STONE MINING ON THE ISLE OF PORTLAND

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Abstract

Despite its limited geographical area (10.8 km^2), during the last 350 years the Isle of Portland in Dorset has yielded many millions of tonnes of dimensional building stone. Stone quarried from Portland has been used to construct hundreds of culturally significant buildings and monuments both within and outside of the UK. Portland Stone has been described as Britain's "pre-eminent building limestone" and is considered to be a strategically important resource. Portland Stone is still in demand for use in new buildings and for the restoration and upkeep of many existing nationally important buildings. There are few remaining "green field" sites suitable for traditional surface quarrying on Portland. The island still has significant reserves of stone, but these are in areas where other land uses preclude quarrying. Depleting quarrying reserves led Albion Stone to develop, for the first time on Portland, underground mining techniques for the extraction of dimension stone from beneath environmentally sensitive areas. The development of a new mine (Jordans Mine) has allowed the recovery of otherwise inaccessible dimension stone reserves from beneath a seven acre site, which contains a much-used cricket field and lies very close to sensitive infrastructure. Despite having a live planning permission for quarrying granted in 1951, surface extraction from this area today would be effectively impossible because of the potential negative environmental impacts to the site's neighbours. The establishment of a new mine involved developing new ground control strategies and working methods in sympathy with the stratigraphy and structural geology of the site. Jordans mine has been in operation since late 2008 and has proved to be stable and economically successful, yielding an average of 60m^3 of high quality Portland Stone each week, with virtually no impacts to the surface environment. Mining potentially offers a way for Portland's stone industry, which directly employs over 100 people on the island, to continue producing stone for many decades into the future.

Godden, M. 2014. Stone mining on the Isle of Portland.
Pp. 51-57 in Hunger, E., Brown, T. J. and Lucas, G. (Eds.)
Proceedings of the 17th Extractive Industry Geology Conference, EIG Conferences Ltd. 202pp.
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INTRODUCTION

The Isle of Portland is situated approximately 200km south-west of London in the county of Dorset, close to the centre of the 152km long Jurassic Coast, a UNESCO geological World Heritage Site.

Portland is a tombolo, linked to the mainland by Chesil Beach. The Upper Jurassic Portland Stone Formation is well exposed at the island's edges in sea cliffs and the cliff-face orientations are largely joint controlled (Figure 1). Portland is a remnant part of the Weymouth Anticline's southern limb, the rocks dipping at around 1.5° to the south-east. The Portland Stone Formation is sandwiched between the overlying Cretaceous, Purbeck Group Limestones and the underlying Portland Sand and Kimmeridge Clay Formations (Figure 2). The Freestone Member is an 8m thick plateau of oolitic limestone at the top of the Portland Stone Formation that contains the economically valuable dimensional building stone beds of Roach, Whitbed and Basebed (Figure 3).

