Most molecular clouds are filamentary or elongated\(^1\)–\(^3\). For those forming low-mass stars (<8 solar masses), the competition between self-gravity and turbulent pressure along the dynamically dominant intercloud magnetic field (10 to 100 parsecs) shapes the clouds to be elongated either perpendicularly\(^4\) or parallel\(^5\) to the fields. A recent study\(^6\) also suggested that on the scales of 0.1 to 0.01 parsecs, such fields are dynamically important within cloud cores forming massive stars (>8 solar masses). But whether the core field morphologies are inherited from the intercloud medium or governed by cloud turbulence is unknown, as is the effect of magnetic fields on cloud fragmentation at scales of 10 to 0.1 parsecs\(^7\)–\(^9\). Here we report magnetic-field maps inferred from polarimetric observations of NGC 6334, a region forming massive stars, on the 100 to 0.01 parsec scale. NGC 6334 hosts young star-forming sites\(^10\)–\(^12\) where fields are not severely affected by stellar feedback, and their directions do not change much over the entire scale range. This means that the fields are dynamically important. The ordered fields lead to a self-similar gas fragmentation: at all scales, there exist elongated gas structures nearly perpendicular to the fields. Many gas elongations have density peaks near the ends, which symmetrically pinch the fields. The field strength is proportional to the 0.4th power of the density, which is an indication of anisotropic gas contractions along the field.

We conclude that magnetic fields have a crucial role in the fragmentation of NGC 6334.

At a distance of about 1.7 kiloparsecs from Earth, NGC 6334 is one of the nearest regions forming massive stars. Other sites forming massive stars are usually too far away to use starlight polarization (owing to extinction from dust grains aligned by magnetic fields, B-fields) effectively to probe the B-field orientations (the starlight polarization is parallel to the orientation of the B-field) in the surrounding intercloud medium. B-field directions can be derived from the polarization of local background stars by subtracting the polarization of local foreground stars\(^13\). To form a typical giant molecular cloud, gas needs to be accumulated from an intercloud medium of a few hundred parsecs\(^14\). Using the optical polarimetry archive from ref. 15, the ambient B-field direction of NGC 6334 is seen to be perpendicular to its elongation (Fig. 1).

If the B-field is dynamically important compared to turbulence during the gas accumulation process, the ambient B-field direction should be preserved inside the cloud\(^8\). Regions forming massive stars have stronger thermal dust emissions than do those forming low-mass stars, which allows probing of the B-fields within dense clouds using polarization of submillimetre thermal dust emissions (the two directions are perpendicular). This has been performed extensively\(^13\)–\(^16\),\(^17\), but never with...
such a wide range in scales as presented here. We use data acquired by the polarimeters SPARO (Submillimeter Polarimeter for Antarctic Remote Observing) (10-pc scale)\textsuperscript{13}, Hertz (1-pc scale)\textsuperscript{18}, and the Submillimetre Array (SMA, 0.1-pc scale)\textsuperscript{6}. Following ref. 19, interpolation of independent 3\(\sigma\) polarimetry detections is used to plot the \(B\)-field lines (Figs 1 and 2).

It is obvious that the field lines at the 10-pc scale are ‘pinched’ near the ends of the dust filament, where the massive-star-forming clumps, I/I(N) and IV, are also located (Fig. 1; N denotes north). Hertz resolved the density peaks, showing that I and I(N) are again situated near field-line pinches at the parsec scale (Fig. 2a).

SMA further zoomed in onto the density peaks of I, I(N), and IV. I (N) is the youngest of the three cores, with weak outflows\textsuperscript{6,10} and a low temperature (~30 K)\textsuperscript{11}; the field lines are again symmetrically pinched (Fig. 2c). The more developed core I is hotter (~100 K)\textsuperscript{12}, and has high-velocity outflows in the northeast–southwest direction\textsuperscript{10,12}, which might have altered the field direction from the larger scale. The curved filament of IV is part of a compression shell due to the H\(\text{II}\) bubble\textsuperscript{20}, which compressed the \(B\)-fields at the same time; hence the field and filament are largely aligned (Fig. 2e).

