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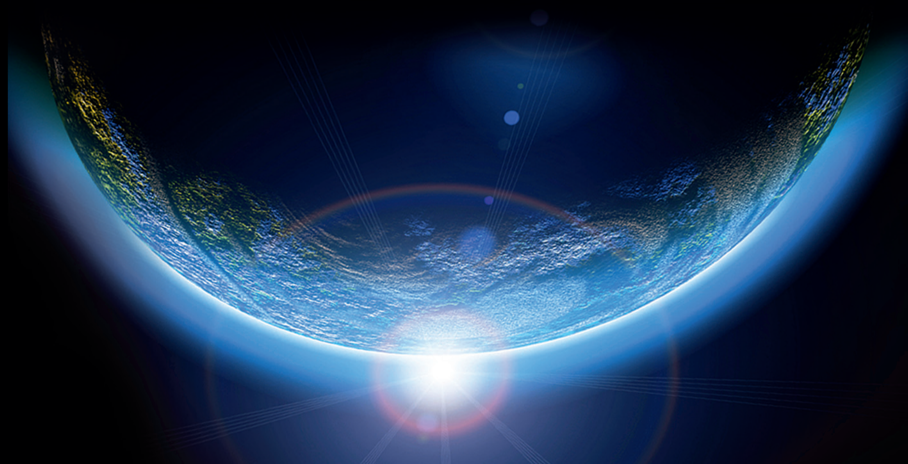
SET IN STONE

Evidence For Earth's Catastrophic Past



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SET IN STONE

EVIDENCE FOR EARTH'S CATASTROPHIC PAST

1. INTRODUCTION

According to modern geology, our world is over four and a half billion years old, and its geological features have been sculpted over vast eons of time.[1]

Everyone knows that Planet Earth is unimaginably ancient. It's common knowledge that geological forces have acted slowly over millions of years to form the rocks beneath our feet.

But what if what everyone 'knows' is wrong?

In this programme, we're taking a journey around the British Isles, the place where modern geology was born.

As we experience this spectacular scenery, awe inspiring landscapes and beautiful coastlines we begin a visual odyssey of discovery.

We're also going to ask some important questions. Were the rocks around us formed slowly and gradually – or suddenly during catastrophic events?

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1 G. B. Dalrymple, *The Age of the Earth*, Stanford University Press, Stanford, California, 1991.

Did the history of the world unfold over vast eras of time or much shorter periods? And what do the rocks really tell us about the geological history of our world?

So join us as we take a closer look at earth's catastrophic past!

We begin our journey on the east coast of Scotland, about 40 miles from Edinburgh.

Siccar Point is a site of international scientific importance, visited by many parties of geologists and students every year. It was just over 200 years ago that the pioneering geologist James Hutton came by boat to Siccar Point with his colleagues John Playfair and James Hall. What they saw here was to lead to a revolution in our understanding of the history of the earth.

PAUL GARNER: Well here we are at Siccar Point, perhaps one of the most famous geological sites anywhere in the world, a place where an old established worldview was completely overturned.

JOHN WHITMORE: This is where Hutton and his friends Playfair and Hall came in 1788 and observed this famous location and from the observations they made here they convinced everyone that the earth was not six thousand years old but that it was perhaps millions of years old didn't they?

PAUL GARNER: That's right. And Hutton famously said he could, contemplating these rocks here, he could see no vestige of a beginning nor prospect of an end.[2]

2. HISTORICAL FOUNDATIONS

Not much more than a century before Hutton, most naturalists and scientists had been men of great religious conviction. They accepted the historical accounts recorded in the Bible – and believed that the early chapters of the book of Genesis provided the key to unlocking the mysteries of the earth's past.

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2 J. Hutton, *Theory of the Earth, with Proofs and Illustrations*, 2 vols., facsimile reprint, Weinheim and Codicote, 1959 (first published 1795).

They included men like Thomas Burnet, who argued that the present surface of the earth had been shaped by the catastrophic worldwide flood that took place in the days of Noah.[3] Another was John Woodward, who thought that the fossils enclosed in the rock layers were the remains of creatures that had perished during the catastrophe.[4] Both men were leading thinkers of their day, and implicitly trusted what the Bible said about the history of the world. They saw the rocks and fossils as a silent testimony to the events of creation and the flood.

But over the next few decades there was a growing separation in people's minds between 'scientific truths' and 'religious truths'. The Bible came to be regarded as a source of moral and religious instruction – but not as a reliable source of knowledge about the physical world. Consciously or otherwise, scholars began to explain the natural world without any reference to God. The biblical events of creation and the flood were sidelined in favour of increasingly speculative ideas about the earth's past.

However, it was not until James Hutton came along that a completely new approach to geology would take root – one that would overturn the biblical catastrophism of the past. While working on his family farm in Berwickshire, Hutton observed the way in which erosion gradually wore away at the rocks, and sediments slowly accumulated in streams, lakes and rivers. He came to believe that these same slow processes, operating over vast periods of time, were sufficient to explain how the earth's rock layers had formed in the more distant past. There was no place in Hutton's mind for catastrophic global floods like the one described in the Bible.

It was while he was developing these theories about geological processes that Hutton came to Siccar Point – triggering an earthquake in the science of geology which still reverberates to this day.

3. HUTTON'S UNCONFORMITY

PAUL GARNER: So what did Hutton and his friends see when they came here

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3 M. J. S. Rudwick, *The Meaning of Fossils: Episodes in the History of Palaeontology*, Macdonald & Co. (Publishers) Limited, London, 1972, pp.77-80.

4 Rudwick, *The Meaning of Fossils*, pp.82-83.

to Siccar Point in 1788? Well, magnificently exposed here on the foreshore are two sets of rock layers. The first set of rock layers are the vertical layers that you can see behind me in this face here. These are layers of sandstone and mudstone and they're standing up on end, they're oriented vertically; and then Hutton noticed that there were other rock layers which were horizontal, above the vertical layers; they're the layers that I'm sitting on here, these reddish sandstone layers. And Hutton realized that you could read the story in the rocks like the story in a book, and he began to realize that as he thought about cycles of erosion and sedimentation, here was a geological sequence of events. Layers of sandstone and mudstone had been laid down horizontally on the floor of an ocean, and then there'd been an episode of folding and uplift, so those rock layers were now standing vertically on end. And then they'd been eroded by some geological process, and then there'd been an episode of subsidence, and more sediments had been laid down horizontally on top. This structure is what geologists now call an angular unconformity.[5] *And to Hutton who had been thinking about how slowly erosion and sedimentation take place today – he'd observed slow stream erosion, he knew how slowly sediments were building up in lakes and rivers and oceans today – he realized that if those same rates had applied in the past, then to form this structure at Siccar Point must have taken vast ages of time.*

4. RETHINKING UNIFORMITARIANISM

In the nineteenth century, Hutton's views were taken up by the geologist and lawyer Sir Charles Lyell.[6] Lyell is credited with developing one of the most fundamental geological principles – the principle of uniformitarianism – often summed up in the phrase 'the present is the key to the past'. Like Hutton, Lyell believed that the same processes of erosion and sedimentation that could be observed today had always operated, but he went even further than Hutton in assuming that they had done so at strictly uniform rates. His popularization of this approach was enormously successful and the 'uniformitarian' dogma came to be adopted by virtually the entire geological

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5 G. Y. Craig, Siccar Point: Hutton's classic unconformity, pp.146-151 in: A. D. McAdam, E. N. K. Clarkson (eds.), *Lothian Geology: An Excursion Guide*, Scottish Academic Press, Edinburgh, 1986.

6 C. Lyell, *Principles of Geology, being an attempt to explain the former changes of the earth's surface, by reference to causes now in operation*, 3 vols., facsimile reprint, New York, 1970 (first published 1830-1833).

community of his generation. His book even had an influence on the emerging theory of evolution, when it was read by a young naturalist named Charles Darwin.[7]

For the next 150 years, the theories of Hutton and Lyell dominated geological thinking. Catastrophism of the kind embraced by earlier generations was considered out of bounds. But the nagging doubts of some geologists wouldn't go away. The evidence in the rocks didn't always fit comfortably with the gradualism of Hutton and Lyell. Many rock layers pointed to processes more rapid and violent than those going on at the present day.

Eventually these growing doubts led some geologists to reconsider the evidence for catastrophism and to move away from the more rigid forms of uniformitarianism. So much so, that within the last 40 years, belief in large-scale geological catastrophes, once regarded almost as heresy, has become fashionable again – even mainstream.

5. THE SUTTON STONE

One of the leading proponents of this 'new catastrophism' was Derek Ager, formerly professor of geology at Swansea University and one-time President of the Geologists' Association. Ager's books make for thought-provoking reading.[8] In one of them he wrote: '…we have allowed ourselves to be brain-washed into avoiding any interpretation of the past that involves extreme and what might be termed "catastrophic" processes.'[9] Ager emphasized that the geological record was full of examples of processes that were far from 'normal' and that sedimentation had often been very rapid and very spasmodic.

Among the evidence for catastrophism to which Ager pointed were rock layers which appeared to have been formed rapidly during storms, hurricanes or typhoons. With tongue in cheek, he would refer to these as 'Tuesday afternoon deposits' in order to convey how quickly they must have been

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7 A. Desmond, J. Moore, *Darwin*, Michael Joseph, London, 1991, pp.117-118.

