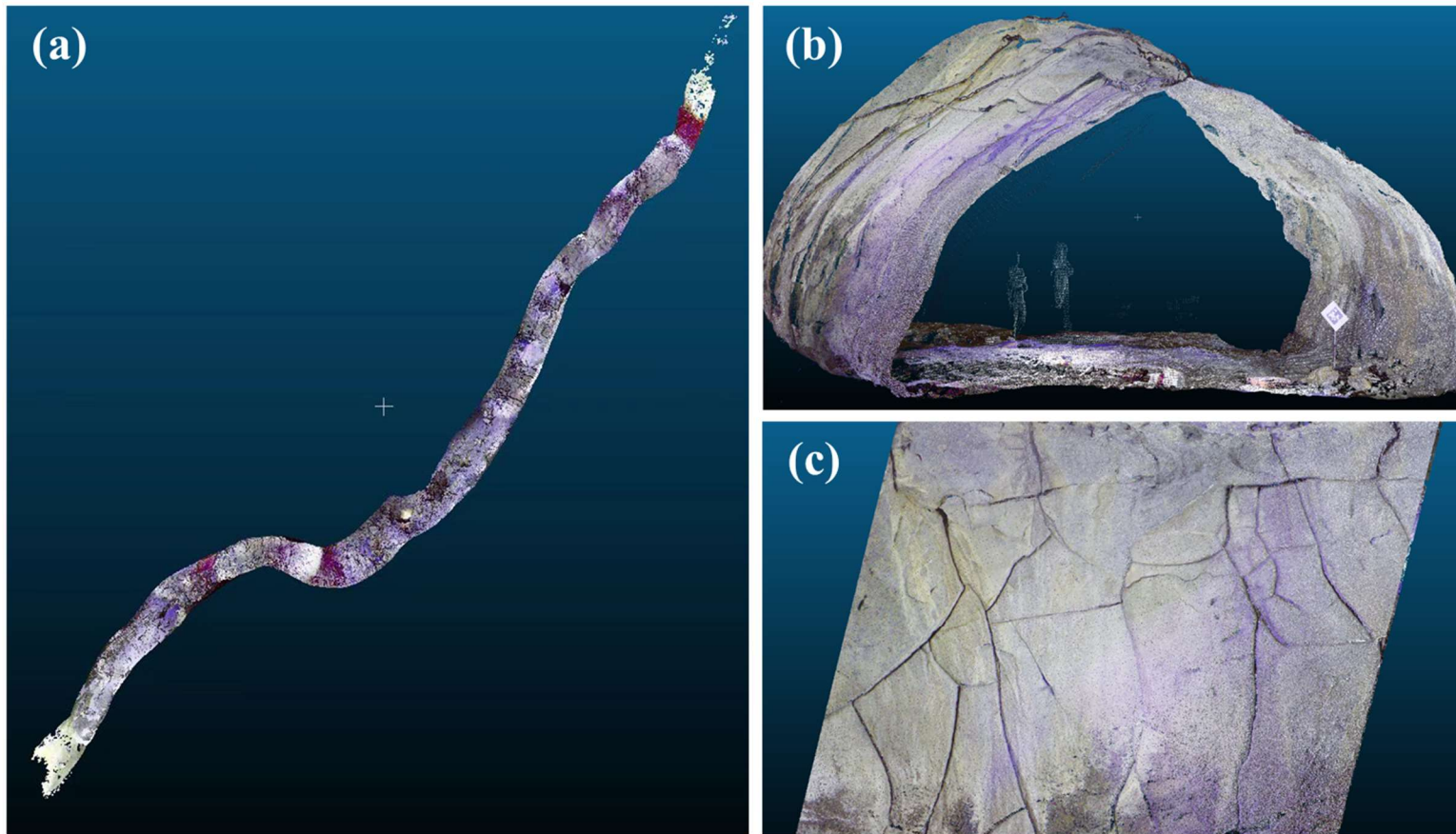
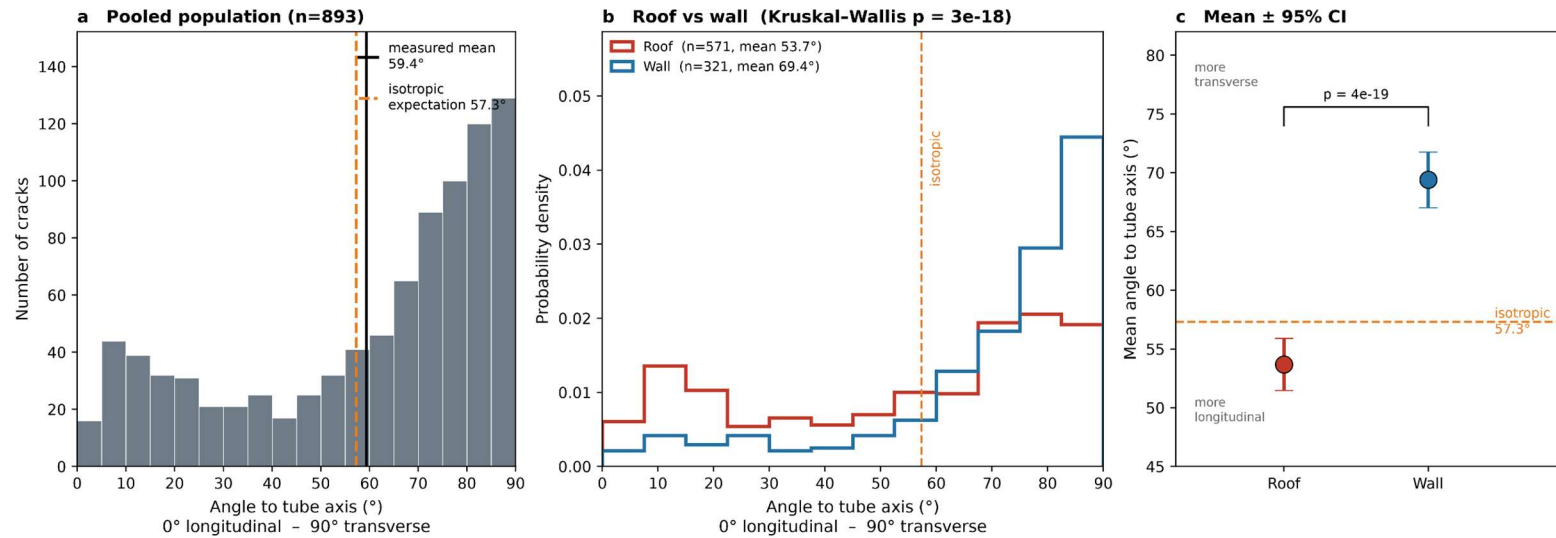