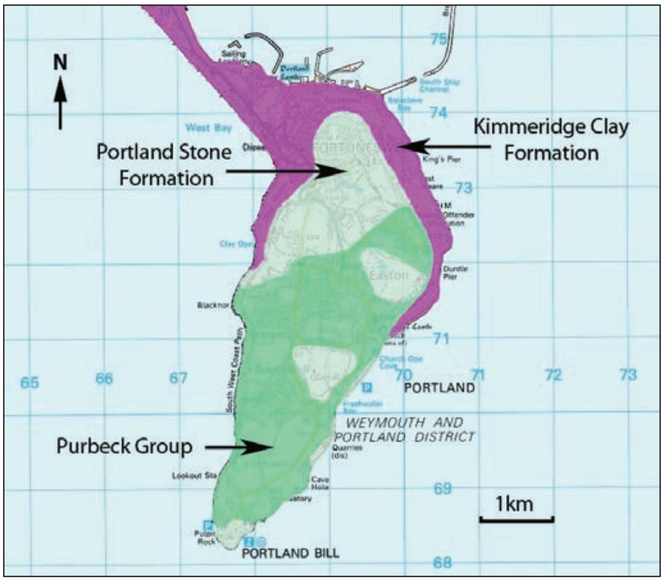

Figure 1. *A simplified geological map of Portland.*

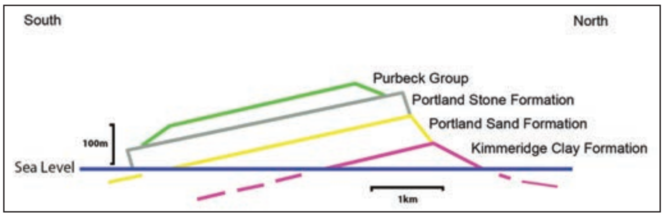

Figure 2. *A simplified cross-section through Portland showing the 1.5° dip to the south-east. (Note: diagram is vertically exaggerated).*

Well dilated, closely parallel, sub-vertical, north–south striking (extensional) master-joints are the principle structural controls upon dimension stone extraction on Portland. These joints are a consequence of mid-Tertiary tectonic activity, possibly linked to the Alpine Orogeny, which also resulted in the formation of the Weymouth Anticline.

An older set of tight, sub-vertical, (compressional) conjugate joints are also very significant controls upon quarrying and, more recently, mining processes on the island.

Despite its limited geographical area of 10.8 km^2, the exploitation of dimensional building stone from Portland has taken place since at least the time of the Roman occupation of Britain in the1st century AD.

Extensive use of Portland Stone in London during the 17th and 18th centuries firmly established its popularity as a building material. Since that time, Portland Stone has been in continuous demand for the construction and upkeep of many culturally significant buildings and monuments, both within the UK and further afield.

Portland Stone has been described by the British Geological Survey as being Britain's "pre-eminent building limestone" (Woods, 2011) and is considered to be a nationally important resource in the Bournemouth, Dorset and Poole Minerals Core Strategy Pre-submission Draft (Dorset County Council, 2012).

All Portland Stone produced on Portland before 2002 came from open quarries. No underground stone mining had ever been attempted on the island before this time.

Modern dimension stone quarries tend to occupy large areas of land. Approximately 36% of Portland's surface has been quarried to-date which probably equates to an output of at least 12 million tonnes of building stone, but few records exist to accurately refine this figure. Portland still has significant reserves of dimension stone but with 12,500 people currently living on the island, there is a high pressure on land-use which effectively precludes surface extraction in most areas.

Shrinking reserves of dimension stone in areas suitable for quarrying, led Albion Stone during the 1990s, to consider underground mining as a potential stone extraction method. During this period, the development, principally in Italy, of poly-crystalline diamond cutting media, fitted to stone cutting machines of ever increasing sophistication, meant that for the first time mining on Portland became feasible.

Mining could provide access to remaining reserves of Portland Stone which are almost exclusively, inaccessible by quarrying.

