# Seathwaite Graphite Mine

*Visit & Analysis of a Fluid Deposited Graphite*

Jeff Wilkinson ©

## Part 1 – The Visit

***Abstract:*** Over the years there have been many theories, hypotheses and scientific studies attempting to find the origins and mechanisms responsible for the unique graphite deposit within Volcanic Rocks of the Ordovician Period at Seathwaite, Borrowdale in the English Lake District. None have been able to give a definitive answer of where the source carbon originated or how it was transported and then deposited as graphite. A recent collaboration between the British Geological Survey (B.G.S.) Edinburgh and the Department of Crystallography and Mineralogy, Complutense University, Madrid resulted in an extensive examination of the mine and laboratory analysis using the latest scientific techniques. The results have now been published in technical papers. This is a record of that visit to the graphite mine and details from the subsequent papers.

***The Project:*** As far back as 2001 the idea had been muted to me that some Spanish scientists wanted to visit Seathwaite at some point. At the beginning of 2006 I got a call from Dave Millward of the B.G.S. in Edinburgh. He informed me that these eminent colleagues of his from the University of Madrid finally wanted to set a date to visit the Borrowdale mine. They also have a high grade graphite mine in southern Spain that lies within volcanic rocks[1]...the only other known occurrence. Having written technical papers on the origins of Fluid Deposited Graphite from various locations around the world[2] they were very enthusiastic about a "hands on" visit to the renowned Cumbrian mine.

I had known Dave Millward since 1993 and had worked with him during the productive examination of the Coniston Copper Mines...resulting in a link between active volcanism and copper mineralization being established[3]. Knowing my background and long interest into the origins of the graphite deposit he asked if I would like to be involved in the project, advise on equipment and look after the safety of the group.

My first job was to come up with a safe, reliable partner to help with these tasks. Although the graphite mine in relative terms is a pretty safe mine "WE" would be responsible for the complete safety of these professional people. Any "incident" would have very serious consequences and repercussions indeed! The obvious choice for me was my old friend Dave Bridge. I have the greatest respect for him, he is safety conscious and just as important he has the same burning curiosity about the origins of the graphite deposit as I do. A visit date was arranged for July 2006. Dave Millward had the unenviable task of obtaining the correct authorisations and paper work from all the relevant authorities and carrying out risk assessments which would include having to have a satellite phone to report in at various times! Some of the authorities who had to be contacted included: The National Trust, The National Park Authority, Natural England and the Secretary of State for Culture, Media and Sport.

A couple of weeks before the said date Dave and I visited the mine with a view to checking out the safety aspects and having a good look from a purely geological point of view. It's amazing how much more you notice in "geological mode" instead of the usual mining history mode!

Right from the beginning of this project I felt it imperative that someone from the group should descend the Grand Pipe to the Old Men's Stage and inspect the lower workings. This would ensure that we had a good overall representation of the mine and also allow the experts to examine structures/exposures from deep within the Grand Pipe itself. It is highly unlikely that such eminent specialists have gained access to this area. This posed the tricky problem of how to get novices safely down and back up the 70 foot pipe? Dave produced a relic from "explorations past" in the form of an electron ladder...a rare sight and privilege indeed! I set up a belay passing a safety rope through a rock climbing stitch-plate on the harness, then up through an anchored pulley-wheel which gave a smooth controllable action. The plan was for them to use the ladder mainly as hand holds while walking the feet down the angled wall rock of the pipe. All seemed to work reasonably well and we agreed that it was "possible" to get a few of them safely down to the lower workings and more importantly BACK UP!