The average orientations of the filamentary cloud, elongated clumps/cores and the \(B\)-fields (defined by “equal weight Stokes mean”\textsuperscript{13}) are summarized in Fig. 3. The orientation of a cloud is defined by the long-axis direction of the autocorrelation function of the intensity map\textsuperscript{3}. There are several intriguing facts revealed by Fig. 3. First, assuming turbulence is the only force that disturbs \(B\)-field orientations and has the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The \(B\)-field within the clumps/cores. a, b, Clumps observed by Hertz/Caltech Submillimeter Observatory (CSO)\textsuperscript{18} with a 0.15-pc resolution. The intensity again peaks near the field line pinches in a. The four field lines passing through the dashed rectangles in a are used to estimate the field curvature. c–e, Cores observed by SMA\textsuperscript{6} with a 0.02-pc resolution. Some field lines in c are extended (as dashed lines to help visualize the pinches) and are used to estimate the curvature. In c, the oval indicates a shell H\(\text{II}\) region\textsuperscript{20}. The contours show the relative intensity of the polarized flux, which tends to increase with the total intensity.}
\end{figure}
same energy density as the B-fields, the dispersion of B-field directions should be 30° based on the Chandrasekhar–Fermi relation. Apart from region IV, all the field orientations in Fig. 3 are within this 30° range. In reality, field dispersions are not only due to turbulence, but also gravity, stellar feedback (for example, region IV) and projection, so the turbulent energy of NGC 6334 should be sub-Alfvenic (see Methods section ‘B-field direction alignment between scales’).

Second, at all the scales, we observed hourglass-shaped or ordered B-fields to be close to perpendicular to cloud elongations unless severely affected by stellar feedback (core IV). This is a signature of the Lorentz force supporting the cloud against gravitational contraction in the direction perpendicular to the field lines. This anisotropic contraction affected by stellar feedback (core IV). This is a signature of the Lorentz force supporting the cloud against gravitational contraction in the direction perpendicular to the field lines. The red dashed lines deviate from the mean intercloud-medium field (optical) by 30°. Except for core IV, B-field directions vary within the range defined by the red dashed lines.

Figure 3 | Self-similar fragmentation and field configurations at 100–0.01 pc. Each solid line shows the mean field direction within a map, whose scale is indicated by the linewidth (key at bottom right). The blue dashed lines show the cloud long-axis directions. At the ends of a dashed line, arrowheads are added if the density peaks at the ends of the field, where the field directions are indicated by the branched lines. The red dashed lines deviate from the mean intercloud-medium field (optical) by 30°. Except for core IV, B-field directions vary within the range defined by the red dashed lines.

Figure 4 | Parameters used to estimate B-field strength. $M_1$ and $M_2$ are the clump masses. $d$ is the clump size (for estimating $V$). $D$ is the distance between clumps. $r$ is the field-line (dashed line) curvature radius. $S$ is the separation between the two tangent points. $F_\text{FP}$, $F_\theta$ and $F_\text{G}$ represent the forces due to magnetic tension, magnetic pressure, and gravity, respectively.

Volume. Field lines near the density peaks and with more prominent curvatures are selected (noted in Figs 1 and 2) to estimate $R$. This will give a lower limit for $R$ (and thus $B$).

If there exists a gradient of the B-field strength, $F_\theta$ should also be considered:

$$F_\theta = -\frac{V}{8\pi} \frac{B^2}{\theta} \frac{V}{8\pi} \frac{B^2 - B_0^2}{r^2}$$

where $B_0$ is the field strength outside the hourglass and $r$ is the distance from the centres of the mass of the clumps.

Finally, approximating $n$ by $(M_1 + M_2)/D^3$ yields $B \propto n^{0.41 \pm 0.04}$ (where $0.04 \sim 2\sigma$; Extended Data Table 1), with an exponent $\sim 13\sigma$ below 2/3. This is the first B–n relation derived from one single cloud covering 10–0.1 pc. Previously, the exponents are mainly based on Zeeman measurements where different values of $n$ are obtained from different types of clouds that do not have any connection with each other. We can further show that the ratios of mass to magnetic flux of the cloud/clump/cores are on average $1.6 \pm 0.5$ relative to the critical value, the ratio at which self-gravity balances magnetic forces (see Methods section ‘Estimate of field strength’).
Methods section ‘Mass-to-flux ratio’). This agrees with the value required to form massive stars in recent numerical studies.