8 D. V. Ager, *The Nature of the Stratigraphical Record*, Second Ed., Macmillan, 1981. D. V. Ager, *The New Catastrophism: The Importance of the Rare Event in Geological History*, Cambridge University Press, 1993.

9 Ager, *The Nature of the Stratigraphical Record*, p.46.

laid down.[10] One of Ager's favourite examples was found on the coast not far from his home in Swansea, south Wales – seen here on a very wet and foggy afternoon! Exposed along the shore near the village of Ogmore-by-Sea is a pebbly rock layer, about three feet thick, called the Sutton Stone. Most geologists have supposed that the Sutton Stone was laid down along the shoreline of an advancing ocean – a beach deposit that took perhaps five million years to be laid down.[11] However, there are some curious features of this rock formation that are inconsistent with the idea of slow accumulation.

When we look at a modern pebbly beach we see that the pebbles are in contact with one another. Each pebble rests on other pebbles just like the raisins in this bowl. That's what the Sutton Stone should look like if it had formed as a slowly accumulating beach deposit. But careful examination reveals that the pebbles in the Sutton Stone are 'floating' within a mass of finer sediment.[12] In fact, they're more like the raisins in this piece of raisin cake – suspended within the finer cake mix. This is an important observation. Pebbles 'floating' in a mass of finer sediment are characteristic of what geologists call 'mass flow deposits' – including those laid down by hurricanes, tsunamis and severe tropical storms.

Based on his careful study of the Sutton Stone, Derek Ager concluded that it must have been deposited by an enormous wave of water carrying mud and pebbles, which dumped them together to form this layer. Far from being deposited slowly over five million years, the Sutton Stone had been formed in a single, sudden event.[13] This was too much for some geologists, who challenged his reinterpretation of the Sutton Stone,[14] but Ager himself

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10 Ager, *The New Catastrophism*, p.117.

11 A. E. Trueman, The Liassic rocks of Glamorgan. *Proceedings of the Geologists' Association* 33:245-284, 1922. J. C. W. Cope, T. A. Getty, M. K. Howarth, N. Morton, H. S. Torrens, A correlation of Jurassic rocks in the British Isles. Part one: introduction and Lower Jurassic. *Geological Society of London Special Report* No. 14, 1980.

12 In geological terminology the Sutton Stone is a 'matrix-supported', rather than a 'clast-supported', conglomerate.

13 D. Ager, A reinterpretation of the basal 'Littoral Lias' of the Vale of Glamorgan. *Proceedings of the Geologists' Association* 97:29-35, 1986.

14 C. J. N. Fletcher, J. R. Davies, D. Wilson, M. Smith, The depositional environment of the basal 'Littoral Lias' in the Vale of Glamorgan – a discussion of the reinterpretation by Ager (1986). *Proceedings of the Geologists' Association* 97:383-384, 1986.

remained unbowed.[15] Whatever caused the layer to be deposited, he insisted it must have happened very quickly. The evidence favoured catastrophism – not the slow accumulation of pebbles on an ancient beach.

But it's not just in the laying down of sediments that catastrophism has made a 'comeback'. In recent years there has been a re-evaluation of other fields of geology too.

6. RAPID GRANITE FORMATION

PAUL GARNER: Consider the formation of igneous rocks which are those that formed from molten magmas. A very common type of igneous rock is granite, which forms much of our loveliest upland scenery. This is a piece of granite that I collected in Cornwall and this is a piece of granite which I collected in Shap in Cumbria. Now although the granite bodies from which I collected these specimens are found today at the earth's surface, the magma from which they formed started off many kilometres below ground.

In fact, granite magmas are formed more than 18 kilometres below the surface of the earth by the melting of rocks in the lower crust.[16] Because the hot magmas are relatively light and buoyant, they begin to rise upwards through the crust – a bit like the rising 'lava' in a 'lava lamp'. Eventually the magma collects as a large body about three to four kilometres below ground, where it solidifies, cools and crystallizes. Finally, erosion strips away the rocks above the granite, exposing it at the earth's surface.

Geologists have usually assumed that this process of granite formation must have taken immense periods of time. Granite magmas were thought to have risen through the crust in enormous, balloon-shaped bodies called diapirs. This was regarded as a very slow process, because the magma literally had to force its way along, making space for itself as it moved upwards.[17] Some

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15 D. Ager, Reply. *Proceedings of the Geologists' Association* 97:384, 1986.

16 M. Brown, The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. *Earth-Science Reviews* 36:83-130, 1994.

17 B. D. Marsh, On the mechanics of igneous diapirism, stoping, and zone melting. *American Journal of Science* 282:808-855, 1982.

estimates suggested that it would take 150,000 years for a magma to make its way from the lower crust to the place where it would collect in the upper crust.[18]

Once in the upper crust, the granite magma would continue to cool and crystallize, eventually becoming a solid igneous rock. This was also considered to be a very slow process. Granite bodies like the one that underlies much of southwest England are so large that it was assumed they must have taken hundreds of thousands or even millions of years to cool down.

But even that's not the end of the story. Once emplaced, the granite would still be buried under three to four kilometres of rock. It would take another few million years of slow and gradual erosion to remove the rocks above the granite body, before it would be exposed at the surface as the familiar tors that we see today.

In other words, the process of forming granites seemed to be a classic example of what Hutton was talking about – slow and gradual activity taking place over millions of years.[19]

But then came a revolution in our scientific understanding of granite formation. In the 1990s geologists began to call into question almost every aspect of the story we've just outlined.[20] Andrew Snelling is a geologist who has studied granite formation in many parts of the world, and he takes up the story.

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18 H. Ramberg, Experimental study of gravity tectonics by means of centrifuged models. *Bulletin of the Geological Institution, University of Uppsala* 42:1-97, 1963. K. I. Mahon, T. M. Harrison, D. A. Drew, Ascent of a granitoid diapir in a temperature varying medium. *Journal of Geophysical Research* 93:1174-1188, 1988. R. F. Weinberg, Y. Podladchikov, Diapiric ascent of magmas through power law crust and mantle. *Journal of Geophysical Research* 99:9543-9559, 1994.

19 'My guess is that a granitic magma pulse generated in a collisional orogen may, in a complicated way involving changing rheologies of both melt and crust, take 5-10 Ma to generate, arrive, crystallize and cool to the ambient crustal temperature.' W. S. Pitcher, *The Nature and Origin of Granite*, Second Ed., Chapman & Hall, London, 1997, p.222.

20 N. Petford, A. R. Cruden, K. J. W. McCaffrey, J.-L. Vigneresse, Granite magma formation, transport and emplacement in the Earth's crust. *Nature* 408:669-673, 2000. J. D. Clemens, Granites and granitic magmas: strange phenomena and new perspectives on some old problems. *Proceedings of the Geologists' Association* 116:9-16, 2005.

ANDREW SNELLING: …well incredibly as it may seem in the last two decades there's been a revolution in thinking about granites because for many years there's been a consistent problem that's gnawed away in the thinking of, in the background in the thinking of geologists, and it's best summed up in the term 'the space problem'[21] *… remember we've got this hot molten blob, this diapir, this whole balloon of molten material that supposedly has melted deep in the earth's crust over millions of years. It's got to somehow rise in the earth's crust, but you've got all this other rock above that is pushing down on it. How is this big balloon going to rise and push aside all that rock? That's what became known as 'the space problem' … so it's led to new investigations and new thinking about how these granite bodies form.*

Geologists began to suspect that granite magmas had risen very rapidly through the earth's crust along narrow fractures – a process up to a million times faster than the slow rise of magmas in balloon-shaped diapirs.[22]

ANDREW SNELLING: … and then they've realized that there are ways in which granite would have formed, the molten material would have formed at depth in little batches that accumulated in fractures, and pressure on those fractures would squeeze the magma up through cracks. … They're thinking in terms of small batches of molten granite accumulating very rapidly, getting into these fractures, and then the fractures closing and the molten material

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21 Pitcher, *The Nature and Origin of Granite*.