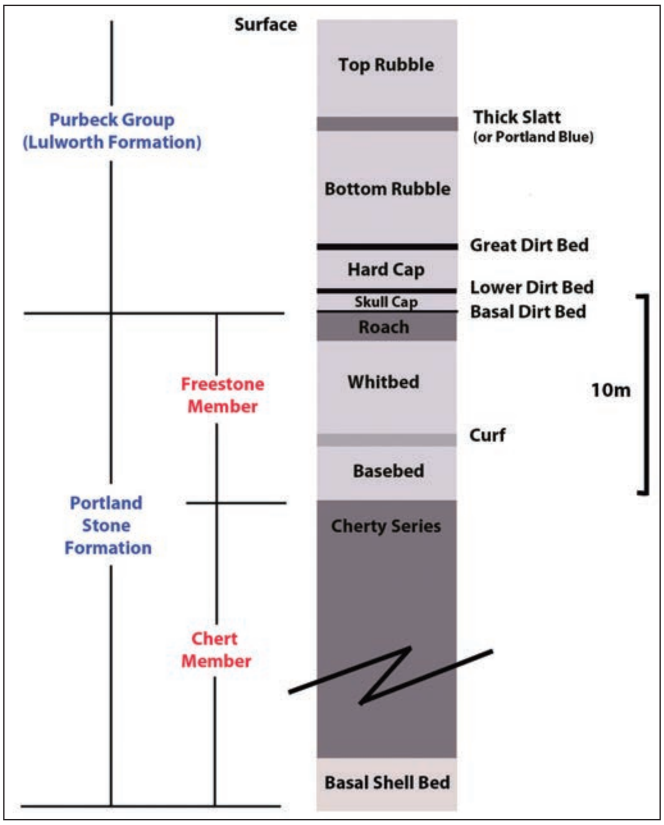

Figure 3. *A simplified stratigraphic section through the Purbeck Group and Portland Stone Formation at Jordans Mine (SY 687720) (Note: the Chert Member is not shown to scale and is in reality ~19m thick).*

Dimension stone has been successfully mined from the softer, and hence more easily cut, Great Oolite in the area around Bath for centuries. The working and ground control techniques used at Stoke Hill Mine, Bath, as well as several other European dimension stone mines located in Italy and Croatia, were closely studied before any attempt at mining on Portland was made.

Bowers Trial Mine (SY682717) was established to extract stone from the Whitbed in Bowers Quarry, Portland by Albion Stone in 2002. The Trial Mine is thought to be the first new dimension stone mine to be started in England for over a century. The Trial Mine's Whitbed operation was rolled out into a second mining district in the Basebed a few years later. The Trial Mine was a largely experimental operation, designed to prove the feasibility of mining on Portland and to establish and refine working methods.

The Development Of Jordans Mine

There were several compelling reasons underpinning Albion Stone's decision to start a new mine within the disused Jordans Quarry. These are summarized below:

- Albion Stone was keen to add the remaining dimension stone at Jordans Quarry to its reserves of Portland Stone.
- The site had a live Planning Permission, granted in 1951 for open quarrying with minimum attached conditions. The environmental issues associated with quarrying the area more than fifty years after

permission was granted would be significant due to the close proximity of housing and other environmentally sensitive infrastructure (Figure 4), along with significantly changed social attitudes amongst local residents.

- The experience gained during the development of the experimental Bowers Trial Mine could be readily used to establish a new production mine at Jordans.
- Quarrying the site would lead to the loss of a much-used local cricket field and involve moving over 200,000m³ of overburden at an 'up-front' financial cost of at least £300,000.
- Overburden removal would probably involve some blasting with inherent environmental impacts of vibration, dust and noise.
- Mining would not disturb the overlying cricket field or significantly impact the visual amenity of site.
- Mining would have virtually no environmental impact upon the site's neighbours.
- The Mineral Planning Authority was supportive of the concept to mine the site from the outset. A successful mine would set a powerful precedent for future planning applications involving the extraction of dimension stone from Portland.

Previous experience had shown that mine roadway orientation would be a critically important control on the yield of useable stone recovered from underground. This is because of the need for mine working faces to be correctly aligned with the systematic conjugate joint sets present within the freestone beds.

A remnant north-south striking Whitbed quarry face at Jordans Quarry (Figure 5), which was abandoned in the 1950s when quarrying ceased, was selected for mining because it would be most appropriate for the cutting of portals and the correct alignment of the initial roadways.

Two mine portals would be cut from the outset, as this would allow the Fantini GU50 mining machine to cut continuously for maximum efficiency. Two portals would also provide two means of egress very early in the mine's life and allow the prompt establishment of a mine ventilation circuit.