The magnetic topography problem\(^{29}\), that is, how the field topography evolves as molecular clouds form out of the interstellar medium and as cores contract to form stars, has puzzled astronomers for decades, largely owing to the difficulties of observation. After a data collection, we finally shed some light on this problem. The Atacama Large Millimeter/submillimeter Array will have adequate sensitivity/resolution to survey B-fields in young massive-star-forming sites beyond NGC 6334.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions H.-b.L. designed and executed the experiment, K.H.Y. measured the field curvatures. F.O. performed the numerical simulations. The Chinese University of Hong Kong team was responsible for the manuscript. The DIA-ASIAA-Hanning team helped with the SMA data acquisition and reduction.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to H.-b.L. (hbl@phy.cuhk.edu.hk).
METHODS

B-field direction alignment between scales. Note that the B-field dispersion test on the relative strength between turbulence and the B-field (Fig. 3) might not work in the close vicinity of stars, where gas rotation and/or stellar feedback govern the field orientations. This may also be why protostellar disks are found to align with fields at the 10^{-3}–pc scale (poloidal) but not at the 10^{-2}–pc scale. The transformation from poloidal (cores) to toroidal (discs) fields43 can orient B-fields in any direction at the 10^{-3}–pc scale.

Estimate of B-field strength. The assumption of $F_{\gamma} = F_g + F_t$. We assumed that self-gravity and magnetic fields are close to virial equilibrium, the so-called critical condition. In practice, we use force equilibrium, $F_{\gamma} = F_g + F_t$, instead of virial equilibrium to estimate field strengths; the latter involves volume integration over the cloud. In Methods section ‘Mass-to-flux ratio’, we show that our result is roughly consistent with virial equilibrium. Here we explain why the cloud should be close to the critical condition.

First, given the hourglass-shaped field morphologies, self-gravity is able to compress the fields. So the cloud cannot be considerably subcritical ($F_{\gamma} \ll F_g + F_t$). Second, given the elongation of the cores and clumps, the cloud cannot be considerably supercritical ($F_{\gamma} \gg F_g + F_t$), either. A spherical contraction happens only when the gas is significantly supercritical and it should not be difficult to appreciate that the stronger the field is, the more elongated the clumps/cores should be. To study the relation between cloud elongation and criticality, we used the ZEUS-MP code44 to simulate cloud contraction. We designed the simulations to be as simple as possible to focus on the interaction between self-gravity and B-fields. The initial condition is a uniform spherical cloud embedded in a uniform B-field, with negligible gas pressure, no turbulence and no anisotropic diffusion. The only variable is the B-field strength, such that the mass-to-flux ratio (MFR) is 1, 2, 4 and 8 times the critical value45. The short-to-long axis ratios obtained after ten million years of contraction are shown in Extended Data Fig. 2. We note that it does not take much supercriticality for a nearly spherical contraction; MFR > 4 is enough. Extended Data Fig. 2 also displays the measured axis ratios of the clumps or cores in NGC 6334; indeed they are found to be close to the critical condition.

Third, recent studies46,47 compared the empirical threshold column density of cloud contraction48,49 with the magnetic critical column density48,50 of the typical Galactic field (∼10 μG) and found a very good agreement. For densities lower than this threshold, the field strength is independent of density24,25, that is, gas is accumulated along the field lines till the cloud becomes critical and able to compress the field lines (pinches)46. The cloud in Fig. 1b indeed looks much more elongated compared to the critical condition in Extended Data Fig. 2. Moreover, owing to flux freezing, field-line compression will not change the magnetic criticality45, and thus magnetic virial equilibrium should be a good approximation for all scales. In this picture, if Zeeman measurements are used to estimate field strengths, we should expect clouds to range from just critical to highly supercritical due to the projection effect (because only the LOS components are detected by Zeeman measurements). This range is indeed observed by ref. 25. We emphasize that this interpretation of the Zeeman measurements is debated; other authors25 interpret the observed range as an indication that some cores can be highly supercritical. Highly supercritical cores, however, are not supported by the surveys mentioned above showing that the contraction threshold agrees well with the magnetic critical column density39. Moreover, it is now understood that Zeeman measurements can potentially underestimate mean field strengths44 owing to B_{LOS} reversals within a telescope beam39,40,41,42. In any case, filaments like NGC 6334 should not belong to the highly supercritical category even if there is one, because of its low short-to-long axis ratio.

