Preliminary studies on mining methods used in Sivand quarries during the Achaemenian period in Fars province, Irán

Estudios preliminares acerca de los métodos de minería usados en las canteras de Sivand durante el período Aqueménida en la provincia de Fars, Irán

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Emami, Seyed Mohammadamin (2010): Preliminary studies on mining methods used in Sivand quarries during the Achaemenian period in Fars province, Iran. [*Estudios preliminares acerca de los métodos de minería usados en las canteras de Sivand durante el periodo Aqueménida en la provincia de Fars, Irán*]. GEOLOGÍA COLOMBIANA, Vol. 35, pp 175-185. Bogotá, Colombia.

Artículo de Investigación Cientifica M anuscrito recibido: 31 de marzo 2010; aceptado: 17 de septiembre de 2010

Abstract

Ancient civilizations all around the world, from China, Persia, Mesopotamia, Egypt and Greece to South America, have attracted archaeologist's and historian's notice for their cultures as well as the techniques they used for extracting natural resources. The palaces, chambers, temples and tombs demonstrate the advanced engineering technologies that have been known at those times. Archaeology based geological methods and observations help scientists to find evidences of the techniques that ancient people used to provide the raw materials for creating their enormous structures. Discovering the compatibility of materials used for constructing buildings or temples has resulted in a revival of stone cutting methods and their processing technology. The enormous blocks of stones, which were excavated from a mountain, had to be prepared suitably for superior usage in such building complexes as Persepolis (Takht-e Djamshid, 600 - 400 BC). Apart from them, one should also consider the preparation process, its influence and the quality of the blocks.

This paper reviews the status of the Sivand quarries in the Fars province of Iran with respect to their technical and mineralogical data. The quality of material from these mines as well as the unique similarities between these rocks and those which were used in Persepolis, suggest them to be one of the raw material sources which were used for the Persepolis complex.

Keywords: Geoarchaeology, quarries, rock cutting, Achaemenian, Persepolis, Shiraz, Iran

Resumen

Las civilizaciones antiguas en todo el mundo, desde la China a Persia, Mesopotamia, Egipto y Grecia hasta Suramérica, han atraído el interés de arqueólogos y historiadores acerca de sus culturas así como de las técnicas que utilizaron para extraer recursos naturales. Los palacios, las salas, los templos y las tumbas demuestran las tecnologías más avanzadas de la ingeniería de su tiempo. Métodos geológicos y observaciones basadas en la arqueología ayudan a los científicos a encontrar las evidencias de las técnicas que los pueblos antiguos usaron para conseguir los materiales naturales para crear sus enormes construcciones. El objetivo de descubrir la compatibilidad de los materiales usados para construir edificios o los templos ha dado lugar a un renacimiento de los métodos de corte de piedras y de su tecnología de proceso. Los bloques enormes de las piedras, que fueron excavadas de una montaña, tuvieron que ser preparados de manera adecuada para su uso fino en complejos de construcción como Persépolis (Takht-e Djamshid, 600 - 400 A.C.). Además, hay que considerar el proceso de preparación y su influencia como tambien la calidad de los bloques.

El presente texto analiza el estado de las canteras de Sivand en la provincia de Fars en Irán con respecto a sus características técnicas y mineralógicas. La calidad del material de estas canteras así como las semejanzas únicas entre estas rocas y las que fueron utilizadas en Persépolis, sugieren que han sido una de las fuentes del material de construcción que fueron utilizados para la construcción del complejo de Persépolis.

Palabras clave: Geoarqueología, canteras, corte de roca, Aqueménida, Persépolis, Shiraz, Irán

Introduction

In ancient civilizations, different kinds of stones were used, not just for their good strength, durability, preferred resistance against humidity or other ambient conditions, but also for their beauty and shape (Dworakowska, 1983). Study of ancient structures with respect to their surrounding influences generates a number of geo-archaeological questions. For instance, from where and how did the ancient people get their resources? How did they take out the rocks and cut the blocks and how did they take advantage of their geographical location to get the best quality of the available resources. (Begemann & Schmitt-Strecker, 2006).