Work to establish a new mine in Jordans Quarry began in 2006, the planning and development stages of the project are summarized in Table 1. The first practical step taken towards the establishment of a new mine involved the construction of a haul-road to provide safe vehicular access into the site (Figure 6). The haul road was built to a high standard because of the possibility that emergency vehicles may need to use it in the event of a future mine

Timing	Description
Early 2006	The Jordans Site was investigated by Albion Stone's staff and the project's geotechnical consultants (Wardell Armstrong).
Summer 2006	A Planning Application was prepared by Wardell Armstrong.
Feb 2007	The Planning Application was submitted.
Spring 2008	The ground control documents were written.
Summer 2008	The area around portals and the faces were prepared for mining.
Autumn 2008	The mining equipment was moved to site and the portals were cut.
Early 2009	Planning Permission was granted and mining commenced.

Table 1. *A summary of the planning and development stages of Jordans Mine.*

Figure 4. *An aerial photograph of the Jordans Site, (SY687720) showing its close proximity to environmentally sensitive infrastructure.*

Figure 5. *A remnant face at Jordans Quarry, pictured in January 2006, was selected for mining because it offered the most appropriate alignment for the cutting of tunnel portals and initial roadways with regard to the strikes of conjugate joint sets within the Freestone Beds.*

Figure 6. *Construction of a new haul road for Jordans Mine which involved the importation of several hundred tonnes of spoil from the nearby Fancy Beach Quarry.*

emergency. A new, carefully levelled working area, coincident with the base of the Whitbed, was then created by lowering an old quarry bank by about 2.5m. This was to allow two parallel tunnels to be driven into the remnant quarry face at the correct mining horizon. After the mining equipment was moved to site from the Trial Mine, it was used to vertically align the Whitbed and

Roach face (into which the mine portals were to be cut), with the face of the overlying Cap Beds. This work was intended to help make mine entrances as stable as possible. To achieve this, two 7m wide rebates, located about 7m apart, were cut into the Whitbed and Roach face using the mining machine. This operation yielded some useable blocks of dimension stone. Excess stone was removed from the back of each rebate using a hydraulic breaker fitted to a backhoe.

Figure 7. *The installation of 30 horizontal rib-bolts designed to stabilize the immediate roof beam over the newly cut portal rebates was undertaken from a man-cage attached to a telescopic-handler.*

Figure 8. *A Fantini GU50 mining machine being used to carefully cut the mine's first advance.*

Thirty, 2.4m long, horizontal rib-bolts were installed at 1m spacings in the Cap Beds which form the immediate roof beam above the two portal positions (Figure 7). The rib-bolts are designed to prevent joint-controlled delamination from the front of the Cap Beds and to help stabilise the roof during the initial stages of portal formation.

Jordans Mine's initial mining horizon lies at the top of the Portland Stone Formation in the Roach and Whitbed. The mine's roof horizon is a very persistent bedding plane associated with a paleosol called the Basal Dirt Bed, which lies at the junction between the Purbeck Group and the Portland Stone Formation.

Removal of the Roach and Whitbed will eventually be followed by a second operational phase to bench mine the underlying Curf and Basebed, which will lower the mine's floor and increase the pillar height to around 8m. This was the dimension that was used as the basis for Jordans Mine's pillar design from the outset.

A Fantini GU50 mining machine was used to cut the mine's first advances. In normal use, this machine is hydraulically locked between a mine's roof and floor to stabilize it. This was not possible whilst cutting Jordans Mine's first advances, so cutting rates were kept very low to ensure that the mining machine remained stable (Figure 8). The Fantini mining machine uses PCD (PolyCrystalline Diamond) cutting media fitted to a 'chain-saw' type blade. The machine is computer controlled to prevent it from over-cutting into the mine's roof, pillars and floor. The width of cut is 40mm and the depth of cut is around 1.7m.