Comparison with the Chandrasekhar–Fermi method. Attributing all the field structures to turbulence, Chandrasekhar and Fermi39,40 proposed that field strength should be estimated as follows:

$$B = \frac{1}{2} \sqrt{4\pi \rho \frac{\delta v}{\delta x}} \text{ gauss}$$

where $\rho$ is gas density (in grams per centimetre cubed), $\delta v$ is the LOS velocity dispersion (in centimetres per second) and $\delta x$ is the B-field direction angle dispersion (in radians); the factor 1/2 is a correction suggested by numerical simulations43. In Fig. 2a, clump I(N), as an example, $\delta x$ is measured as 17.5° (ref. 44). The full-width half-maximum line width of CO(2-1) emission is detected as 13.7 km s^{-1} for core I and 12.1 km s^{-1} for core I(N) at the 26′′ scale (the beam size)44. Using the separation between cores I and I(N), 106.8°, as an estimate of the clamp size, the linewidth at the clamp scale can be estimated by

$$\frac{106.8°}{2} \left( \frac{13.7 + 12.1}{2} \right) = 26.1 \text{ km s}^{-1}$$

assuming a 0.5 exponent for the turbulent velocity spectrum46. Converting the linewidth to the velocity dispersion gives $\delta v = 11.1 \text{ km s}^{-1}$. Assuming $\rho(H_2) = 10^5 \text{ cm}^{-3}$ and a mean molecular mass of 2.8, the above equation gives $B = 1.4 \mu G$, which is comparable to our estimate of $1.2 \pm 0.7 \mu G$ (Extended Data Table 1). Note that apparently gravity also plays a part in determining the field structure of Fig. 2a (the hourglass shape), so the estimate from the Chandrasekhar–Fermi method should be a lower limit.

Mass-to-flux ratio. From Extended Data Table 1, we can roughly estimate the MFR, which is familiar to astrophysicists when comparing gravitational and magnetic forces. The critical MFR (that is, when self-gravity and magnetic fields reach virial equilibrium) is sensitive to cloud geometries; for example, 1/2π, $G$ for a disk25 and 2/3π, $G$ for a spherical cloud50, where $G$ is the gravitational constant. Assuming $D$ from Extended Data Table 1 to be the cross-sectional diameters, the MFRs normalized to the critical value are approximately 1.1 ± 0.24, 2.4 ± 0.74, 2.2 ± 0.54 and 1.7 ± 0.32 for the cloud, clump I(N), core I(N) and core I, respectively, based on the equation from ref. 35; correspondingly, the values are 0.83 ± 0.18, 1.8 ± 0.55, 1.7 ± 0.41 and 1 ± 0.25 based on ref. 47. The shapes of our objects fall between a disk and a sphere, and the average of the above values is 1.6 ± 0.5. Although the approximations of the cloud shapes and cross-sections are rough, the cloud is unlikely to be highly supercritical.

We can check the consistency between the observed MFR and $B$–$n$ relation using the same sets of simulations discussed in Methods section ‘Estimate of field strength’. The $B$–$n$ relations for the first ten million years are shown in Extended Data Fig. 2. The 0.4-power indeed occurs when the MFR is 1 to 2 times the critical value, which is consistent with our observation.