22 N. Petford, R. C. Kerr, J. R. Lister, Dike transport of granitoid magmas. *Geology* 21:845-848, 1993. N. Petford, Dykes or diapirs? *Transactions of the Royal Society of Edinburgh: Earth Sciences* 87:105-114, 1996. J. D. Clemens, C. K. Mawer, Granitic magma transport by fracture propagation. *Tectonophysics* 204:339-360, 1992. J. D. Clemens, N. Petford, C. K. Mawer, Ascent mechanisms of granitic magmas: causes and consequences, pp.145-172 in: M. B. Holness (ed.), *Deformation-Enhanced Fluid Transport in the Earth's Crust and Mantle*, Chapman and Hall, London, 1997. N. Petford, J. R. Lister, R. C. Kerr, The ascent of felsic magmas in dykes. *Lithos* 32:161-168, 1994. W. J. Collins, E. W. Sawyer, Pervasive granitoid magma transport through the lower-middle crust during non-coaxial compressional deformation. *Journal of Metamorphic Geology* 14:565-579, 1996. R. S. D'Lemos, M. Brown, R. A. Strachan, Granite magma generation, ascent and emplacement within a transpressional orogen. *Journal of the Geological Society of London* 149:487-490, 1992. M. Brown, G. S. Solar, The mechanism of ascent and emplacement of granitic magma during transpression: a syntectonic granite paradigm. *Tectonophysics* 312:1-33, 1999. N. Petford, Granite on the move. *New Scientist* 130(1773):44-48, 1991.

being pumped up through that fracture[23] through what we call a dyke, a large vertical fracture in which there is a channel for the molten material to come up, and they're thinking now in terms instead of tens or hundreds of thousands of years for the molten material to rise and accumulate in the upper crust, say two to three miles down, they're talking about six, ten, twenty years at most for some of these bodies to accumulate ...[24]

PAUL GARNER: Confirmation that granite magmas rose so rapidly through the crust of the earth has come from a study of the minerals that we find in granites including a mineral called epidote. Now epidote is only stable at very high pressures, which means that it must have formed when the granite magma was a long way below ground, and the only way that we could find epidote crystals in granites at the surface today is if they were transported upwards with the magma very, very quickly. In fact a study of granites in Colorado in the USA which contain epidote crystals suggested that those magmas had travelled through the earth's crust in less than 50 years.[25]

But what about the time it would take for such enormous bodies of granite magma to cool down once they'd been emplaced? Surely they would still require millions of years? Most of the older estimates of cooling times were based on conductive heat loss from the granite magmas to the surrounding rocks – and that was undoubtedly a very slow process. But geologists began to realize that the circulation of water within and around a granite body would have been very efficient at removing heat. This would have cooled the

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23 M. Brown, T. Rushmer, The role of deformation in the movement of granitic melt: views from the laboratory and the field, pp.111-144 in: M. B. Holness (ed.), *Deformation-Enhanced Fluid Transport in the Earth's Crust and Mantle*, Chapman and Hall, London, 1997.

24 Estimates of filling times suggest that most igneous bodies less than 100 km across could have been emplaced in much less than 1,000 years, and perhaps even as little as 40 days. See N. Harris, D. Vance, M. Ayres, From sediment to granite: timescales of anatexis in the upper crust. *Chemical Geology* 162:155-167, 2000. Petford et al., Granite magma formation, transport and emplacement in the Earth's crust. Even a batholith of 1,000 km^3 composed of many smaller igneous bodies could be constructed in only 1,200 years. See Clemens, Granites and granitic magmas: strange phenomena and new perspectives on some old problems.

25 A. D. Brandon, R. A. Creaser, T. Chacko, Constraints on rates of granitic magma transport from epidote dissolution kinetics. *Science* 271:1845-1848, 1996.

granite much faster than previously thought.[26]

ANDREW SNELLING: ...they're also realising that as the granite starts to cool, it has water dissolved in it, and that water is released as what we call hydrothermal fluids or hot waters, and we see the outworking of those hot waters in places like down in Cornwall where the hot waters have collected metals from the cooling granite and accumulated them in fractures in quartz veins to make those metal deposits, the tin lodes. Well that means the water in the granite is coming out as the granite crystallizes and cools, and the water is starting to travel down fractures, breaking up the granite as it cools[27] and travelling out into the surrounding rock that's been intruded by the granite. ... The steam as it were – the hot water and steam that's coming out of the granite is fracturing the outer rim of the granite that's cooling and hardening – and also the surrounding country rock – and allows the cool country rock water to come into the granite as well – the groundwater – so you set up a circulation system of water coming, cool water coming from outside mingling with the hot water in the granite and taking the heat out. We call that convective cooling, and when you start to do the calculations on this convective cooling cycle the

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26 L. M. Cathles, An analysis of the cooling of intrusives by ground-water convection which includes boiling. *Economic Geology* 72:804-826, 1977. P. Cheng, W. J. Minkowycz, Free convection about a vertical flat plate embedded in a porous medium with application to heat transfer from a dike. *Journal of Geophysical Research – Solid Earth* 82B:2040-2044, 1977. H. C. Hardee, Permeable convection above magma bodies. *Tectonophysics* 84:179-195, 1982. D. Norton, Sourcelines, sourceregions, and pathlines for fluids in hydrothermal systems related to cooling plutons. *Economic Geology* 73:21-28, 1978. D. Norton, J. Knight, Transport phenomena in hydrothermal systems: cooling plutons. *American Journal of Science* 277:937-981, 1977. E. M. Parmentier, Numerical experiments on ^{18}O depletion in igneous intrusions cooling by groundwater convection. *Journal of Geophysical Research – Solid Earth* 86B:7131-7144, 1981. F. Spera, Thermal evolution of plutons: a parameterized approach. *Science* 207:299-301, 1980. K. E. Torrance, J. P. Sheu, Heat transfer from plutons undergoing hydrothermal cooling and thermal cracking. *Numerical Heat Transfer* 1:147-161, 1978. D. O. Hayba, S. E. lngebritsen, Multiphase groundwater flow near cooling plutons. *Journal of Geophysical Research – Solid Earth* 102B:12235-12252, 1997. E. M. Parmentier, A. Schedl, Thermal aureoles of igneous intrusions: some possible indications of hydrothermal convective cooling. *Journal of Geology* 89:1-22, 1981.

27 R. B. Knapp, D. Norton, Preliminary numerical analysis of processes related to magma crystallization and stress evolution in cooling pluton environments. *American Journal of Science* 281:35-68, 1981. R. B. Knapp, J. E. Knight, Differential thermal expansion of pore fluids: fracture propagation and microearthquake production in hot pluton environments. *Journal of Geophysical Research – Solid Earth* 82B:2515-2522, 1977. J. Zhao, E. T. Brown, Thermal cracking induced by water flow through joints in heated granite. *International Journal of Rock Mechanics* 29:77-82, 1992. P. A. Candela, Physics of aqueous phase evolution in plutonic environments. *American Mineralogist* 76:1081-1091, 1991.

timeframes suddenly diminish to days and hours and weeks and years, rather than tens and hundreds of millions of years.

What's more, it has become evident that most granite bodies are flat and lack deep roots.[28] Their sheet-like shape gives them a very large surface area through which heat can be rapidly lost.

ANDREW SNELLING: Then it's been discovered that when they've done seismic studies over some of these granite bodies, for example in the Lake District in northern England,[29] where you set off explosions or pound the earth's surface and you record the passage of the sound waves, and the sound waves of course bump off – bounce off – layers, they've actually been able to show that instead of the granite at the surface now going down a mile or more into the earth's crust below, they've actually found that the granite has been made up of thin sheets and this is being reinforced with studies in the Sierra Nevada of central California where they've found outcrops showing the sheet-

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28 See, for example: N. Petford, J. D. Clemens, Granites are not diapiric! *Geology Today* 16:180-184, 2000. A. R. Cruden, On the emplacement of tabular granites. *Journal of the Geological Society of London* 155:853-862, 1998. K. J. W. McCaffrey, N. Petford, Are granitic intrusions scale invariant? *Journal of the Geological Society of London* 154:1-4, 1997. D. H. W. Hutton, Granite sheeted complexes: evidence for the dyking ascent mechanism. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 83:377-382, 1992. L. Améglio, J. L. Vigneresse, Geophysical imaging of the shape of granitic intrusions at depth: a review, pp.39-54 in: A. Castro, C. Fernández, J. L. Vigneresse (eds.), *Understanding Granites: Integrating New and Classical Techniques*, Geological Society of London Special Publication 168. L. Améglio, J. L. Vigneresse, J. L. Bouchez, Granite pluton geometry and emplacement mode inferred from combined fabric and gravity data, pp.199-214 in: J. L. Bouchez, D. H. W. Hutton, W. E. Stephens (eds.), *Granite: From Segregation of Melt to Emplacement Fabrics*, Kluwer Academic Publishers, Dordrecht. M. Haederle, M. P. Atherton, Shape and intrusion style of the Coastal Batholith, Peru. *Tectonophysics* 345:17-28, 2002. J. Grocott, A. A. Garde, B. Chadwick, A. R. Cruden, C. Swager, Emplacement of rapakivi granite and syenite by floor depression and roof uplift in the Palaeoproterozoic Ketilidian orogen, South Greenland. *Journal of the Geological Society of London* 156:15-24, 1999. B. Scaillet, A. Pêcher, P. Rochette, M. Champenois, The Gangotri granite (Garhwal Himalaya): laccolithic emplacement in an extending collisional belt. *Journal of Geophysical Research – Solid Earth* 100B:585-607, 1995. J. J. Norton, J. A. Redden, Relations of zoned pegmatites to other pegmatites, granite, and metamorphic rocks in the southern Black Hills, South Dakota. *American Mineralogist* 75:631-655, 1990. J. Wilson, E. C. Ferré, P. Lespinasse, Repeated tabular injection of high-level alkaline granites in the eastern Bushveld, South Africa. *Journal of the Geological Society of London* 157:1077-1088, 2000.

29 D. J. Evans, W. J. Rowley, R. A. Chadwick, D. Millward, Seismic reflections from within the Lake District batholith, Cumbria, northern England. *Journal of the Geological Society of London* 150:1043-1046, 1993. D. J. Evans, W. J. Rowley, R. A. Chadwick, G. S. Kimbell, D. Millward, Seismic reflection data and the internal structure of the Lake District batholith, Cumbria, northern England. *Proceedings of the Yorkshire Geological Society* 50:11-24, 1994.

like structure of the granite bodies at the earth's surface.[30]

The circulating waters that helped to cool the magma also played a role in bringing the granite rapidly to the earth's surface. The hot magma would have caused the surrounding groundwater to turn into steam, resulting in violent explosions.[31] These steam explosions would have broken up the rocks surrounding the granite body and accelerated their erosion and removal. In this way, a granite body a couple of miles below the ground could be rapidly brought to the surface – just as we see today in places like Dartmoor and Exmoor.