Supplementary Information

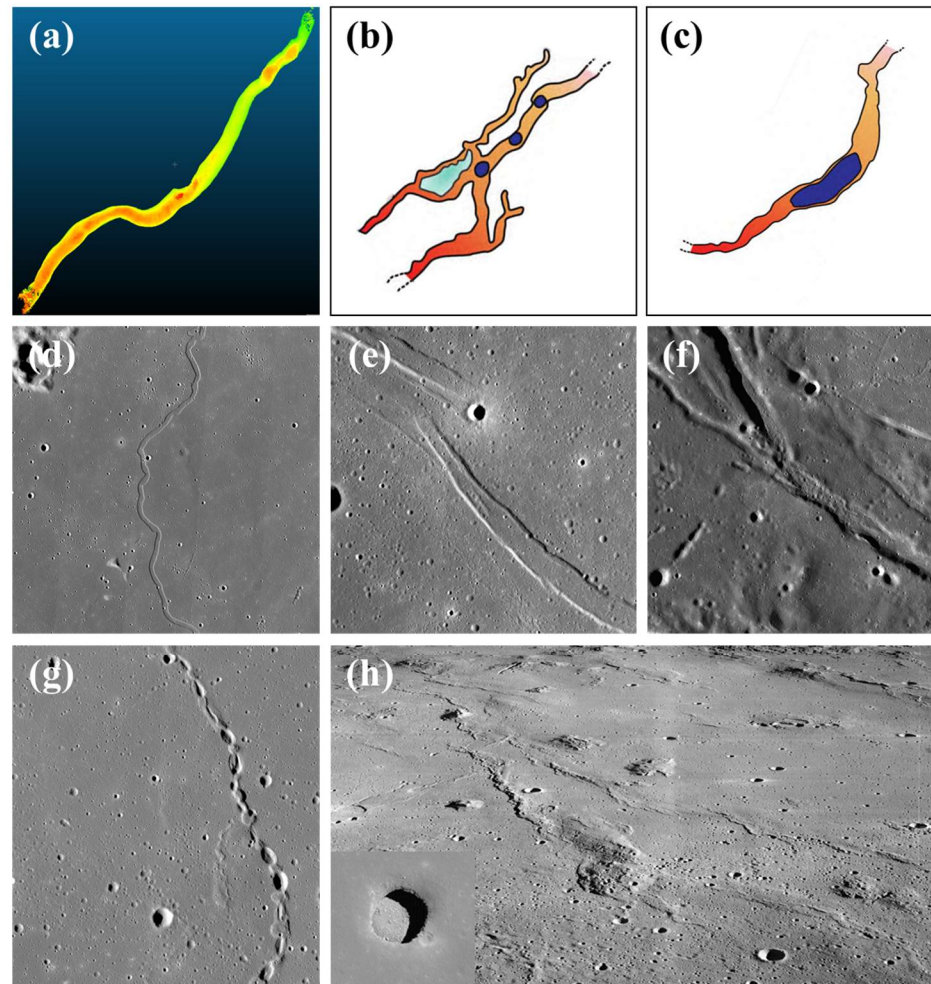
Transformer-based three-dimensional crack detection in lava
tubes: from a terrestrial analogue toward lunar subsurface
exploration



