

# Ice proved cool way to move stones for Forbidden City

Ice-lubricated sledges were the most efficient way to transport multi-tonne stones for Beijing's centre.

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li jingwang/Getty

A bronze lion in Beijing's Forbidden City, which was built in part with stones transported over ice roads using sledges.

Some of the largest stones used to construct Beijing's Forbidden City beginning in 1406 were hauled from distant quarries on wooden sledges along ice roads, ancient Chinese documents have revealed. Calculations now reported in *Proceedings of the National Academy of Sciences* show that, on uneven, winding roads, this method is safer, more reliable and much easier than using wooden rollers or dragging the sledges over bare ground<sup>1</sup>.

The imperial palace and surrounding buildings in the Forbidden City, a complex that has long served as the figurative centre of China's capital city, were built in the early 1400s, but construction in and around the complex continued to the late 1500s and beyond. Many of the largest stones in the complex came from a quarry located about 70 kilometres from Beijing, says Howard Stone, a fluid mechanist at Princeton University in New Jersey, and a member of the team that performed the study. "You go to the Forbidden City and see these massive rocks, and you ask yourself: 'How in the world did they ever move this rock here?'" he says.

A few historians have briefly noted that some enormous stones in the Forbidden City had been transported by sledges pulled by teams of men in the depths of winter. But Jiang Li, a mechanical engineer at the University of Science and Technology Beijing, recently stumbled across a more-detailed description related to one particular stone in the complex.

The ancient document reported that the monolith, a 49-cubic-metre slab estimated to weigh almost 112 tonnes, was hauled to Beijing in 1557 over the course of 4 weeks — which works out as an average speed of about 8 centimetres per second. Other blocks of rock were even heavier, Stone says.

The documents, which were later translated into English, raised several questions. Foremost, says Stone, is why weren't the monoliths transported on wheeled vehicles, which had been used in China since the fourth century bc? Moreover, he asks, was hauling sledges on an ice road the best method available?

The first question is fairly easy to answer, says Stone. Even into the late 1500s, Chinese wheeled vehicles could not carry loads

exceeding around 86 tonnes, necessitating the use of wooden sledges for larger burdens.

### Head count

Answering the second question takes a bit more analysis. For one thing, Stone notes, using wooden rollers — imagine telegraph-pole-sized tree trunks as large bearings — is tricky on winding roads. The technique also requires a smooth, hard surface to prevent the rollers from becoming mired. Dragging a 112-tonne sledge over bare ground would require more than 1,500 men, Stone and his colleagues estimate. Pulling the same sled across bare ice or across wet, wooden rails would require at least 330 men.



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An aerial view of the Forbidden City.

But if the stone-burdened toboggan were hauled along an ice road lubricated by a film of water, the researchers say, fewer than 50 men would be needed to tow the load.

Hauling massive stones long distances over ice roads “is an interesting and plausible idea”, says Michael Parker Pearson, an archaeologist at University College London. But although winters in northern China were typically cold enough to allow the use of ice-lubricated highways, other parts of the world where large stone monuments are found — Stonehenge is a prime example, he notes — did not have the consistently cold winters required to reliably employ the technique.

The team’s results “are wonderful and well written”, but probably substantially underestimate the number of men needed to haul a 112-tonne sledge, says Thomas Mathia, an expert in tribology — the science of friction and lubrication — at the Lyon Central School in France. For example, the effort to get the sledge moving from a standstill is much larger than that needed to keep it moving. So, around two to three times more men would be needed to transport the stone-burdened sled than Stone and his colleagues estimate, he notes. Furthermore, that is over a flat roadway, says Mathia. To pull the sledge up a 10° slope, you would need another 270 people or so.

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### Corrections

**Corrected:** The version of this article published on 4 November incorrectly referred to Howard Stone's first name as Thomas.

### References

1. Li, J., Chen, H. & Stone, H. A. *Proc. Natl Acad. Sci. USA* <http://dx.doi.org/10.1073/pnas.1309319110> (2013).