***<u>The Visit:</u>*** (July 2006). We all met up on the road beneath the mine at 10.00am and sorted out the equipment. There were two members from the B.G.S. and four from the University of Madrid. Also present on the first day was the National Trust's Archaeologist Jamie Lund; the mine lies on land owned by them. I have to admit that I was a little concerned at the outset that an overzealous official might jeopardise a very important visit. Visions of someone with a clip board waving a stern finger in disapproval flashed across my mind! This concern turned out to be totally wrong. Jamie allowed the experts to take whatever samples they deemed necessary and he was a pleasure to work with. I know he really enjoyed the day and found it very informative. After a brief summary of the local geology by Dave Millward we weaved our way up the old miners track to the entrance of Gilberts Stage which intersects the Grand Pipe near its base. Unfortunately the visit took place during a major heat wave. The temperature was around 100°F (hotter than it was in Madrid!) even the Spanish visitors used to such high temperatures found it way too hot for walking up a steep fellside. We entered the cool draft of Gilberts Stage where it became immediately apparent that these people knew exactly what they were looking for. Half an hour was spent at the base of the Grand Pipe taking samples of rock, minerals and graphite. We then moved higher up the fell and entered the extensive Gill Stage level where a number of locations exhibiting interesting geology were pointed out. These showed fractures (faults) in the volcanic rocks which were mineralized and would later become known as "late graphite-chlorite veins." After much sampling and many photographs we dropped down to Farey's Stage, traversed across the Grand Pipe and continued with the observations and sampling. From this level a number of "graphite pipes" were studied in detail. I had abseiled these in the past but had never noticed the extensive brecciation of the wall rock until they were pointed out. Watching and listening to these people was extremely informative. Observing the overwhelming delight and enthusiasm of the Spanish visitors at finally being in this world famous Cumbrian mine was really quite infectious. Thankfully our initial fear that the mine may be worked out and devoid of useful, relevant geology was resigned to the dustbin!!
We could not have been more wrong.

Day two was another very hot one. The plan on this day was for the two B.G.S. and Jose of the Spanish contingent to descend the Grand Pipe while the others collected samples from the dumps. We set up the electron ladder and ropes while the rest geared up outside and took in the sun. Everything was double checked at the edge of the Grand Pipe then Dave descended to receive the three visitors. *Amusingly before each made the step across onto the wobbly electron ladder (all be it with a safety rope attached) there was a meaningful look in their eyes that said "I hope you know what you're doing!"* On the way down Jose became quite animated, not about the descent, some features within the wall rock of the pipe seemed of great interest to him.
As always it was a great pleasure to re-visit the classic "hand-driven" coffin level in the Old Men's Stage, it never disappoints. We made our way below the Old Men's Stage where there was a very interesting stoped area which contained large amounts of in-situ graphite and exhibited interesting geology. We had identified this area on our earlier visit and we were pleased to let the experts see it. After a good look round we started the ascent of the Grand Pipe. This turned out to be a bit strenuous for our visitors but they took their time and the task went more or less to plan and was completed without incident. The comprehensive study of this most fascinating mine by leading experts in their field was now complete. After a group photo we said our goodbyes. We (Dave and I) had been given a small package as a thank you for looking after them. When they were opened later we were very surprised to see a personalized watch of the University of Madrid; a really nice gesture indeed.
Being a part of this project has been fantastic. Hoping for a new, up-to-date mineralogical survey of the graphite mine was one thing, but being involved, that was something else!

Before the specialists returned home they collected samples of various Skiddaw Slate rocks for later analysis. This was deemed important because these older marine mudstones and sandstones are the basement rocks that underlie the B.V.G. It was suggested that the biogenic material they contain may in some way be responsible for the original source of carbon that has later been deposited at Seathwaite as graphite.

***Waiting:*** So that was the quick part of the operation completed. Now it was the long wait while all the technical lab work was completed and the papers penned. Unfortunately to the layperson these things seem to take longer than geological time itself! We would have to be very patient indeed. During this long hiatus we would have plenty of time to ponder whether those long standing questions would finally be answered...or would the mysteries still remain? Time would tell.

Finally in January 2009 we received two PDF files (of four) about the graphite mine, took a deep breath and then inwardly digested.