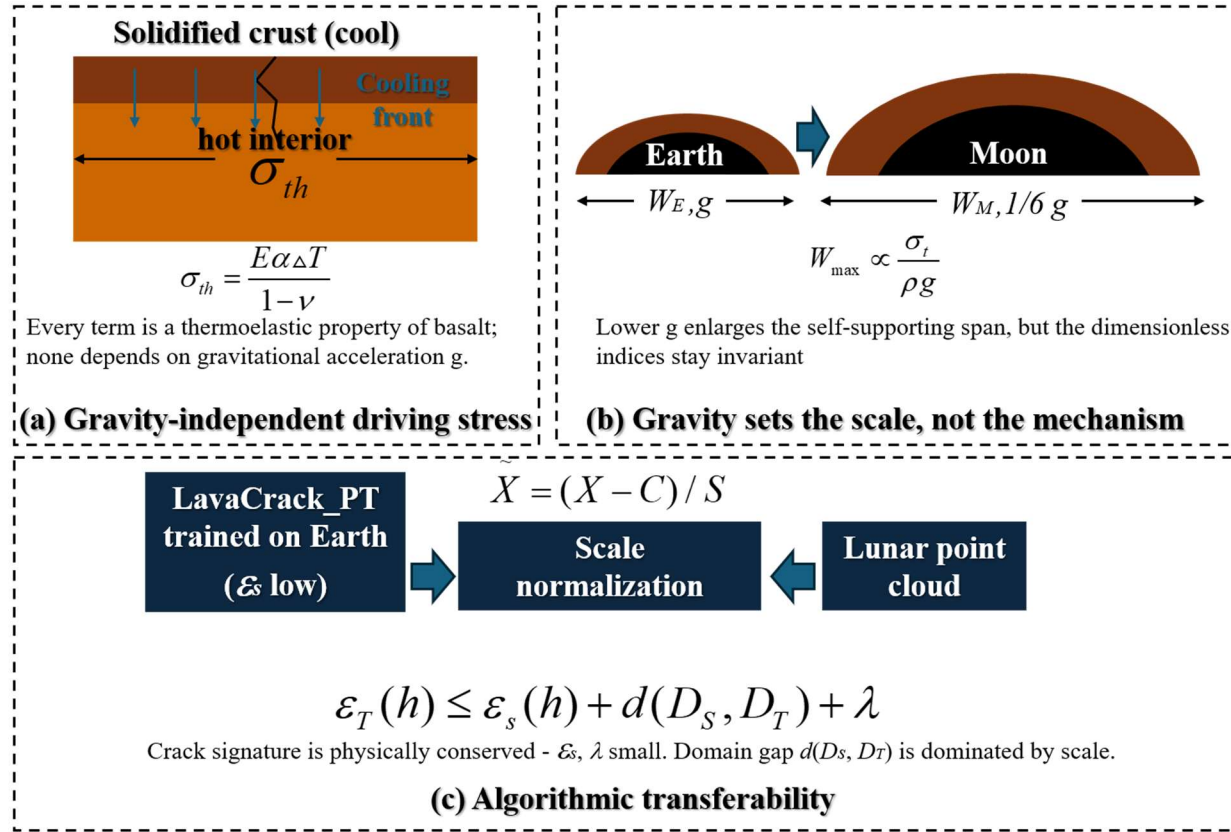
Supplementary Fig. 1 Overall image of the Hainan Xianren Cave lava tube and partial crack details