To form the mine's first advance, the face at the portal was sub-divided by a series of vertical and horizontal cuts into six discrete cantilevered blocks (Figure 9). Four horizontally orientated hydro-bags (Figure 10) were inserted, evenly spaced along one of the central horizontal cuts. When the four hydro-bags were inflated they exerted a combined force, equivalent to over 800 tonnes (normal to the line of the cut) causing the overlying and underlying cantilevered blocks to shear on their rear faces. The loosened blocks were then removed (from the top downwards) using a telescopic handler fitted with specially adapted loading forks.

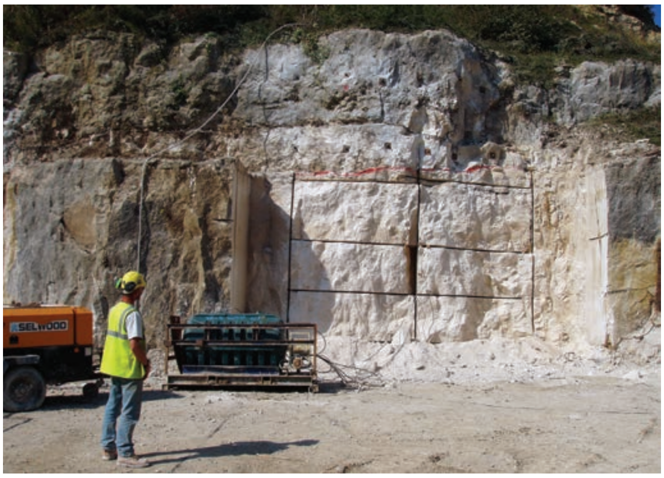

Figure 9. *After cutting, the face has been sub-divided by a series of vertical and horizontal cuts into six discrete cantilevered blocks.*

Figure 10. *Un-inflated (left) and inflated (right) Hydro-bags. Hydro-bags are 3mm thick, 1m² high tensile steel envelopes that were originally developed for use in the Italian marble industry, these have now become a key part of Albion Stone's mining (and quarrying) processes on Portland, effectively replacing explosives. In use, each hydro-bag is inflated with water to a pressure of around 20 bar, producing a force equivalent to just over 200 tonnes.*

The mine's first advances were wedge-shaped (Figure 11) because the new roadway orientations were aligned with a conjugate joint set as opposed to being absolutely perpendicular to the old quarry face.

Following removal of the mine's first advance, the newly exposed area of roof was supported using rock bolts. These bolts were installed into the mine's roof using an "inverted" drill rig that was custom built for the operation in Italy by Marini (Figure 11).

The immediate roof beam of Jordans Mine comprises the Purbeck Group's Hard Cap and basal Skull Cap units. These are massive and competent algal limestones separated by a weak and persistent paleosol called the Lower Dirt Bed. The anchor horizon for roof bolts lies in the centre of the Hard Cap.

The Fantini mining machine was kept cutting for maximum efficiency (Figure 12) by oscillating it between the two new portals; whilst one portal was being cut, the other was being extracted and bolted.

As the portals were deepened, the full heading width was systematically supported using three (fully resin encapsulated) 2.4m long AT rockbolts for each 1.7m mining machine advance. This bolting pattern is designed to support the full gravitational load of the Skull Cap with 33% bolt redundancy.

The topmost (8m) section of the remnant quarry face into which the portals are cut has an average face angle of around 45° and as such, is considered to be reasonably stable, but to completely eliminate any risks from falling material, crash decks were installed over each portal. As mining progressed beyond the mine's portals, the operation began to yield large blocks of good quality, useable Portland Stone. A specially adapted Doosan DT160 telescopic handler with a 16 tonne lifting capacity is used to remove stone from faces within the mine. Over the last three years the mine has expanded rapidly and now has multiple faces and many pillars.

The room and pillar mine is laid out on a notional 6m x 6m grid with a 75% maximum aerial extraction ratio. In practice it is often necessary to create over-sized pillars to accommodate dilated joints which results in a slight local reduction in the aerial extraction ratio. Roadway orientations are closely aligned with a conjugate joint set to help maximize the yield of good quality stone recovered.