**References**


[1]***Vein-Type Graphite in Jurassic Volcanic Rocks of the External Zone of the Betic Cordillera, Southern Spain***
*Jose F. Barrenechea, Francisco Javier Luque and Magdalena Rodas. Canadian Mineralogist 1997©*
[2]***Natural Fluid-Deposited Graphite: Mineralogical Characteristics and Mechanisms of Formations***
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[3]***Pre-Acadian copper mineralization in the English Lake District***
*D. Millward B. Beddoe-Stephens B. Young. Geol. Mag. 1999©*


# PHOTO GALLERY 1

*Pictures Wilkinson collection ©*

**Jose Barrenechea traversing across the Grand Pipe to reach Farey's level**

**Dave Millward descending the Grand Pipe lit up in a shaft of brilliant sunlight.**
***Note brecciated wall rock:*** *see following report.*

**Looking 100ft up the Grand Pipe from Old Men's Stage to the surface.**
***Note fragmented quartz and brecciated wall rock of the pipe:*** ***see following report.***

**The classic "hand-driven" coffin level in Old Men's Stage** circa 1625

***Sample:* graphite nodules have replaced the original minerals in the much altered volcanic rock; *width 15cm*.**

*The team:* **L/R Dave Millward, Lorena Ortega, Jose Barrenechea, Javier Luque, Jeff Wilkinson, Stu Clarke, Dave Bridge - Missing from this picture is Magdalena Rodas.**

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## Part 2 — The Results

Any attempts to interpret in laymen's terms highly scientific papers by leading academics is at times going to be clumsy...and always difficult! My soul aim is to bring this important information to as many interested parties as possible. Not everyone has access to or can grasp the very technical nature of the original works, so apologizes in advance for any clumsiness!

Anyone who looks past the mining history aspects of this mine will inevitably end up asking probing questions about this rare graphite deposit. Some of the older papers written about the deposit did a good job at putting their theories and hypotheses across but due to the knowledge and technology available to them at that time they could not really scientifically prove their theories.

Some of the questions that often arise relating to the deposit are:

- **Where did the source carbon originate?**
- **How was the carbon mobilized?**
- **How did the graphite get deposited?**
- **Why only graphite at Seathwaite?**

Graphite at Seathwaite occurs as large masses (often nodules) within mineralized pipe-like bodies - late graphite-chlorite veins and disseminations within the host rocks.
It has the greatest variety of crystalline morphologies in a single deposit.

The source carbon originated from the Skiddaw Slate rocks. These older marine mudstones and sandstones are the basement rocks that underlie the Borrowdale Volcanic Group (B.V.G.) and have a thickness of at least 3 miles. Preserved within these rocks is a small percentage of biogenic material. This took the form of algae, soft bodied graptolites (part of the marine plankton community) and other organic material.
Due to the proximity of intensely hot, andesitic magmas from the B.V.G. the Skiddaw Slate rocks were thermally altered. This caused the release of carbon atoms, primarily as $CO_2$ which became assimilated into a rich hydrothermal fluid.
The analytical method used to determine this result was - **Stable Carbon Isotopic Analyses**.
There are three possible sources of carbon in Fluid Deposited Graphite:
(1) Removal of volatiles from carbonaceous sediments.
(2) Carbon derived from carbonate rocks.
(3) Carbon derived from the mantle.
Each carbon source has a distinct signature. The "light" isotopic signatures from various graphite morphologies tested are consistent with the carbon source being of a biogenic origin.

C-O-H rich hydrothermal fluids migrated up through fissures and fractures in the host volcanic rocks. Andesite and dioritic rocks next to the veins were intensely, hydrothermally altered to a propylitic assemblage containing chlorite, epidote, sericite and albite. The mineralizing fluids evolved from $CO_2$-$CH_4$-$H_2O$ to $CH_4$-$H_2O$ mixtures. In all recorded fluid-derived graphite deposits worldwide the temperature of the fluid has always been extremely high however research has shown that the fluids responsible for graphite precipitation at Seathwaite were of moderate-temperatures in the region of 500°C. This is the first time such low temperatures have ever been recorded for a volumetrically large graphite occurrence.