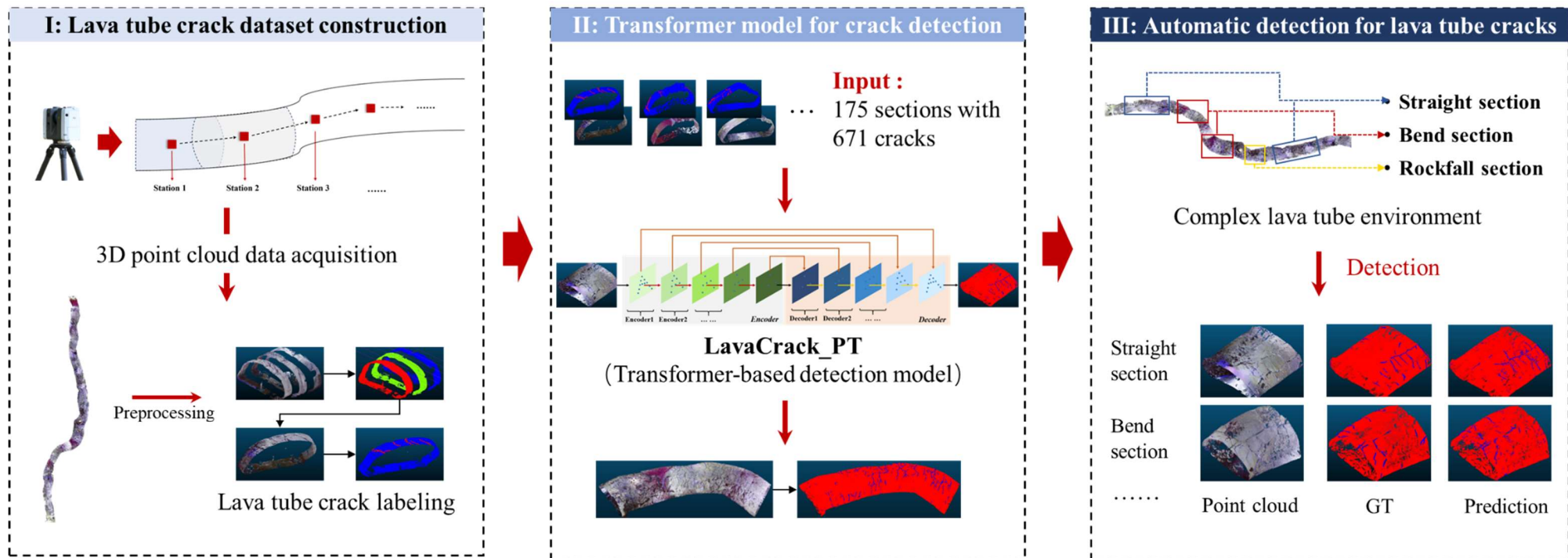
Supplementary Fig. 2 Quantitative, position-resolved test of crack orientation against stress-field predictions, over the whole tube. The angle is measured between each crack and the local tube axis (0° longitudinal, 90° transverse); $n = 893$ elongated cracks (elongation ≥ 2) resolved over all 175 cross-sections. a, The pooled population has a mean angle of 59.4° (95% confidence interval 57.7-61.1°), only marginally above the 57.3° expected for an isotropic three-dimensional orientation field, so the tube-averaged population is at most weakly anisotropic. b, Splitting the same cracks by position (roof, wall or floor, assigned from the crack's normalized height z_{norm} within its cross-section using thresholds $z_{\text{norm}} = 0.20$ and 0.66) reveals a strong gradient (Kruskal-Wallis $H = 80.9$, $p = 3 \times 10^{-18}$): roof cracks ($n = 571$) lie close to the axis while wall cracks ($n = 321$) are markedly more transverse. c, Group means with bootstrap 95% confidence intervals; roof cracks are significantly more longitudinal than wall cracks (one-sided Mann-Whitney $p = 4 \times 10^{-19}$, a roof-wall mean difference of $\approx 16^\circ$). Floor cracks are not shown because only one floor crack met the elongation criterion. Source data are provided with this paper.