Persépolis and Pasargadae are places located in the Marvdasht Plain near Shiraz in Fars province in south of central Iran, which is also the birthplace of the advanced art and techniques of the Achaemenid period engineers in about 600 - 400 BC (Tilia, 1978). The first step of the study of the old settlement of "Parseh", the capital of the Achaemenian dynasty, is to find out how the raw materials were mined and carried to the city (Schmidt, 1957).

The Takht-e-Djamshid palace complexes were built during different periods and it is possible that the methods for the mining and the haulage of the stones were also different in each period. In fact, these differences demonstrate the evolution of the mining industry and transportation technology for each time in the Achaemenid era.

There are of course many different mines with different physical and chemical properties in the Marvdasht Plain and it is also possible that the different kinds of stones were used for different purposes in the Persepolis complex (Calmeyer, 1990). To find the answer, petrological studies and geochemical modelling are necessary to obtain the origin of the rocks that were used in the structures of the Persepolis complex (Dickin, 1997). The distribution of the rare elements in the rocks or other archaeological subjects, such as ceramic or bones can provide more information about the places where the stones have been quarried (McGreevy *et al.,* 2000).

In the Marvdasht plain, nearby of the several Achaemenid monuments, several quarries exist which are distributed in the area (Rapp, 1975; Sumner, 1986). For our purpose, several mines have been studied, and a series of studies were carried out on the methods of mining. The mines, which have been explored, are the “White Stone” Mines, the “Mercy Mountain” Mines and the “Black Stone” Mines (Tab. 1).

Table 1. Details of the explored mines

Name	Name in Persian languaje	Location
"White Stone"	Maadan-e Sang-e Sefid, Sivand	Mount Sivand (Tonbe-e Karam, local: Madan-e Almaas Bori
"Mercy Mountain"	Maadan-e Kooh-e Rahmat	Eastern side of Takht-e Djamshid
"Black Stone"	Maadan-e Sang-e Siyah-e Majd Abaad	Mount Majd Abaad southwest of Takht-e-Djamshid

The "White Stone" Mines (Maadan-e Sang-e Sefid), in Mount Sivand, known as Tonbe-e Karam, with the local name of "Madan-e Almaas Bori".

"Mercy Mountain" Mines (Maadan-e Kooh-e Rahmat) located on the eastern side of Takht-e Djamshid.

"Black Stone" Mines of Majd Abaad (Maadan-e Sang-e Siyah-e Majd Abaad), located in Mount Majd Abaad southwest of Takht-e-Djamshid.

This case study is focused on the Sivand Mine, located in the north of Takht-e Djamshid in the Mountains of Sivand. Because of the topographical and geographical changes in the Marvdasht Plain during the centuries and because of active geomorphological changes in this region, such as changes in the course of rivers like the Sivand River and the Kour River, and construction work for roads and dams, it is impossible to find approximately the same path that people used to transport the materials from the mine to the city through the foothills (Yaghmaei, 2004). Some of the suggestions given in this article are based on the observations made by the researchers.

Geographical Location of the Sivand Mine

Sivand or "Sang-e Sefid" Mine (White Stone Mine) is located in the northern side of Mount Sivand, 18 km northeast of Persepolis complex (Fig. 1). The altitude of the mountain is 1974 masl Mount Sivand is connected to Mount Hossain and Mount Palangi (Mount Tiger) in the north and Mount Seidan in the east through the Sivand River. "Dasht-Ball", "Khalaf-Tahoneh", "Shool", and "Sardin" are villages located at the foothills of Mount Sivand. Sivand Mine is at 30° 7' 5'' N longitude and 52° 54' 65" E latitude. The mine has seven burden surfaces for mining. Like other ancient mines in the Takht-e Djamshid region, there are many stonecutting quarries in each section of the mine. All these pits are located on the southern side of the mountain, where there is a steep slope towards the foothills. The elevations of the quarries vary and they are not located on the same topographical lines (Guisan *et al.*, 2007). With regarding to the slope and the corrosion reaction of rivers in this plain, the geographic aspect of this region has been changed during that time (Kraft *et al.,* 1980). Ambient temperature could play a major role in erosion. Increasing temperature usually causes increased rates of erosion (Davidson & Lewin, 1980; Lamb, 1982). The localities of these mines and the topographic nature of the field are shown in Figure 1.