Initial precipitation of carbon into graphite from the hydrothermal fluid was probably the result of its vigorous reaction with the host volcanic rock minerals and the rapid cooling of the fluid. In particular, water was removed from the fluid due to hydration reactions of the primary minerals. This, in turn, caused relative carbon enrichment in the fluid that eventually became supersaturated with respect to graphite. As the main mineralizing phase along the pipe-like bodies continued the reaction was $CO_2 \rightarrow C + O_2$. Data indicates that graphite first precipitated out as cryptocrystalline and spherulitic aggregates. As the fluid content/temperature decreased the carbon became enriched and the graphite precipitated out as flaky crystals...the most common in the deposit. At this point, in addition to the above reaction, graphite precipitation could also occur by $CH_4 + O_2 \rightarrow C + 2H_2O$. Such a reaction involving oxidation of methane was probably dominant during the formation of the late graphite-chlorite veins.
Some of the crystal morphologies found at Seathwaite have not been recorded from any other deposit worldwide; another first for the mine. The scientific method used to study the crystallinity of the graphite was **Raman Spectroscopy**.

The evocative question of *"why only graphite at Seathwaite and nowhere else?"* is a very good one indeed. Skiddaw rocks underlie the whole of the B.V.G. yet we do not have any other fluid deposited graphite deposits what-so-ever! There has to be some unique and unusual geological coincidences to form the Seathwaite deposit. It has been known and reported for many years that within the mine there is a probable hypabyssal dioritic intrusion. This intrusion was in the vicinity of a deep-seated active fault system which allowed a pathway for the hot C-O-H fluids. These two features were crucial for the mobilization of carbon bearing fluids.
Although there is one other known occurrence of graphite within volcanic rocks in southern Spain, Seathwaite mine is unique in that it is the only deposit that has economic concentrations.
The suggested scenario is as follows:

Under normal circumstances of sub-aerial volcanism, carbon volatiles assimilated from the Skiddaw Slate mudstones would be released to atmosphere during volcanic eruptions. At Seathwaite a section of the magma chamber started to crystallize out (dioritic intrusion) giving a totally different scenario...effectively creating a barrier which prevented the assimilated carbon volatiles from escaping. Crystallization of primary anhydrous minerals in this intrusion allowed the magma to become highly enriched in volatiles. This caused a massive increase in vapour pressure which eventually overcame the surrounding rock leading to their extensive hydraulic brecciation. Subsequent expansion of the volatiles within the magma allowed the upwards mobilization of andesitic/dioritic rocks and/or melt, fragmented pieces of quartz and carbon-rich fluids leading to the formation of the breccia pipe bodies.
*Exposures viewed in the mine clearly show extensive hydraulic brecciation of the wall rock and fragmented pieces of quartz...ripped from their original location and transported upwards.*
Analysis of fluid inclusions within the quartz fragments revealed the earliest circulating fluid at the time of the event. Initially this was a vapour rich, over-pressurized, supercritical phase evolving into

a liquid rich fluid as deposition continued. Data also revealed fluid temperatures as well as changing $CO_2$-$CH_4$-$H_2O$ concentrations.

Graphite mineralization at Seathwaite is described as a "catastrophic mineralization event." In the opinion (speculative) of one of the Spanish authors the time scale was short even at the human time scale, perhaps only seconds! Although it can also only be viewed as speculation the estimated speed of the magma ascent up through similar structures (pipe-like bodies) in diamondiferous kimberlites has been reported as much as 70 km/h...an astonishing speed.
Again this would tend to point to a very fast mineralization process.

**Summary:**
Large graphite occurrences in volcanic environments are extremely rare due to low carbon content of magmas and normal de-gassing during eruptions. Interaction of several key factors and coincidences were required to produce the deposit. These include:

- Unusually high carbon content of the magmas (assimilated from Skiddaw Slate mudstones.)
- A hydrothermal fluid, rich in assimilated $CO_2$-$CH_4$.
- A dioritic intrusion that created a barrier...blocking normal de-gassing of carbon volatiles.
- Close proximity to the barrier of a major active fault system which provided an already weakened, fractured zone, which due to massive, increasing vapour pressure eventual ruptured the barrier.
- The active fault system provided a pathway for over-pressurized fluids, rock/melts etc that led to the formation of the brecciated pipe like bodies.
- Temperature changes and hydration reactions of primary minerals lead to carbon "super-saturation" of the fluid causing disequilibrium in the system leading to massive graphite precipitation.