Supplementary Fig. 3 Morphologies of lava tubes and collapse pits on Earth and the Moon. (a) Xianren cave lava tube in northern hainan. (b) kazumura lava tube (<https://kazumuracave.com/>). (c) Undara Lava Tubes (From Wikipedia). (d) Rima Sharp in Oceanus Procellarum (46°N Lat, 309°E Lon). (e) Rima Cauchy in Mare Tranquillitatis (10°N Lat, 38°E Lon). (f) Rimae Sulpicius Gallus in Mare Serenitatis (20°N Lat, 10°E Lon). (g) Gruithuisen (34.7°N Lat, 316.6°E Lon). (h)Marius Hills and a Hole



Supplementary Fig. 4 Mechanistic basis for transferring an Earth-trained crack detector to the Moon. a, Gravity-independence of the crack-driving stress: the thermoelastic tensile stress $\sigma_{th} = E\alpha\Delta T/(1-\nu)$ (equation 1) depends only on basalt material properties, which differ by at most a few per cent between Earth and the Moon, so the fracture-generating physics is essentially identical on both bodies. b, Gravity sets scale, not process: the maximum unsupported span $W_{max} \propto \sigma_t/(\rho g)$ (equation 2) grows by $\approx 6\times$ under lunar gravity, but non-dimensionalizing the elastic-shell problem (groups Π_1 – Π_3 , equation 3) shows that mechanically similar tubes crack in geometrically similar ways at any scale, consistent with the morphometric invariants of Supplementary Table 3. c, From mechanical similarity to algorithmic transferability: the domain-adaptation bound $\epsilon_T \leq \epsilon_s + d(D_S, D_T) + \lambda$ (equation 4) links the low Earth error ϵ_s to a low lunar error ϵ_T because shared physics keeps the source–target divergence small; the measured robustness to point-cloud density (Fig. 3e) is an empirical proxy that this divergence is already controlled.



Supplementary Fig. 5 Overall schematic of the entire thesis technical system

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Supplementary Table 1. Morphometric parameters of typical lava-tube collapse pits on Earth and the Moon.

Body	Lava tube	Long axis (m)	Short axis (m)	Depth (m)	Volume, mean (m ³)	Linear volume, mean (m ³ m ⁻¹)	Volume, s.d. (m ³)	Linear volume, s.d. (m ³ m ⁻¹)	Width-to-depth ratio
Earth	Kazumura	13.9	7.4	5.2	na	29	na	18	1.4
	Corona	62.2	37.6	9.8	10.3×10 ³	316	9.1×10 ³	177	3.9
	Undara	250	68	5-25	/	/	/	/	5-6
	Wolong Cave	11.7	7.2	7.7	/	24	/	17	0.94
	Valentine Cave	/	10-15	5-10	/	498	/	/	1.5-2
	Manjanggul	/	18	23	/	7416	/	/	0.78
	Umm Jirsan	/	45	8-12	/	1481	/	/	3.8-5.6
	Thurston	/	6	3-6	/	600	/	/	1-2
Lunar	South of Marius	1070.3	573.9	87	16.5×10 ⁶	41.4×10 ³	13.8×10 ⁶	25.5×10 ³	6.6
	North of Marius	1358	527.4	95.8	21.7×10 ⁶	42.0×10 ³	22.3×10 ⁶	27.3×10 ³	6
	Gruithuisen	1333.7	858.5	189.9	81.7×10 ⁶	141.6×10 ³	78.2×10 ⁶	100.9×10 ³	5
	Mare Tranquillitatis	146	100	105	/	45-80	/	/	0.95
	Mare Ingenii	130	100	60-80	/	/	/	/	1.5-1.7
	Lacus Mortis	260	180	/	/	/	/	/	/

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