According to satellite images, there exist two kinds of information, which can be used for interpreting the data; namely *spectral* information that indicates electromagnetic reflexes and radiations of each pixel that contains objects on the ground; and *spatial* information that indicate the neighborhood as well as relationship between objects that create shapes and patterns on the ground (Klaus, 2000). In the present research we shall use spatial information rather than spectral (figs. 2 a-b). In future work spectral information of ancient sites will be used and these properties will be combined with other data to find similar locations in the research area. Images show simultaneous visualization of the map and DEM (Digital Elevation Methods) data, which have been overlapped in ERDAS software to allow spatial analyses (Klaus, 2000). The maps are collections of elevation lines (contours) represented as vector data in digital format. DEM data have been created from the contours as raster data and they are used for slope, aspect, elevation and view sheet analyses (Briuer, 1988).

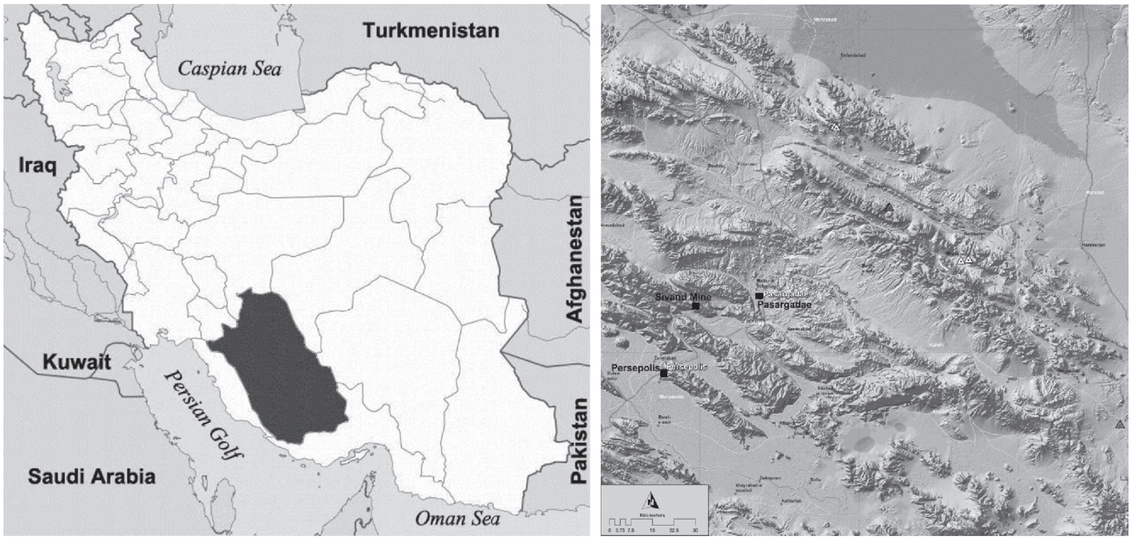

Figure 1. Location of Fars province in Iran and general topographic map of Marvdasht-plain in the central of Iran. The location of mines is signed by the dark area on the left side.