Research still continues, but there is now little reason to think that more than a few thousand years is required for the emplacement and cooling of even the largest bodies of granite.[32]

While granite magmas are emplaced deep underground, other magmas are known to reach the earth's surface where they are erupted as lava flows from volcanoes and fissures. Volcanic eruptions take place today in geologically active regions of the world like Iceland, which sits on the boundary between two of the earth's grinding tectonic plates. But even modern eruptions like these would have been dwarfed by some of the catastrophic eruptions known to have taken place in the earth's past.[33]

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30 D. S. Coleman, A. F. Glazner, J. S. Miller, K. J. Bradford, T. P. Frost, J. L. Joye, C. A. Bachl, Exposure of a Late Cretaceous layered mafic-felsic magma system in the central Sierra Nevada batholith, California. *Contributions to Mineralogy and Petrology* 120:129-136, 1995.

31 This process is known as phreatic stripping. See L. J. P. Muffler, D. E. White, A. H. Truesdell, Hydrothermal explosion craters in Yellowstone National Park. *Geological Society of America Bulletin* 82:723-740, 1971. R. J. Wold, M. A. Mayhew, R. B. Smith, Bathymetric and geophysical evidence for a hydrothermal explosion crater in Mary Bay, Yellowstone Lake, Wyoming. *Journal of Geophysical Research – Solid Earth* 82B:3733-3738, 1977.

32 Severe time constraints on granite formation are imposed by the processes involved in the formation of parentless polonium radiohalos observed to occur abundantly in granitic rocks. See A. A. Snelling, J. R. Baumgardner, L. H. Vardiman, Abundant Po radiohalos in Phanerozoic granites and timescale implications for their formation. *Eos, Transactions of the American Geophysical Union* (Fall Meeting Supplement, Abstract V32C-1046) 84(46):F1570, 2003.

33 The 1783 Lakagígar eruption in Iceland, possibly the largest since the end of the ice age, generated around 12.3 km^3 of basalt – two orders of magnitude smaller than many ancient continental flood basalts. See S. Thorarinsson, The Lakagígar eruption of 1783. *Bulletin Volcanologique* 33:910-929, 1970.

7. OUTPOURINGS OF LAVA

Our journey continues as we travel northwards along the coast of Ireland to a place where one of these massive outpourings of lava occurred. Our destination is the beautiful coastline of County Antrim. Antrim might seem an unlikely place to study volcanic catastrophes, but as we shall see its peacefulness and tranquillity today is deceptive.

About half a million people come to the Antrim coastline every year to visit the Giant's Causeway. According to local legend, the causeway was built by the giant Finn MacCool. And, sure enough, the strange columns look as though they might have been carved and placed there by a giant. But in fact the causeway is the product of a series of extensive lava flows that poured out across this landscape in the distant past.[34] As the lavas cooled, they began to shrink and crack, leaving the distinctive hexagonal columns that we see today, some of them over 300 feet high.[35]

In fact, these lava flows are just part of a much larger volcanic province that once covered much of the North Atlantic.[36] Similar lava flows can be found today in the western isles of Scotland, as well as the Faroe Islands, Greenland and Rockall. Together these lava flows amount to over one and a half million cubic kilometres of erupted lava – and they all formed at about the same time.

Similar volcanic provinces are known from other parts of the world and the speed with which they formed is astonishing. In some cases, individual

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34 J. Preston, Eruptive volcanism, pp.351-368 in: D. S. Sutherland (ed.), *Igneous Rocks of the British Isles*, John Wiley and Sons, Chichester, 1982.

35 Basaltic Volcanism Study Project, *Basaltic Volcanism on the Terrestrial Planets*, Pergamon Press, Oxford, 1981, p.89. P. Lyle, J. Preston, Geochemistry and volcanology of the Tertiary basalts of the Giant's Causeway area, Northern Ireland. *Journal of the Geological Society of London* 150:109-120, 1993.

36 A. P. Dickin, The North Atlantic Tertiary Province, pp.111-149 in: J. D. Macdougall (ed.), *Continental Flood Basalts*, Kluwer Academic Publishers, Dordrecht, 1988.

lava flows travelled hundreds of kilometres in just a matter of days.[37] Eruption followed eruption, generating stacks of lava flows extremely quickly. These ancient outpourings were so massive and erupted so suddenly that they have become known as 'flood basalts'. It is difficult for us to imagine what such eruptions must have been like. They were many times larger than any known historic eruption and they leave us wondering how representative of the past the present really is.[38]

8. GLACIAL MEGAFLOODS

Even the formation of landscapes, an area of geology long dominated by uniformitarian thinking, has had to be reconsidered. Geologists have tended to view landscape formation in terms of processes we can see going on around us – like the slow and steady wearing down of the land by streams and rivers. But few landforms seem to be the product of processes that are currently acting.[39] Most are relict features that were formed by processes more energetic than those going on today.[40]

For example, evidence of the catastrophic flooding associated with the rapid melting of the ice sheets at the end of the ice age can be seen in landscapes

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[37] H. R. Shaw, D. A. Swanson, Eruption and flow rates of flood basalts, pp.271-299 in: E. H. Gilmour, D. Stradling (eds.), *Proceedings of the Second Columbia River Basalt Symposium*, Eastern Washington State College Press, Cheney, Washington, 1970. D. A. Swanson, T. L. Wright, R. T. Helz, Linear vent systems and estimated rates of magma production and eruption for the Yakima Basalt on the Columbia Plateau. *American Journal of Science* 275:877-905, 1975. S. P. Reidel, T. L. Tolan, Eruption and emplacement of flood basalt: an example from the large-volume Teepee Butte Member, Columbia River Basalt Group. *Geological Society of America Bulletin* 104:1650-1671, 1992. A. M. Ho, K. V. Cashman, Temperature constraints on the Ginkgo flow of the Columbia River Basalt Group. *Geology* 25:403-406, 1997.

[38] Ager, *The New Catastrophism*, pp.153-163.

[39] A. L. Bloom, Teaching about relict, no-analog landscapes. *Geomorphology* 47:303-311, 2002.

[40] For example, 'underfit streams', which are much smaller than the valleys in which they are contained, suggest much larger discharge volumes in the past. See G. H. Dury, *Theoretical implications of underfit streams*, United States Geological Survey Professional Paper 452-C, 1965.

all across the northern hemisphere.[41] Recent sonar surveys of the floor of the English Channel – the narrow seaway between England and France – revealed a stunning network of large valleys which are thought to have been eroded by the catastrophic drainage of a large glacial lake.[42] Large-scale discharges of glacial meltwater may even have been responsible for the permanent separation of Britain from mainland Europe.[43]

Catastrophic events have now become an acceptable – even necessary – part of the modern geological worldview. Most geologists still maintain, however, that the history of the earth has lasted billions of years. They regard the catastrophes as rare occurrences separated by long periods of time when no sediments were being laid down or when erosion was occurring. In one of his books, Derek Ager summed this up by saying that 'the history of any one part of the earth, like the life of a soldier, consists of long periods of boredom and short periods of terror.'[44]

If this view of earth history is correct, then the geological record consists mainly of gaps with only occasional pulses of sedimentation. Long periods of time must have passed between the laying down of the preserved sedimentary layers.

But is that what the evidence suggests? We've already seen that many individual rock layers were formed quickly – but quite often the next layer

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41 See, for example: J. H. Bretz, The Lake Missoula floods and the Channeled Scabland. *Journal of Geology* 77:505-543, 1969. H. E. Malde, *The catastrophic Late Pleistocene Bonneville Flood in the Snake River Plain, Idaho*, United States Geological Survey Professional Paper 596, 1968. A. E. Kehew, Catastrophic flood hypothesis for the origin of the Souris spillway, Saskatchewan and North Dakota. *Geological Society of America Bulletin* 93:1051-1058, 1982. J. A. Clayton, J. C. Knox, Catastrophic flooding from Glacial Lake Wisconsin. *Geomorphology* 93:384-397, 2008. C. Lopes, A. C. Mix, Pleistocene megafloods in the northeast Pacific. *Geology* 37:79-82, 2009. A. N. Rudoy, V. R. Baker, Sedimentary effects of cataclysmic late Pleistocene glacial outburst flooding, Altay Mountains, Siberia. *Sedimentary Geology* 85:53-62, 1993. Furthermore, the first glacial megafloods to be documented in the southern hemisphere have now been reported in S. A. Austin, J. A. Strelin, Megafloods on the Santa Cruz River, southern Argentina, *Geological Society of America Abstracts with Programs* 43:249, 2011.

42 S. Gupta, J. S. Collier, A. Palmer-Felgate, G. Potter, Catastrophic flooding origin of shelf valley systems in the English Channel. *Nature* 448:342-345, 2007.

43 P. Gibbard, Europe cut adrift. *Nature* 448:259-260, 2007.

44 Ager, *The Nature of the Stratigraphical Record*, pp.106-107.

seems to have been added quickly too. We can illustrate this by taking a look at the rock layers exposed here in the Peak District of Derbyshire.