A second Fantini GU50 mining machine was introduced to the operation in June 2011. This effectively doubled the mine's output of dimension stone, taking it to typically 60m^3 per week. The mine's yield is on average around 25%.

Operations are coordinated to ensure that the mining machines can work continuously, by moving them around the mine to new faces as necessary. Newly cut faces can then be extracted and bolted away from the cutting operation.

Mining machines are electrically driven; each machine requires a 400 v, 60 A supply. The mine generates its own electricity from an externally located 350 kVA diesel generator, which also provides power for lighting, ventilation and other ancillary equipment. Following initial set-up, the mining machines can be left to complete cuts under the control of their internal computers, leaving the operators free to complete other tasks. The mine currently employs 5 miners who were all trained in-house.

Master joints form major vertical release planes in the mine's roof and can therefore be difficult to mine through (Figure 13). Crossing these dilated joints usually involves the installation of additional support in the form of spot bolts, cell straps and mesh to the adjacent roof. For this reason, master joints are routinely mapped and projected onto mine working plans, with the aim of providing an early warning of potentially difficult ground conditions in adjacent working areas. Horizontal rib-bolts and cell straps are routinely used to stabilize pillars bisected by conjugate joints to prevent joint controlled delamination (Figure 14).

A 5 tonne Hitachi backhoe fitted with a hydraulic breaker, which has been adapted for use within the mine is used to trim irregularities from mined faces before the roof is bolted (Figure 15).

Rough blocks of stone taken from the mine's faces are squared using a JCB machine fitted with an articulated 3.4m long Fantini chain saw blade (Figure 16). This

Figure 11. *The wedge-shaped first advance of Jordans Mine and Marini bolting rig being used to install rock blots into the newly exposed area of roof.*

Figure 12. *Oscillating (or place changing) the mining machine between the portals allowed it to cut continuously for maximum efficiency. It typically takes or 12 hours to cut a mine face which is the longest part of a production cycle.*

Figure 13. *Very persistent master joints are routinely mapped and projected onto mine working plans, with the aim of providing an early warning of potentially difficult ground conditions in adjacent working areas.*

Figure 14. *A jointed pillar which has been stabilised using rib bolts and cell straps.*

Figure 15. *Trimming irregularities from a mine face using a backhoe fitted with a hydraulic breaker.*

Figure 16. *A JCB machine fitted with a Fantini chainsaw blade is used to "square" blocks taken from the mine faces, before they are sold.*

process removes irregularities and non-conforming features from blocks before they are sold and is a very important part of the operation's quality control procedure.

Geotechnical And Safety Aspects Of The Mine Operation

Because the mine's roof is a persistent bedding plane, roof bolts can be installed very close to working faces without fouling the cutting blade of the mining machine. This offers a significant safety advantage over a cut roof horizon, where it is necessary to maintain an aperture of unbolted roof adjacent to each working face to ensure an adequate clearance for the mining machine's blade. Using a bedding plane as the roof horizon effectively means that all cutting operations within the mine can take place beneath a roof beam which has been strengthened to its full extent by roof bolts.

Jordans Mine is force ventilated to ensure that fresh air is continuously delivered to the deeper parts of the mine and that any diesel emissions are efficiently flushed from the workings. During working hours the mine's atmosphere is continuously monitored for oxygen, carbon monoxide, methane and nitrogen dioxide gas concentrations using Impact Pro electronic gas detectors. To date, no harmful concentrations of any naturally evolved gasses have been encountered within the mine. Interestingly, trace quantities of radon have been detected by a specialist contractor, but good ventilation is expected to prevent a build up of significant concentrations of this gas.

Tributary analysis suggests that gravitationally induced vertical stress at the top of each 6m x 6m pillar is likely to be around 1.48 Mpa (equal to ~150 tonnes m^{-2}). There are no significant horizontal stresses within Jordans Mine.