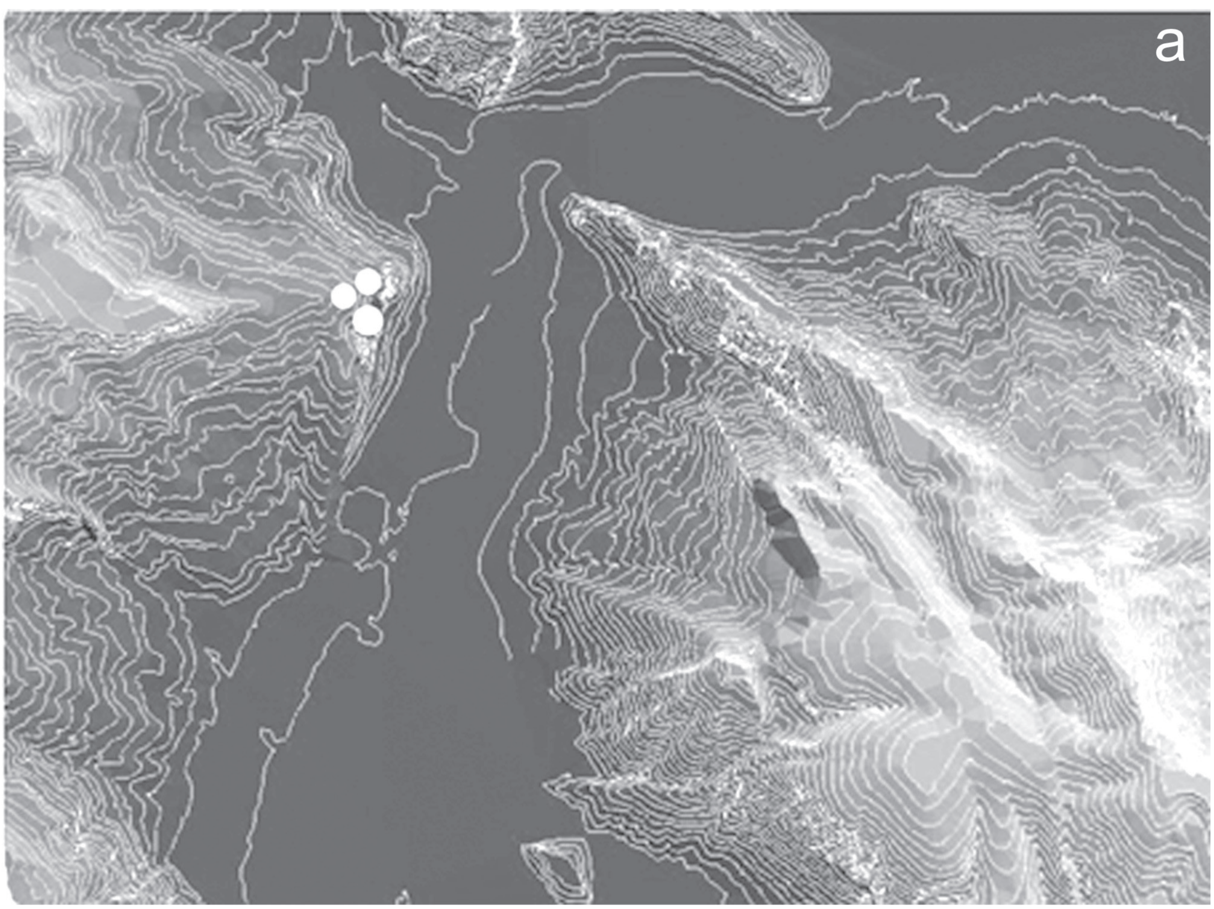

Figure 2 a-b. Synchronic visualization map of the Sivand region and the localities of Almaas Bori mines. Scale: 1:25000