9. MAM TOR

This is Mam Tor – a popular place with walkers as well as geologists. Exposed in the east face of Mam Tor is a thick series of sandstone and mudstone layers – and they tell a fascinating story of rapid sedimentation uninterrupted by long time gaps.

PAUL GARNER: The whole cliff face here at Mam Tor is about 100 metres high and because each of these sandstone layers is on average about one metre thick[45] that means there are about 100 of them in this cliff face. Now if the conventional geological dates are correct this whole cliff face must represent something like one million years of geological time. And because there are 100 of these layers in this cliff, that means that these must represent something like ten thousand years of geological time for each layer, but what does the evidence actually tell us?

Well here we have one of these sandstone layers at Mam Tor. On the eighteenth of November in 1929 a remarkable event occurred. An earthquake, the Grand Banks earthquake struck the eastern seaboard of Canada and the maritime provinces there,[46] and caused a mass of sediment that was in the shallow water on the continental shelf to slump into deeper water. Now as that flow travelled it snapped transatlantic cables[47] and so we know exactly how far that flow had travelled and it turns out that in less than 13 hours that slurry of sediment had travelled almost 500 miles and it deposited a layer of sediment about two to three feet thick that covered about one hundred thousand square miles of ocean floor. Geologists call that kind of current a turbidity current and the sediment

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45 The layers actually vary between 0.9 and 2.4 m thick, so an average thickness of 1 m is conservative. See J. C. Cripps, C. C. Hird, A guide to the landslide at Mam Tor. *Geoscientist* 2(3):22-27, 1992.

46 W. W. Doxsee, The Grand Banks earthquake of November 18, 1929. *Publications of the Dominion Observatory, Canada Department of Mines and Technical Surveys, Ottawa, Ontario* 7(7):323-335, 1948.

47 B. C. Heezen, M. Ewing, Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. *American Journal of Science* 250:849-873, 1952.

that it leaves behind is called a turbidite. Now the significance of this is that these sandstones at Mam Tor are turbidites;[48] *these were laid down by that same kind of catastrophic underwater flow, so each of these sandstone layers represents just a few minutes of geological activity.*

Well if the geological time is not represented by the sandstones perhaps it's represented by these shale layers – the mudstones that you find in between the sandstones – and that's what most geologists I think would assume: that this was mud which was laid down in quiet conditions in between each of these catastrophic turbidite events. The problem is that if this mud formed the sea floor for an extended period of time then there ought to have been time for animals, marine animals to colonize this sea floor and we really don't see evidence of a normal sea floor community in here.[49] *There are fossil shells, but if there were animals that were living here for any length of time then they ought to have burrowed into this mud, into the sediment and disrupted the mud layers and yet if you look at these mud layers they're very well preserved and that suggests that there wasn't a great deal of time involved in the laying down of these mudstone layers either.*[50]

So here's the problem: Mam Tor is meant to represent something like one million years of geological time but we've seen that the time is not represented by the sandstone layers which were laid down in just a few minutes each and it doesn't look as if much time is represented by the mudstone layers either so the question is, where is the geological time at Mam Tor?

The available evidence suggests that the cliff face at Mam Tor represents a short time interval – not one million years. The same reasoning can be applied to other parts of the geological record and it leads to the same conclusion – larger and larger amounts of time must be accounted for in fewer and fewer layers. Convincing evidence for long ages of geological time is difficult to find.

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48 J. R. L. Allen, The Mam Tor Sandstones: a "turbidite" facies of the Namurian deltas of Derbyshire, England. *Journal of Sedimentary Petrology* 30:193-208, 1960.

49 The data suggests the availability of nutrients and oxygenated bottom waters. See B. K. Holdsworth, A preliminary study of the palaeontology and palaeoenvironment of some Namurian limestone 'bullions'. *Mercian Geologist* 1:315-337, 1966.

50 See also D. J. W. Piper, Turbidite origin of some laminated mudstones. *Geological Magazine* 109:115-126, 1972.

10. DATING THE ROCKS

Today the beautiful scenery of the British Isles seems far removed from the catastrophic events that shaped it in the past. The tranquillity of these cool, running streams and flowing waterfalls in County Antrim provide a wonderful escape for local people and visitors to relax and pass the time.

But as we contemplate the slow processes that can be observed going on today, we're faced with important questions about the dates that geologists apply to the rock layers. Haven't sophisticated dating methods been developed that demonstrate conclusively that the earth's rock layers were deposited over vast ages?

The most widely used geological 'clocks' are based on the decay of naturally occurring radioactive isotopes in rocks and minerals like these.[51] An unstable parent isotope decays into a stable daughter isotope. This decay process is used to estimate when the rock or mineral sample in question was formed.

However, in all of these methods it is necessary to make some assumptions – in particular about the starting conditions, the rate at which the decay process occurred in the past and the history of the sample being dated.[52]

This candle helps to illustrate the point. Imagine we wanted to know how much time had passed since the candle started burning. We could work it out if we knew certain things – how long the candle was originally, how fast it had been burning and whether or not it had been tampered with.

Likewise, in order to date a rock we need to know how much of the daughter isotope the sample contained in the beginning, how fast the parent isotope had been decaying in the past, and whether the amounts of parent and daughter had been altered by any process other than radioactive decay.

We can verify our assumptions provided a human observer is present. But when dealing with rocks that formed in the past we usually have no way of knowing whether our assumptions are correct. In fact, many lava flows formed

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51 Dalrymple, *The Age of the Earth*, pp.79-124.

52 G. Faure, T. M. Mensing, *Isotopes: Principles and Applications*, Third Ed., John Wiley and Sons, New Jersey, 2005, pp.57-60.

during recent volcanic eruptions give very old dates by radioactive methods[53] – revealing problems with the standard assumptions.[54]

One of the best known dating methods uses the radioactive isotope, carbon-14. Carbon-14 is commonly used to date samples of wood, shell or bone. However, carbon-14 decays very quickly compared to some radioactive isotopes – so quickly, in fact, that any samples that were truly millions of years old would not contain any carbon-14 because it would long since have decayed away.[55]

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53 G. B. Dalrymple, $^{40}Ar/^{36}Ar$ analyses of historic lava flows. *Earth and Planetary Science Letters* 6:47-55, 1969. D. Krummenacher, Isotopic composition of argon in modern surface volcanic rocks. *Earth and Planetary Science Letters* 8:109-117, 1970. I. McDougall, H. A. Polach, J. J. Stipp, Excess radiogenic argon in young subaerial basalts from the Auckland volcanic field, New Zealand. *Geochimica et Cosmochimica Acta* 33:1485-1520, 1969. D. E. Fisher, Excess rare gases in a subaerial basalt from Nigeria. *Nature* 232:60-61, 1971. R. L. Armstrong, K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics* 21:685-698, 1978. R. P. Esser, W. C. McIntosh, M. T. Heizler, P. R. Kyle, Excess argon in melt inclusions in zero-age anorthoclase feldspar from Mt. Erebus, Antarctica, as revealed by the $^{40}Ar/^{39}Ar$ method. *Geochimica et Cosmochimica Acta* 61:3789-3801, 1997. C. S. Noble, J. J. Naughton, Deep-ocean basalts: inert gas content and uncertainties in age dating. *Science* 162:265-267, 1968. G. B. Dalrymple, J. G. Moore, Argon-40: excess in submarine pillow basalts from Kilauea Volcano, Hawaii. *Science* 161:1132-1135, 1968. J. G. Funkhouser, D. E. Fisher, E. Bonatti, Excess argon in deep-sea rocks. *Earth and Planetary Science Letters* 5:95-100, 1968. J. G. Funkhouser, I. L. Barnes, J. J. Naughton, Problems in the dating of volcanic rocks by the potassium-argon method. *Bulletin Volcanologique* 29:709-717, 1966. D. E. Fisher, U/He ages as indicators of excess argon in deep sea basalts. *Earth and Planetary Science Letters* 14:255-258, 1972. J. Dymond, Excess argon in submarine basalt pillows. *Geological Society of America Bulletin* 81:1229-1232, 1970.

54 Another difficulty concerns the gas helium, which is a by-product of the radioactive decay of uranium. Some years ago, large amounts of helium were discovered in rocks thought to be hundreds of millions of years old. But this puzzled geologists, because helium is very mobile and experiments have shown that it ought to have leaked out of these rocks rather rapidly. One solution to this puzzle is that large amounts of radioactive decay may have taken place in the relatively recent past, say within the last few thousand years. This raises the intriguing possibility that radioactive decay rates have not always been constant. See R. V. Gentry, G. L. Glish, E. H. McBay, Differential helium retention in zircons: implications for nuclear waste containment. *Geophysical Research Letters* 9:1129-1130, 1982. D. R. Humphreys, J. R. Baumgardner, A. A. Snelling, S. A. Austin, Recently measured helium diffusion rate for zircon suggests inconsistency with U-Pb age for Fenton Hill granodiorite. *Eos, Transactions of the American Geophysical Union* 84(46):F1570, Fall Meeting Supplement Abstract V32C-1047, 2003.

55 Carbon-14 decays to nitrogen-14 with a half-life of 5,730 years. At this rate, any carbon-containing materials would have carbon-14 levels below detection limits after 50,000-95,000 years. For example, see S. Bowman, *Interpreting the Past: Radiocarbon Dating*, British Museum Publications, London, 1990.