A technical term from the final paper to explain the deposit has been given and that is:
***"AN EXAMPLE OF A SELF-ORGANIZED CRITICAL SYSTEM."***

**Finally:**
It would be a reasonable assumption to regard the graphite deposit at Seathwaite as one of *"NATURE'S FREAKS"* being that it is so unique.

Having delved into the mysteries of this intriguing, rare deposit I would like to suggest a more evocative view:

**"This mine is one of nature's greatest wonders."**

**"This mine is one of nature's greatest tricks."**

Jeff Wilkinson - Updated June 2012 ©

**Please note: The mine is a scheduled site under the Ancient Monuments and Archaeological Act 1979 and also a Geological Conservation Review site.**
**It is illegal to cause damage or remove material from anywhere on this site.**

**Acknowledgments:**

This article could not have been produced without the kindness, encouragement and information provided by Javier Luque, senior lecturer at the University of Madrid.

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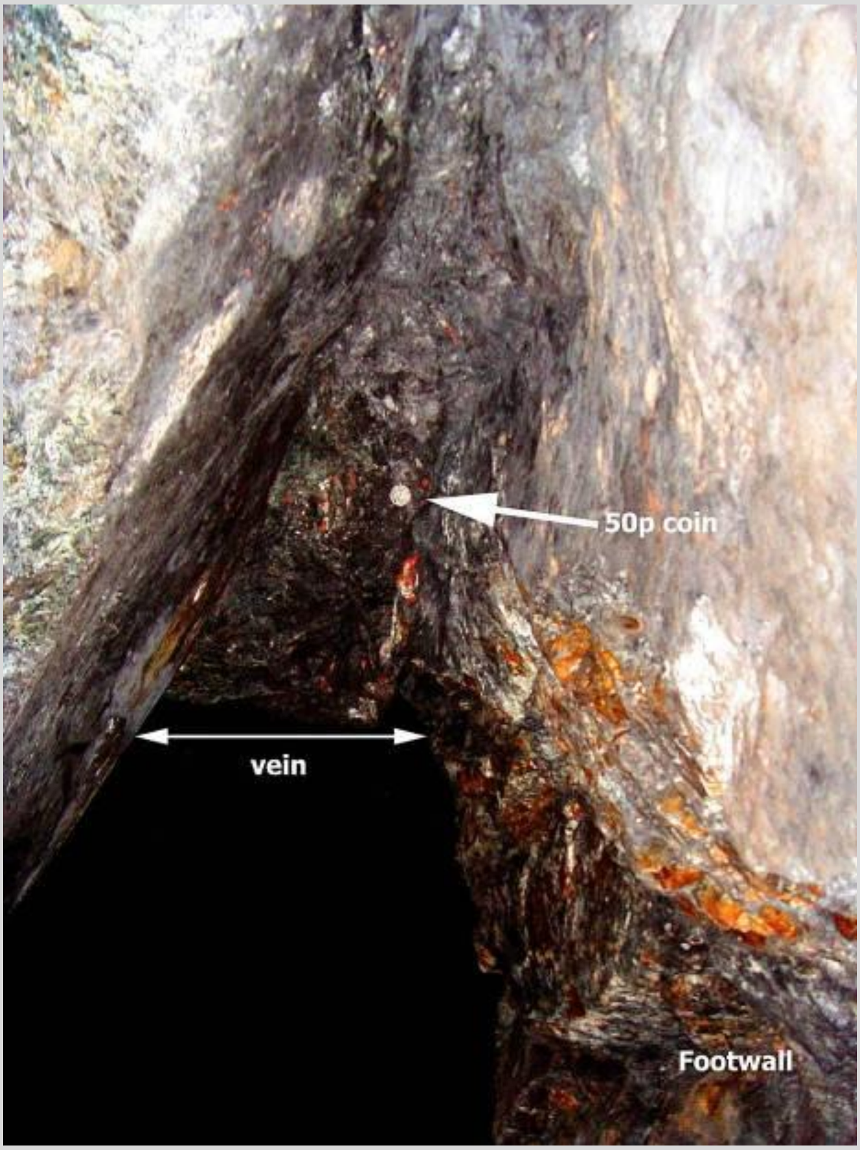
*Journal of the Geological Society, London* - 2012©