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Extended Data Figure 1 | A fitting of the observed $B$ and $n$ weighted by the signal-to-noise ratio. $B$ is from Extended Data Table 1 and $n$ is approximated by $(M_1 + M_2)/D^3$. The uncertainties of $M, D, d,$ and $R$ (Extended Data Table 1) are propagated to $B$ and $n$; the error bars of $1\sigma$ are shown. The slopes of the two dashed lines are 0.37 and 0.44. The ‘Curve Fitting’ toolbox of Matlab is used to fit the data. While projection may affect measurements of field strengths (though not much in our case owing to the special LOS), the exponent is less affected, because the effect is the same for all the densities if the field directions are aligned (Fig. 3).
Extended Data Figure 2 | Simulated $B$–$n$ relations and cloud elongation with various magnetic criticality numbers. Blue lines are the results from the simulations (see text) with various initial uniform field strengths $B_0$. The initial uniform density of the spherical cloud is $n_0$. $B$ and $n$ are the mean values within a cloud (regions with $n > n_0$). The MFRs normalized by the critical value $^{43}$ (criticality numbers) are shown near the ends of each blue line. The slope should never go beyond $2/3$ (the red dashed line), the condition of isotropic contraction. A simulation with the criticality number of 600 was also performed and the slope is exactly $2/3$. The observed slope of NGC6334 with a 95% confidence bound is shown by the shaded zone. The short-to-long axis ratio after ten million years of each simulation is shown within a blue oval shaped with the same axis ratio. For simplicity, the contour of 20% of the peak value is used to define the short and long axes of a cloud. The ratios are measured in the same way for Fig. 2a–d, and their mean and standard deviation are also shown within the green oval.
Extended Data Table 1 | Parameters used to estimate B-field

| scale | \( M_1 \) 100\( M_\odot \) | \( M_2 \) 100\( M_\odot \) | \( D(M_1, M_2) \) (parsec) | clump size \( d \) (parsec) | \( B \) curvature radius \( R \) (parsec) | \( B \) (\( \mu G \)) |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|
| 10 \(^{(a)}\) | 90±18 \(^{(26)}\) | 70±14 \(^{(26)}\) | 6.0±0.1 \(^{(26)}\) | 1.7±0.1 \(^{(26)}\) | 1.3±0.45 | 0.19±0.08 |
| 1 | 30±6 \(^{(26)}\) | 20±4 \(^{(26)}\) | 0.9±0.1 \(^{(26)}\) | 0.6±0.1 \(^{(26)}\) | 0.49±0.14 | 1.2±0.7 |
| 0.1 (\( \text{IN} \)) | 0.5±0.25 \(^{(27)}\) | 0.5±0.25 \(^{(27)}\) | 0.04±0.01 \(^{(b)}\) | 0.04±0.01 \(^{(c)}\) | 0.05±0.0075 | 13±10 |
| 0.1 (\( \text{I} \)) | 0.5±0.25 \(^{(27)}\) | 0.5±0.25 \(^{(27)}\) | 0.05±0.01 \(^{(d)}\) | 0.05±0.01 \(^{(e)}\) | \( \infty \) | 11±7.5 |

The parameters needed to estimate field strength based on \( F_0 = F_1 + F_2 \) are listed here. All these parameters are derived assuming a distance of 1.7 kiloparsecs to NGC 6334\(^{26}\), which has a ±25% uncertainty\(^{27}\). This uncertainty, however, will not affect the estimate of \( B \), because \( M \) (ref. 26) and thus \( F_0 \) are proportional to the square of distance, and so are \( F_1 \) and \( F_2 \) (see the equations in main text).

\((a)\) For example, \( M_1 \) and \( M_2 \) in the 10-parsec map are defined as follows. The total mass is estimated to be \( 1.6 \times 10^4 \) solar masses (ref. 26). \( M_1 \) is mainly the I/IN region (which also defines \( d \)) with the centre of mass at \( 17^\circ20'53.5'' \pm 35.4'' \pm 23.0'' \) \( (J2000) \). The rest of the mass is defined as \( M_2 \), with the centre of mass at \( 17^\circ20'17.2'' \pm 54.5'' \pm 46.6'' \) \( (J2000) \), which is very close to the peak of core IV. The two centres of mass are 6 pc apart in the sky.

\((b)\) Defined by the separation between the two intensity peaks in Fig. 2.
\((c)\) Approximated by \( D(M_1, M_2) \).
\((d)\) Error estimate: \( M \) is 20% and 50% based on refs 26 and 27; \( D \) and \( d \) are based on the beam sizes of refs 26 and 27; \( R \) is the standard error of the measurements from Figs 1 and 2. \( B \) is propagated from previous columns.