Nevertheless, measurable amounts of carbon-14 are routinely found in samples of fossil materials, including coal and oil, causing us to question whether these samples are anything like as old as most geologists assume.[56]

Some have tried to avoid this conclusion by claiming that the carbon-14 must be due to contamination, perhaps when the samples were handled and processed in the laboratory. However, the technicians in dating laboratories meticulously clean such samples with hot strong acids and other treatments to remove contamination – and yet the samples still contain measurable amounts of carbon-14.[57]

Other processes point to much younger ages than most radioactive dating methods.

11. MISSING SALT AND SEA FLOOR SEDIMENT

Consider, for example, the accumulation of salt in the oceans. Rivers and other sources transport more than 450 million tons of salt into the oceans every year.[58] Only a quarter of this salt leaves the oceans and the rest simply builds up over time.[59]

Even with the assumption that the sea had no salt to begin with, the present amount could have accumulated in less than 42 million years – but the oceans are presumed to be over three and a half billion years old.

Of course, the amount of salt entering and leaving the ocean may have been different in the past. However, even the most generous calculations have been

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56 J. R. Baumgardner, D. R. Humphreys, A. A. Snelling, S. A. Austin, The enigma of the ubiquity of ^{14}C in organic samples older than 100 ka. *Eos, Transactions of the American Geophysical Union* 84(46):F1570, Fall Meeting Supplement Abstract V32C-1045, 2003.

57 For example, see M.-J. Nadeau, P. M. Grootes, A. Voelker, F. Bruhn, A. Duhr, A. Oriwall, Carbonate ^{14}C background: does it have multiple personalities? *Radiocarbon* 43(2A):169-176, 2001.

58 For example, see M. Meybeck, Global chemical weathering of surficial rocks estimated from river dissolved loads. *American Journal of Science* 287:401-428, 1987.

59 See Table 5-14 in H. D. Holland, *The Chemistry of the Atmosphere and Oceans*, John Wiley, New York, 1978, pp.234-235.

unable to explain why the oceans are not much saltier than we observe today.

Another well-studied process is the accumulation of sediment on the ocean floor. Most of this sediment is transported into the ocean by rivers. Estimates of how much sediment is carried into the oceans vary considerably but a conservative estimate is about 20 billion tons per year.[60]

At this rate the oceans could have been filled with sediment 19 times over in their presumed long history. In fact, the sediment on the ocean floor averages less than 400 metres thick,[61] causing us to wonder why so much of the expected sediment is missing. Perhaps some of it was recycled by tectonic processes but it's difficult to see how that could resolve the discrepancy completely.[62]

12. ERODING CONTINENTS

The rate at which the land is being worn down is also a problem for conventional dating. Geologists estimate that a continent like North America is being eroded by water and wind at a rate of about 60 millimetres every 1,000 years.[63] That means about half a centimetre of material will be eroded from this rocky landscape during an average human lifetime.

Measured in this way the erosion rate seems very slow, but it suggests that North America could have been worn down to sea level in only 10 million years. According to the conventional timescale, the continents have been around for over three and a half billion years, and in that period the continents could have been completely levelled more than 340 times.

Rates of erosion are even greater in areas of high topographic relief. High

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60 J. D. Milliman, J. P. M. Syvitski, Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *Journal of Geology* 100:525-544, 1992.

61 W. W. Hay, J. L. Sloan, C. N. Wold, Mass/age distribution and composition of sediments on the ocean floor and the global rate of sediment subduction. *Journal of Geophysical Research* 93(B12):14933-14940, 1988.

62 Hay, Sloan, Wold, Mass/age distribution.

63 S. Judson, D. F. Ritter, Rates of regional denudation in the United States. *Journal of Geophysical Research* 69:3395-3401, 1964.

mountain ranges such as the Himalayas are being eroded at a rate of about 1,000 millimetres every 1,000 years.[64]

With such high erosion rates, it is reasonable to ask how mountain ranges believed to be hundreds of millions of years old could have survived to the present-day. Even with a very low erosion rate no continent should have remained above sea level after a few hundred million years.

13. FOSSIL GRAVEYARDS

The fossil record also points to short timescales for the build up of sediments. Fossils are the remains or traces of animals and plants that lived in the past. The remains of most organisms will be lost to decay unless they are buried quickly. In modern environments, sediments are typically laid down too slowly to preserve fossils, but the abundance of fossils in older sediments suggests that they must have been laid down rapidly.[65]

The Dorset coastline in the southern part of England is a favourite haunt of fossil hunters and collectors. The cliffs here are composed of alternating layers of mudstone and limestone which were laid down in a marine environment. Exposed on the rock ledges are hundreds of fossils of ancient sea creatures, including these coiled shells known as ammonites.

Ammonites were advanced predators in the ancient oceans, somewhat similar to the modern nautilus. The fossils preserved on the Dorset coast record the death and burial of large numbers of animals, perhaps in some kind of mass mortality event. Geologists sometimes refer to such accumulations as fossil graveyards.

Another type of fossil graveyard even helps to fuel our economy. Coal is the result of the accumulation, compaction and alteration of plant remains.

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[64] H. W. Menard, Some rates of regional erosion. *Journal of Geology* 69:154-161, 1961.

[65] Taphonomy, the study of the fate of organisms after they die, has revealed several factors that promote fossil preservation. They include rapid burial, possession of hard parts, burial in fine-grained sediments (which helps to preserve detail) and a low oxygen environment. The most important of these is rapid burial.

These thick coal seams are composed of vast amounts of buried vegetation – and what's more, they can often be traced over vast distances. Some individual seams cover hundreds or even thousands of square miles.[66] The Coal Measures as a whole are known to extend from the United States, across Europe and into the Donetz Basin north of the Caspian Sea.[67]

The fine-scale structure of many coal layers reveals evidence of the orientation and sorting of particles, indicating the transportation of plant material by water – not the slow burial of vegetation in peat swamps.[68]

Laboratory experiments have even shown that the alteration of plant material to form coal does not require millions of years, but can be achieved rapidly by a short heating process.[69]

Other fossils also indicate rapid processes of fossilization. Consider this

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66 Geological correlation suggests that the Broken Arrow coal (Oklahoma), the Croweburg coal (Missouri), the Whitebrest coal (Iowa), the Colchester No. 2 coal (Illinois), Coal IIIa (Indiana), the Schultztown coal (western Kentucky), the Princess No. 6 coal (eastern Kentucky) and the Lower Kittanning coal (Ohio and Pennsylvania) form a single vast coal seam exceeding one hundred thousand square miles in area.

67 'Whatever the vertical and lateral changes in the Coal Measures, we still have to account for a general facies development in late Carboniferous times that extends in essentially the same form all the way from Texas to the Donetz coal basin, north of the Caspian Sea in the U.S.S.R. This amounts to some 170º of longitude, and closing up the Atlantic by a mere 40º does not really help all that much in explaining this remarkable phenomenon. One looks in vain for a similar geographical situation at the present day.' Ager, *Nature of the Stratigraphical Record*, p.7.

68 A. D. Cohen, An allochthonous peat deposit from southern Florida. *Geological Society of America Bulletin* 81:2477-2482, 1970.

69 G. R. Hill, Some aspects of coal research. *Chemical Technology*:292-297, May 1972. R. Hayatsu, R. L. McBeth, R. G. Scott, R. E. Botto, R. E. Winans, Artificial coalification study: preparation and characterization of synthetic macerals. *Organic Geochemistry* 6:463-471, 1984. W. H. Orem, S. G. Neuzil, H. E. Lerch, C. B. Cecil, Experimental early-stage coalification of a peat sample and a peatified wood sample from Indonesia. *Organic Geochemistry* 24:111-125, 1996. A. D. Cohen, A. M. Bailey, Petrographic changes induced by artificial coalification of peat: comparison of two planar facies (Rhizophora and Cladium) from the Everglades-mangrove complex of Florida and a domed facies (Cyrilla) from the Okefenokee Swamp of Georgia. *International Journal of Coal Geology* 34:163-194, 1997. S. Yao, C. Xue, W. Hu, J. Cao, C. Zhang, A comparative study of experimental maturation of peat, brown coal and subbituminous coal: implications for coalification. *International Journal of Coal Geology* 66:108-118, 2006. See also A. Davis, W. Spackman, The role of the cellulosic and lignitic components of wood in artificial coalification. *Fuel* 43:215-224, 1964.

petrified log, in which the woody tissues have been replaced by the mineral silica.

Under the right chemical conditions wood can be readily petrified by silica-rich waters, even at normal temperatures and pressures.[70] In fact, the process is now so well understood that scientists can rapidly make petrified wood in their laboratories.[71]

In 2004, a team of scientists discovered that wood that had naturally fallen into a small lake in a volcanic crater in central Japan had become petrified with silica. Hot, mineral-rich fluids had rapidly soaked into the pore spaces in the wood. In experiments the team found that only seven years were needed for this extraordinary process to take place.[72]

We've already noted that fossils usually require rapid burial in order to be preserved. Even hard parts such as shells will eventually break down or dissolve in sea water,[73] and fragile shells will break down more quickly than strong shells. If the fossil record formed slowly, with individual rock layers taking hundreds or thousands of years to accumulate, we would expect fragile shell material to be relatively uncommon. Most of the shells we find

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70 A. C. Sigleo, Organic geochemistry of silicified wood, Petrified Forest National Park, Arizona. *Geochimica et Cosmochimica Acta* 42:1397-1405, 1978.