**E-mail communications** – Jeff Wilkinson – Javier Luque.
**E-mail communications** – Jeff Wilkinson – Dave Millward.

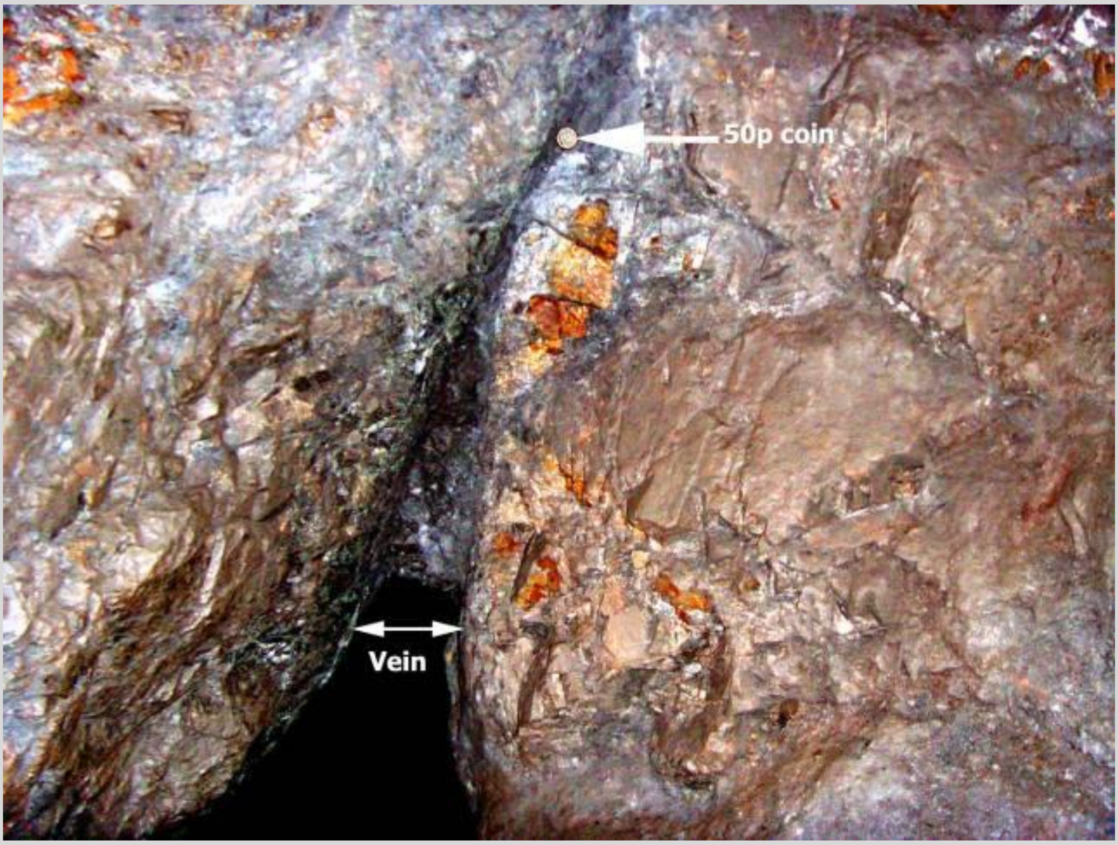
# PHOTO GALLERY 2

*Wilkinson collection © (pictures enhanced for clarity)*


***Late graphite-chlorite vein:*** **note fragmented quartz (white/brown) in the footwall.**




*Late graphite-chlorite vein:* **As well as graphite green chlorite visible.**




***Late graphite-chlorite vein:*** **Note fragmented quartz and hydraulic brecciation of the host volcanic rock.**

*Same vein:* **Note the continuation and "nipping in" of the vein/fault**


*A graphite vein formed within a fault plane*


*Late graphite-chlorite veins:* **Silver metallic lustre of graphite and chlorite clearly visible.**

**Close up of the above picture**

Extensive graphite deposit.

***Within the Grand Pipe:*** **white fragmented quartz evident, as is brecciation of the host volcanic rock.**


***Late graphite-chlorite vein:*** **Many features visible in this vein**