Pillar Strength calculations based upon both the shortened Q' system and the RMR$_{89}$ System were undertaken by Wardell Armstrong as part of Jordans Mine's planning process (Wardell Armstrong, 2006). The shortened Q' System yielded a predicted pillar strength of 8.25 Mpa. The RMR$_{89}$ system yielded a more conservative predicted pillar strength of 5.9 Mpa, which was adopted in the mine design providing a minimum predicted factor of safety of 4 on each pillar.

Geotechnical calculations to determine safe roof spans were also undertaken. These suggested that 6.5m maximum roadway widths with systematic support are expected to be stable under all reasonably foreseeable circumstances. Continuous monitoring of the mine's pillars and roof since mining commenced has served to validate these design parameters.

Rotary tell-tales are installed throughout Jordans Mine at 10m spacings to provide an unambiguous visual indication of any de-lamination within the mine's immediate roof beam.

In addition to the use of tell-tales, roof to floor convergence monitoring, using an Ealey digital tape extensometer, is undertaken weekly throughout the mine. Extensometer stations are installed every 10m of roadway advance. No convergence greater than 6.5mm has been recorded at any station within Jordans Mine to date.

Conclusion

Jordans Mine has about 1km of (6m wide x 3.85m high) roadway cut in the Roach and Whitbed to-date (October 2012), which covers around 70% of the area permitted under planning (Figure 17). No Basebed has been extracted from the mine and work on this horizon is expected to commence in 2013. Jordans Mine has proved to be stable and economically successful, with virtually no impacts to the surface environment.

Recent projects that used stone extracted from Jordans Mine include:

- Green Park Station in Piccadilly, London, improved in advance of the Olympic Games using Roach and Whitbed.
- The Darwin Centre at London's Natural History Museum, opened in September 2009, incorporating 1000m² of 40mm thick Whitbed paving.
- The Bomber Command Memorial, Green Park, London, unveiled by the Queen on 28 June 2012 and constructed using 300m³ of Basebed and 100m³ of Whitbed.
- A set of Olympic Rings (Figure 18), produced for Weymouth Railway Station, carved from mined Whitbed and mounted on a Roach plinth.

The stone for these projects was extracted and the most of the masonry was manufactured by Albion Stone on Portland.

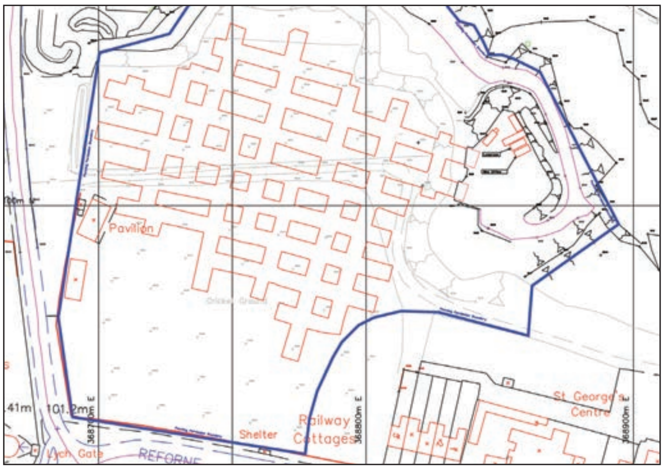

Figure 17. *A recent plan showing the extent of Jordans Mine which now covers ~70% of the area permitted under planning.*

The development of mining techniques on Portland has set a positive planning precedent for future dimension stone extraction on the island by establishing a method of working with a much lower environmental impact than quarrying.

Mining provides access to reserves of Portland stone that are inaccessible through quarrying. Mining of these reserves potentially offers a way for Portland's stone industry, which directly employs over 100 people on the island, to continue producing stone for many decades into the future.

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Figure 18. *The Olympic Rings produced for display at Weymouth Railway Station during the 2012 Olympic Games and then permanently re-located to Portland to commemorate Weymouth and Portland's hosting of the sailing events.*