71 P. McCafferty, Instant petrified wood? *Popular Science*:56-57, October 1992. H. Hicks, *Mineralized sodium silicate solutions for artificial petrification of wood*. United States Patent Number 4612050, 16 September 1986. R. W Drum, Silicification of *Betula* woody tissue *in vitro*. *Science* 161:175-176, 1968. R. F. Leo, E. S. Barghoorn, Silicification of wood. *Harvard University Botanical Museum Leaflets* 25:1-47, 1976. R. C. Merrill, R. W. Spencer, Sorption of sodium silicates and silicate sols by cellulose fibers. *Industrial and Engineering Chemistry* 42:744-747, 1950.

72 H. Akahane, T. Furuno, H. Miyajima, T. Yoshikawa, S. Yamamoto, Rapid wood silicification in hot spring water: an explanation of silicification of wood during the Earth's history. *Sedimentary Geology* 169:219-228, 2004.

73 M. M. R. Best, S. M. Kidwell, Bivalve taphonomy in tropical mixed siliciclastic-carbonate settings. I. Environmental variation in shell condition. *Paleobiology* 26:80-102, 2000. S. M. Kidwell, M. M. R. Best, D. S. Kaufman, Taphonomic trade-offs in tropical marine death assemblages: differential time averaging, shell loss, and probable bias in siliciclastic vs. carbonate facies. *Geology* 33:729-732, 2005. S. M. Kidwell, K. W. Flessa, The quality of the fossil record: populations, species, and communities. *Annual Review of Earth and Planetary Science* 24:433-464, 1996. T. D. Olszewski, Modeling the influence of taphonomic destruction, reworking, and burial on time-averaging in fossil accumulations. *Palaios* 19:39-50, 2004.

in the fossil record should be thick and durable.

However, studies have shown that small, thin-shelled fossils are just as likely to be preserved in the fossil record as large, thick-shelled fossils.[74] This is evidence that the sediments in which they are buried were most probably formed catastrophically. Rapidly accumulating sediments would have indiscriminately buried both fragile and durable material together.

14. THE MUDSTONE REVOLUTION

Of course, not all the rocks speak so eloquently of catastrophism and short timescales. Some deposits appear to have required longer periods of time or to have been deposited under calm conditions.

Mudstones are among the most difficult rocks to explain by catastrophic processes. As in the case of the mudstone layers at Mam Tor, they are usually thought to have been laid down by the very slow settling of fine particles of clay in quiet water. Under turbulent conditions, mud gets stirred up and is only re-deposited when tranquil conditions are resumed. Even then, the mud particles take a long time to settle out into layers. For this reason, it's been assumed that layers of mudstone, like these ones in Kimmeridge Bay in Dorset, must have taken thousands or even millions of years to be laid down. Furthermore, mudstones are very common rocks,[75] comprising up to three-quarters of the entire sedimentary record, so this is a very significant problem for catastrophism.

Once again, however, conventional thinking about mudstones is being challenged by recent research. Geologists have known for some time that fine mud particles have a tendency to clump together into fluffy or lumpy flakes about the size of sand grains. This process causes the mud to settle out of suspension much more rapidly than it would as individual mud particles.

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74 A. K. Behrensmeyer, F. T. Fürsich, R. A. Gastaldo, S. M. Kidwell, M. A. Kosnik, M. Kowalewski, R. E. Plotnick, R. R. Rogers, J. Alroy, Are the most durable shelly taxa also the most common in the marine fossil record? *Paleobiology* 31:607-623, 2005.

75 'Fine-grained sedimentary rocks such as shales or mudstones – with an average grain size of less than 62.5 μm – are by far the most common sedimentary rocks preserved close to Earth's surface.' J. H. S. Macquaker, K. M. Bohacs, On the accumulation of mud. *Science* 318:1734-1735, 2007. Quotation on p.1734.

Laboratory experiments have now shown how this remarkable process allows mud to be transported and deposited quickly by flowing water currents.[76] These experiments are causing many geologists to reconsider the conditions under which mudstones are thought to have been deposited.[77] Mudstone layers like these in Dorset were probably formed rapidly in stormy conditions and not slowly in quiet water as many geologists have assumed.[78]

15. ALGAL BLOOMS AND CHALK DEPOSITION

Another type of sediment that seems difficult to explain by catastrophic deposition is chalk. Chalk is a soft and often crumbly limestone composed of the remains of billions of tiny marine creatures.[79] Under a high-powered microscope, the countless tiny particles that make up the chalk can be clearly seen. These tiny particles once made up the shell-like structures of microscopic algae. Similar algae can be found living in the surface waters of our oceans today.[80]

Over time, these shell-like structures typically fall apart to produce fragments which sink slowly through the water and build up as a kind of 'chalky ooze' on the sea floor. Most geologists think that the great thicknesses of chalk, like these seen on the south coast of England, accumulated very slowly in just this

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76 J. Schieber, J. Southard, K. Thaisen, Accretion of mudstone beds from migrating floccule ripples. *Science* 318:1760-1763, 2007. J. Schieber, J. B. Southard, Bedload transport of mud by floccule ripples – direct observation of ripple migration processes and their implications. *Geology* 37:483-486, 2009.

77 'The results call for critical reappraisal of all mudstones previously interpreted as having been continuously deposited under still waters ... mud accumulation can occur in higher-energy conditions than most researchers had assumed.' Macquaker and Bohacs, On the accumulation of mud, pp.1734, 1735.

78 P. B. Wignall, Sedimentary dynamics of the Kimmeridge Clay: tempests and earthquakes. *Journal of the Geological Society of London* 146:273-284, 1989. See also E. B. Bailey, J. Weir, Submarine faulting in Kimmeridgian times: east Sutherland. *Transactions of the Royal Society of Edinburgh* 57:429-466, 1932-1933.

79 J. M. Hancock, The petrology of the Chalk. *Proceedings of the Geologists' Association* 86:499-535, 1975.

80 E. Paasche, Biology and physiology of coccolithophorids. *Annual Review of Microbiology* 22:71-86, 1968. M. Black, Coccoliths. *Endeavour* 24:131-137, 1965.

fashion. Based on current rates of accumulation, it would take about 100,000 years for three feet of chalk to build up. If similar rates applied in the past, very long periods of time would be required to form the hundreds of feet of chalk that we see in the geological record.

But there are some problems with the standard theory of chalk formation. For example, modern chalky sediments tend to build up in the very deep ocean – but there's abundant evidence that the ancient chalk was laid down in shallow water.[81] Furthermore, the ancient chalk is very pure. It's composed almost entirely of shelly material with very little mixture of other sediments.[82] If it was laid down slowly over millions of years, it's hard to see how mud or sand could have been prevented from being washed in and mixed with it. These facts cause us to question whether the slow accumulation of chalk ooze in the deep ocean is really a good model for understanding how the chalk beds of the geological record were laid down.

Could large amounts of chalk have built up quickly in the past? Given suitable conditions, the answer seems to be yes. Recent studies have shown that the concentration of marine algae in sea water increases dramatically under the right conditions of turbulence, nutrients and temperature.[83] The chemistry of the sea water is also significant, with rapid population growth rates more likely when calcium concentrations are high.[84] Blooms of marine

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81 Modern-day deep sea oozes form at depths of up to 4,500-5,000 m. By contrast, the Upper Cretaceous Chalk probably built up in water 100-600 m deep. See Hancock, The petrology of the Chalk, pp.517-519.

82 'The problem of the Chalk today is not so much where the material came from, as how other material was kept out. The remarkably pure organic Chalk is almost completely without any trace of land-derived sediment.' D. V. Ager, *Introducing Geology: The Earth's Crust Considered as History*, Second Ed., Faber and Faber, London, 1975, p.174.

83 H. H. Seliger, J. H. Carpenter, M. Loftus, W. D. McElroy, Mechanisms for the accumulation of high concentrations of dinoflagellates in a bioluminescent bay. *Limnology and Oceanography* 15:234-245, 1970. W. B. Wilson, A. Collier, Preliminary notes on the culturing of *Gymnodinium brevis* Davis. *Science* 121:394-395, 1955. D. Ballantine, B. C. Abbott, Toxic marine flagellates; their occurrence and physiological effects on animals. *Journal of General Microbiology* 16:274-281, 1957. R. D. Pingree, P. M. Holligan, R. N. Head, Survival of dinoflagellate blooms in the western English Channel. *Nature* 265:266-269, 1977.

84 S. M. Stanley, J. B. Ries, L. A. Hardie, Seawater chemistry, coccolithophore population growth, and the origin of Cretaceous chalk. *Geology* 33:593-596, 2005. See also N. Meskhidze, W. L. Chameides, A. Nenes, Dust and pollution: a recipe for enhanced ocean fertilization? *Journal of Geophysical Research – Atmospheres* 110:D03301, 2005. F. Pearce, Extra iron makes blue deserts bloom. *New Scientist* 152(2051):4, 1996.

algae have been known to turn the oceans milky white and can be so massive that they are detectable from space. It is quite conceivable that intense blooms could have been generated during catastrophic events in earth history, resulting in the rapid production of large amounts of chalk. In fact rapid deposition would explain why the chalk layers in the geological record are so pure – there simply wasn't enough time for other sediments to get mixed in.