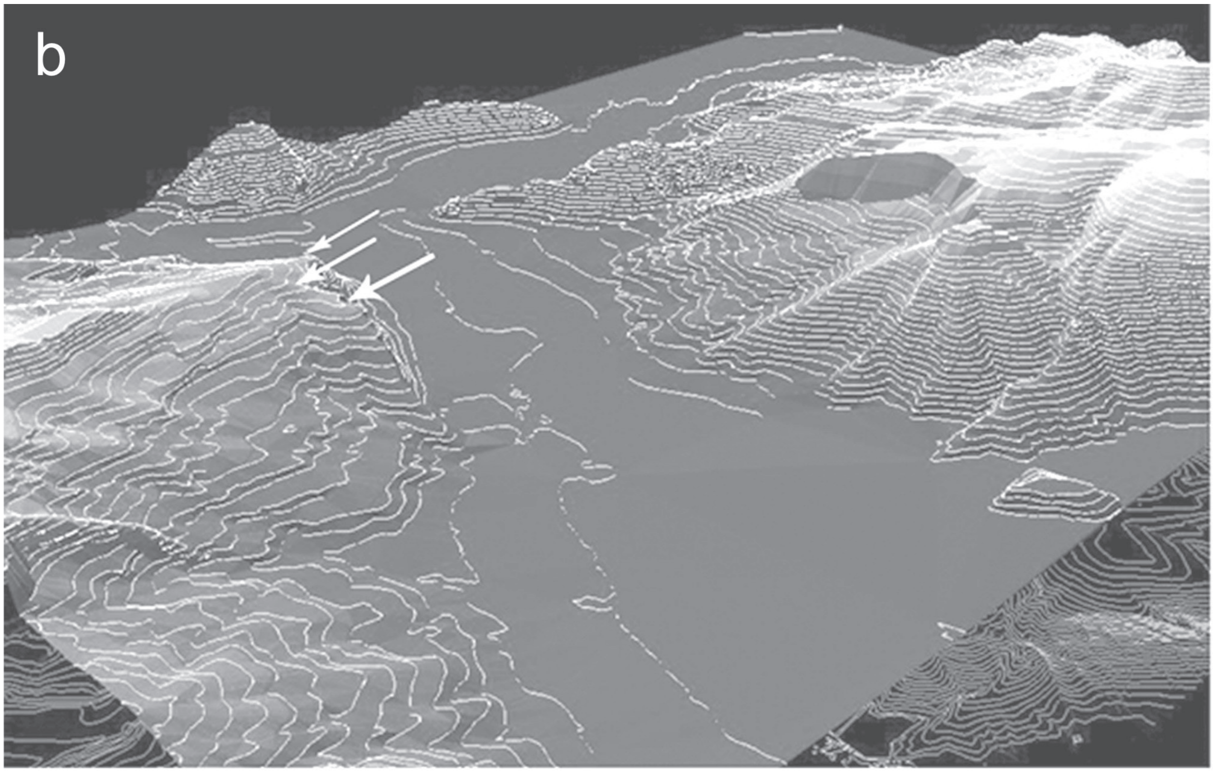

Figure 2 a-b. Synchronic visualization map of the Sivand region and the localities of Almaas Bori mines. Scale: 1:25000

Geological Formation and the Types of Rocks in "Sivand Mine"

"Sarvak" Formation

The lithological composition of the rocks in this formation is limestone, marl (argillaceous limestone) and shale. The order of the strata in this formation from the oldest to the youngest is as follows (Alipour & Hushmandzadeh, 1997):

a) A thin to moderate layer of gray to dark gray argillaceous limestone with thin layers of green to gray shale. The total thickness of this layer is about 50 m. Agzogiral and ammonite from the fossils are found in this layer.

b) Layerings of limestone formation occurrences in light gray to tan with a thickness of about 20 m.

c) A layer of about 40 m of dark gray to black argillaceous limestone.

d) Gray limestone with scattered iron compounds in its top sections, with a depth of about 40 m.

The fossils found in the "*Sarva*k" Formation are *Tertularia spine, Miliolid sp., Agthamina sp., Echinoids sp., Ostracoda, Rotalia sp., Valvulammina sp., Cylindroporalla sp., Vidalina sp., Nezzazata sp., Pseudolituonella sp.* and *Fawenina sp*., all belonging to the late Albian–Cenomanian period, which proves that the "Sarvak" Formation was depositated in the Cenonian geological era. Below the "Sarvak" layer is the compatible "Kajdomi" (Scorpion) layer (Bariand *et al.,* 1965). Indeed, such fossils as described above could be observed macroscopically in some stones in Persepolis.

In order to determine the possibility of usage of the rocks quarried from the "Sivand Mine" in the Persepolis monuments, samples have been studied according to two different aspects, the texture and structure. The petrographical studies provide information in which part of the Takht-e-Djamshid complex the Sivand´s rocks have been used (Michael & Joerg, 2005, not inv). The rocks from Sivand Mine are mostly exogenous and, according to Figure 3, the flowstones belong to the sedimentary terrigenous component category. According to the same diagram from a chemical point of view this group of rocks belongs to IA-impure allo-chemical rocks (Matthes, 2000). In the non-oxidized young section of this layer, small coherent particles of quartz and feldspar are observed, which give a bright colour to the cross-section (Fig. 4). At the edges of the lode, in the old section of the geological strata, chert coating can be seen, where the surface of the rock is black or dark red. Chert shows that chemical oxidation happened very rapidly in this area. The varieties in colour appear due to changes in chemical composition, which are caused by changes in the percentage of decomposition of $CaCO_3$ to $CaMg(CO_3)_2$.

