chern number decreases by 1 between each insulating gap as \( \nu \) increases, our measurements indicate repeated occupancy of Chern \( \pm 1 \) bands. A Haldane mass term provides exactly this, by ensuring that \( C_2 \)-related partner sub-bands in the K and K′ valleys have the same Chern numbers (Fig. 4b). The sign of the Haldane mass determines the sign of each sub-band.

**Theoretical model**

To understand the mechanism driving the formation of these Chern insulating phases, we start with the single-particle electronic structure of the MATBG flat bands, schematically shown in Fig. 4a. In the non-interacting limit, MATBG has a composite \( C_7T \) symmetry that protects the Dirac points between the valence and conduction flat bands. Interactions can gap the Dirac points through a \( C_2 \)- and/or T-symmetry-breaking mass term, producing degenerate, flat Chern bands with Chern number \( \pm 1 \). This lowers the Landau free energy \( F \) by decreasing (increasing) the energy of occupied (unoccupied) sub-bands. Previous studies discovered a Chern insulating phase near \( \nu = +3 \) with \( C = +1 \) in devices in which a \( C_2 \)-breaking mass was imposed externally by hBN alignment. This created isolated flat sub-bands in the K and K′ valleys with opposite Chern numbers (Fig. 4b). Subsequently, interactions can spontaneously break time-reversal symmetry and valley-polarize this system, creating a single unoccupied Chern sub-band consistent with the experimentally observed \( C = +1 \) state.

numbers \( C = 0, \pm 1, \pm 2, \pm 3, \pm 4, \pm 8, \pm 12 \) (Fig. 3b). In addition, however, we observe a hierarchy of correlated Chern insulating phases with Chern numbers \( C = \pm 1, \pm 2, \pm 3 \) emanating as a function of magnetic field from integer flat-band fillings \( \nu = \pm 3, \pm 2, \pm 1 \), respectively. All Chern insulating phases appear to be stabilized by a magnetic field \( B \), with the \( C = +2 \) insulator developing at fields as low as 1 T (about 0.04\( \Phi_0 \)), the \( C = \pm 1 \) insulator at around 3 T (about 0.1\( \Phi_0 \)), and the \( C = \pm 3 \) and \( C = -2 \) insulators around 6 T (about 0.2\( \Phi_0 \)).

![Fig. 3](image-url) (Quantized magnetic-field response of strongly correlated Chern insulating phases.) a. Scatter plot of the gate voltage and magnetic field for extracted spectroscopic gaps from \( \pm (V_g, V_p) \) measurements on one device (Device A). Purple shaded bars depict the expected quantized field response of the LL gaps with LL filling factors \( V_g \in [-4, 4] \). Red and blue shaded bars depict the expected quantized field response of Chern insulating gaps with \( C = \pm 1, \pm 2, \pm 3 \) emanating as a function of magnetic field from integer flat-band fillings \( \nu = \pm 3, \pm 2, \pm 1 \), respectively. The width of the shaded bars is derived from the error in determining band full (\( \nu = \pm 3, \pm 2, \pm 1 \)), respectively. All Chern insulating phases appear to be stabilized by a magnetic field \( B \), with the \( C = +2 \) insulator developing at fields as low as 1 T (about 0.04\( \Phi_0 \)), the \( C = \pm 1 \) insulator at around 3 T (about 0.1\( \Phi_0 \)), and the \( C = \pm 3 \) and \( C = -2 \) insulators around 6 T (about 0.2\( \Phi_0 \)).

b. Magnetic-field response of Chern and LL gaps for three devices (devices A, B, and C), reparameterized by the number of magnetic flux quanta per superlattice unit cell \( \Phi/\Phi_0 \) and flat-band filling \( \nu \). The three solid lines emanating from each non-zero integer \( \nu \) depict the expected quantized field response of insulators with Chern numbers \( C = \pm 1, \pm 2, \pm 3 \). Solid red and blue lines indicate the only Chern numbers consistent with our data. The error bars represent the entire density range over which each gap is observed, with markers placed at the centre of each range.
competing topologically trivial states are favoured near zero field\(^4\). A second, more interesting possibility is that the system may form domains with different Chern numbers, masquerading as a topologically trivial insulator near zero field, while weak magnetic fields may unify the sample into a single domain.