There is also growing evidence that the ancient chalk sea was far from calm and placid. Many of the fossils in the chalk must have been rapidly buried in order to account for their excellent preservation. The chalk is sometimes piled into great heaps and banks over 150 feet high, indicating the activity of strong currents.[85] And layers of volcanic ash within the chalk demonstrate that explosive volcanic eruptions were happening at the same time.[86] These thin clay layers in the chalk at Peacehaven, East Sussex, for example, have recently been shown by chemical analysis to be volcanic ash layers.[87] The chalk is an extraordinary rock formation which has no obvious parallel today.[88]

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85 W. J. Kennedy, P. Juignet, Carbonate banks and slump beds in the Upper Cretaceous (Upper Turonian-Santonian) of Haute Normandie, France. *Sedimentology* 21:1-42, 1974. R. N. Mortimore, B. Pomerol, Upper Cretaceous tectonic disruptions in a placid Chalk sequence in the Anglo-Paris Basin. *Journal of the Geological Society of London* 148:391-404, 1991. A. A. Ekdale, R. G. Bromley, E. Nygaard, Allochthonous chalk in northwestern Europe. *Geological Society of America Abstracts with Programs* 16:499, 1984.

86 D. S. Wray, A. S. Gale, The palaeoenvironment and stratigraphy of Late Cretaceous Chalks. *Proceedings of the Geologists' Association* 117:145-162, 2006. The Smoky Hill Chalk Member of the Niobrara Chalk (Upper Cretaceous) of western Kansas contains more than 100 bentonite seams. See D. E. Hattin, *Stratigraphy and depositional environment of the Smoky Hill Chalk Member, Niobrara Chalk (Upper Cretaceous) of the type area, western Kansas*, Kansas Geological Survey Bulletin 225, University of Kansas Publications, Lawrence, Kansas, 1982, pp.1-108.

87 Newhaven to Brighton in: Volume 23: British Upper Cretaceous Stratigraphy. Chapter 3: Southern Province, England. Site: Newhaven to Brighton (GCR ID: 216). http://www.thegcr.org.uk/Sites/GCR_v23_C03_Site0216.htm

88 'It is obvious that one will not find Cretaceous species of mollusc, foraminifera and coccolith-bearing algae forming sediment today anywhere on Earth. However, one would expect it to be possible to find examples of coccolith-dominated pelagic sediment forming at an intermediate depth, but no exact analogue of Cretaceous chalk can yet be quoted.' J. M. Hancock, The significance of Maurice Black's work on the Chalk, pp.86-97 in: C. V. Jeans, P. F. Rawson (eds.), *Andros Island, chalk and oceanic oozes*, Yorkshire Geological Society, Occasional Publication 5, 1980. Quotation on p.92. See also A. Hallam, *Facies Interpretation and the Stratigraphic Record*, W. H. Freeman and Company, Oxford, 1981, pp.114-118.

16. RETURN TO SICCAR POINT

It's now time to go back to where we began to ask whether James Hutton drew the right conclusions from the rocks that he studied. Was Hutton correct when he said that there was conclusive evidence of long geological timescales at Siccar Point?

JOHN WHITMORE: It's time to take a second look at Siccar Point and see some of the things that James Hutton seemed to have missed. First of all notice these greywackes.[89] The sandstones right here are very resistant to erosion and tend to stand out whereas the shales in the middle right here weather out very quickly and this is what modern coastal erosion does. Modern erosion differentially weathers the softer shales and the more resistant sandstones stand out. We don't see that underneath of the flat unconformity that was described by James Hutton – instead the shales and the sandstones are uniformly worn away, and we think that's evidence that this contact was made very quickly and not exposed for long periods of time as Hutton suggested.

What could have caused the hard and soft layers to be planed off equally? Slow and gradual erosion today always produces an uneven surface. But the evidence at Siccar Point suggests the kind of violent and sheet-like erosion associated with the run-off of water during a catastrophic event.

PAUL GARNER: One of the other things to notice here at Siccar Point is the nature of this breccia bed[90] which is directly above the unconformity surface, above the erosion surface, and if we take a close look at it we can see that it's made up of broken pieces of other rocks including the rocks that are found below the unconformity – the Silurian greywackes, the shales and sandstones – and when we take a look at these pieces of broken rock we find that there's a whole range of sizes from very small fragments to much larger fragments. We also find that the fragments are very angular, they have jagged sharp edges and what this tells us is that this deposit did not take very long to be laid down. If these fragments had been rolling around on an ancient surface for a long time they would have become sorted and graded by size and shape and the edges

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89 Greywackes are sedimentary rocks made of poorly sorted sand grains.

90 Breccias are sedimentary rocks made of angular pebbles and boulders.

would have become smoothed and rounded and everything that we see here in this breccia deposit tells us that it was laid down rapidly and catastrophically.

Clearly there wasn't enough time for the eroded cobbles and boulders to become smooth and rounded, and sorted by size and shape. It seems that whatever eroded the unconformity surface must have done so quickly.

And what about the rock layers below the unconformity? Closer examination reveals evidence that they were also laid down rapidly.

JOHN WHITMORE: The rocks that I'm sitting on are these Silurian greywackes and these we now know are turbidite deposits, and turbidites form very quickly in modern settings. There's a sandstone portion of the turbidite and then a finer grained shale portion to the turbidite. This entire sequence right here was one quick event that probably was made within minutes.

We have dozens and dozens of these rapidly deposited turbidite beds at Siccar Point.

The evidence at Siccar Point indicates catastrophic processes and short timescales, with sediments being laid down and eroded rapidly. But during his visit in 1788, James Hutton apparently failed to understand the significance of the evidence in front of him. He assumed that the present was the key to understanding the past, and therefore concluded that large amounts of time must have passed as these sediments were laid down, uplifted and eroded, and new sediments deposited on top. But closer examination of these rocks now causes us to question this assumption.

17. CONCLUSION

JOHN WHITMORE: Hutton was a real pioneer when it came to geologic thought. He was able to show the world that history was preserved in the rocks that he studied. However, Hutton proposed the idea of uniformitarianism. He said that long gradual processes were recorded in the rocks. As we looked at the rocks at Siccar Point we did not see evidence for those long gradual processes. Instead we saw evidence for rapid catastrophic processes, processes that happened very quickly over short periods of time.

PAUL GARNER: Well we began our journey and we've ended our journey here at Siccar Point, and along the way we've visited some spectacular coastlines, much loved countryside and some iconic geological sites, and what we've seen is that the evidence in the rocks doesn't support James Hutton's dogma of uniformitarianism. We've seen evidence of vast sedimentary rock layers, evidence of fast moving currents, evidence of explosive volcanoes and the role that all these things have played in the formation of the landscape we see around us here in Great Britain. James Hutton's dogma of uniformitarianism may have triumphed in the geological community for almost 200 years – but perhaps it did so in spite of the evidence and not because of it.

In the twenty-first century, a new approach to geology is needed – perhaps a revolution as radical as the one brought about by Hutton in the eighteenth century. While catastrophic processes have been rediscovered in the last few decades, they are still locked into the idea of long geological timescales and continue to be regarded as rare events that punctuated an otherwise tranquil past. Today, we need to see catastrophism for what it is – the dominant force that has shaped our geological history. We have seen that the evidence for large-scale catastrophic events – colossal eruptions, massive storms and gigantic floods – is all around us.

Catastrophism is alive and well on planet earth – and the evidence is rock solid!

CONTRIBUTORS

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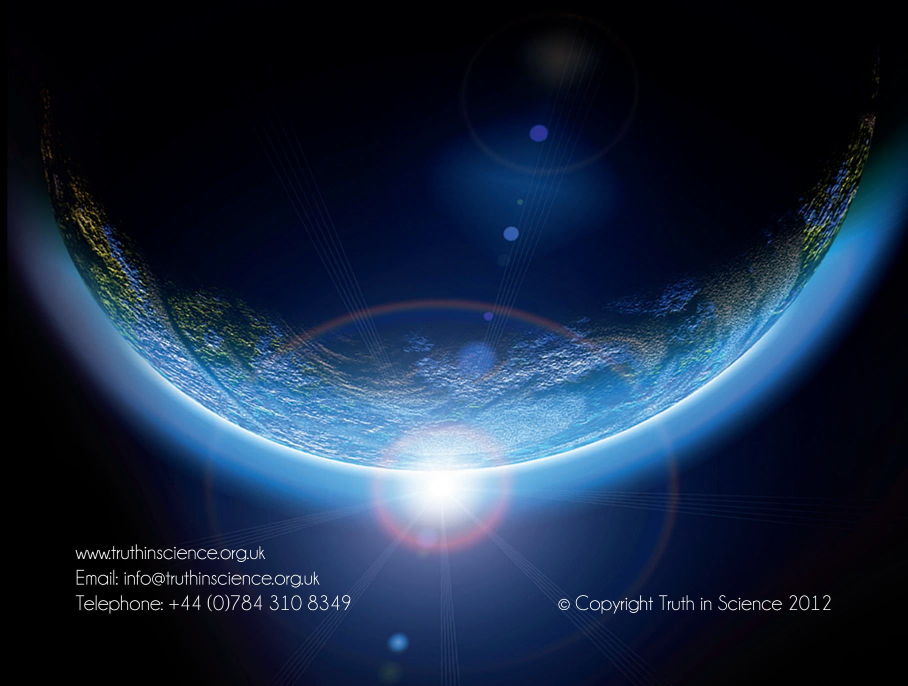

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