**Many-body behaviour of the ZLLs**

In addition to producing the correct sequence of SCCI states, our interpretation can be further corroborated by examining the spectroscopic behaviour of the ZLLs. When a Dirac cone is gapped to form a pair of Chern bands, its corresponding ZLL is replaced by an unpaired LL that emerges from the edge of the Chern +1 band (also called a ZLL for simplicity)\(^5\). A C\(_2\) breaking mass in MATBG would create conduction (valence) sub-bands with opposite Chern numbers in the K and K’ valleys, thus creating a symmetric spectrum of ZLLs emerging from the conduction bands of one valley and the valence bands of the other. By contrast, the Haldane mass yields conduction (valence) sub-bands with the same Chern number in the two valleys, thus creating an asymmetric spectrum of ZLLs that all emerge from either the valence or the conduction bands, depending on the sign of the Haldane mass (Fig. 4c). In Fig. 2a, we find that the ZLLs are closer in energy to the valence or conduction flat-band Van Hove singularity when MATBG is n-doped (for example, \(V_g = 11\) V) or p-doped (for example, \(V_g = -7\) V), respectively. This behaviour is consistent with the proposed sign-switching Haldane mass. At \(V_g = 1.5\) V, the ZLLs appear symmetric (with the single-particle splitting discussed previously) because the Haldane mass is zero at the CNP. A more detailed model, which includes field-induced and AA-site-associated localization effects, can produce the fine features of the DT-STS data (Supplementary Information section M). Finally, corroborating evidence for the Chern states uncovered here can be found in early magneto-capacitance measurements of MATBG, which showed signatures of compressibility changes at some of the fillings examined here\(^6\). However, in absence of spectroscopic information, the previous study could not identify the many-body origin of these features.

Looking ahead, we anticipate that the strong interactions responsible for the SCCI states in MATBG without hBN alignment may also be capable of stabilizing fractional Chern insulators, similar to those recently proposed for aligned samples\(^38\–40\). Furthermore, the capability of DT-STS to clearly distinguish trivial and topological many-body gaps by measuring their Chern numbers, as demonstrated here, can be extended to study different topological phases in a wide range of 2D material and moiré platforms\(^20\–42\). A key advantage of this technique is the ability to circumvent the need for micrometre-scale device homogeneity or complex device geometries owing to its versatility as a local probe method.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-3028-8.

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Methods

STM measurements
Measurements were performed on a homebuilt, ultrahigh-vacuum (UHV), dilution-fridge STM with base electron temperature $T_{\text{electron}} \approx 200$ mK. All tungsten tips were prepared on a Cu(111) single crystal and subsequently calibrated against the Cu(111) Shockley surface state. MATBG devices were electrostatically gated via a degenerately p-doped Si back-gate. The sample was biased by a voltage $V$, relative to a virtually grounded tip. DT-STS measurements were performed using a standard lock-in technique, where the a.c. response to a small sinusoidal voltage $V_{\text{rms}}$ applied to the sample was measured while tuning the sample bias and gate voltage.

Sample preparation
Devices were prepared using a method nearly identical to the one described in ref. 21. Briefly, MATBG devices were assembled using the ‘tear-and-stack’ method, where a polyvinyl alcohol/scotch-tape/polydimethylsiloxane (PDMS)/glass-slide transfer handle was first used to pick up hBN from an SiO$_2$/Si wafer. Next, hBN was used to contact half of a monolayer flake of graphene (exfoliated on a piranha-cleaned SiO$_2$/Si wafer using a hot cleave method). Graphene was torn at the edge of the hBN flake and the second half of the graphene was picked up using the handle-adhered stack after a $1.2^\circ$–$1.3^\circ$ relative rotation of the transfer station stage (which accounts for an observed rotation relaxation). Finally, the stack was transferred onto a PDMS/glass-slide transfer handle, which inverted the stack’s vertical orientation for STM measurements, and transferred onto a prepatterned SiO$_2$/Si wafer with Au/Ti electrodes. The sample was then cleaned with water and/or various solvents before annealing in UHV for 12 h at 170 °C, followed by a 2-h anneal at 400 °C.

Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
K.P.N., M.O., D.W. and A.Y. designed the experiment. K.P.N., D.W. and M.O. fabricated samples, carried out STM/STS measurements and performed the data analysis. B.L. and B.A.B. performed the theoretical calculations. K.W. and T.T. synthesized the hBN crystals. All authors discussed the results and contributed to the writing of the manuscript.

Competing interests
The authors declare no competing interests.

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