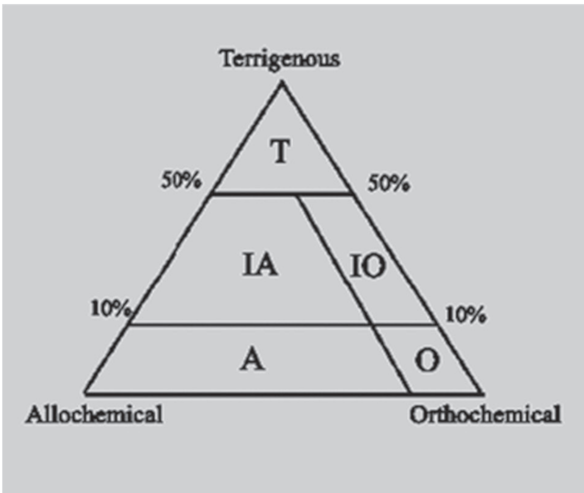

Figure 3. The general classification of flowstones. After Matthes, 2000

Figure 4. Shows a sample taken from the "Sivand Mine"

The solubility of limestone increases with increase of carbonate ions, and therefore with increasing the temperature the solubility of carbonate ions in water will decrease. Increasing the temperature decreases the solubility of calcite and hence, it starts to recrystallize.

$CaMg(CO_3)_2 \rightarrow CaO + MgO + CO_2$ (Matthes, 2000). In this reaction magnesium oxide has two functions.

a) This phase has the ability to transfer iron through the surface of the rock, which brings red, orange and sometimes black colours to the exterior surface of some rocks. Usually in these cases, recrystallization has occurred.

b) Carbonate magnesium releases carbonate ions at a temperature higher than 700° C, which results in recrystallization of calcite (Emami *et al.,* 2008).

According to petrological observations the rocks have porous structure consisting of quartz, calcite, and some magnesite (McGreevy *et al.,* 2000). Phases or opaque elements can also be seen in the texture of stone. Based on the carbonate compounds in the Sivand region, these opaque textures are probably iron phases or iron carbonates as siderite. Based on the size of the granules, the texture behaves as sprite. Elements show noticeable properties in the mined rocks. Quartz, based on its structure, is a common constituent in these formations. Calcite is the second common structure and can also be observed in the samples. The Rocks are fine gravel and hence, the oxidation on the surface is identified as chert (SiO_2).

Mining Methods in the "Sivand Mine"

The mining or rock cutting methods observed in the "Sivand Mine" are among the rarest and most advanced methods in mining engineering as well as the usage of natural resources during ancient epochs. Though there were many other advanced methods of mining in ancient times in Iran depending on the material which has been mined. Each method was unique and special. The high quality of rocks and enormous quantity of the mining used in the Achaemenid era makes it even more notable (Butzer, 1982; Stölner, 2003). Based on field examinations and study of more than twenty mines in the Marvdasht Plain it seems obvious that during the Achaemenid era, the miners have paid deep attentions to all factors in the mines, including two important ones:

1. Gaining the materials with the best quality and most quantity from the available sources.

2. The amount of material taken from the mine and estimating the reservoir of resources in each area.

Studies show that the workers used stone wedges for mining in the “Sivand Mine”, although this method is one of the rarest mining methods used in ancient times, not many studies have been performed about this method of mining. In this method the rocks are first loosened in a place using a stone wedge, therefore a large amount of vertical pressure exerted to the body of the rocks, giving rise to its breaking down (figs. 5 (a) and (b)).

In the Achaemenid era, mining was carried out in two steps. First the stone wedges technique was used and in a second step, the broken pieces were shaped for the desired use. To break rocks into pieces, traditional methods were also employed by using of water and wood chips (Calmeyer, 1990).

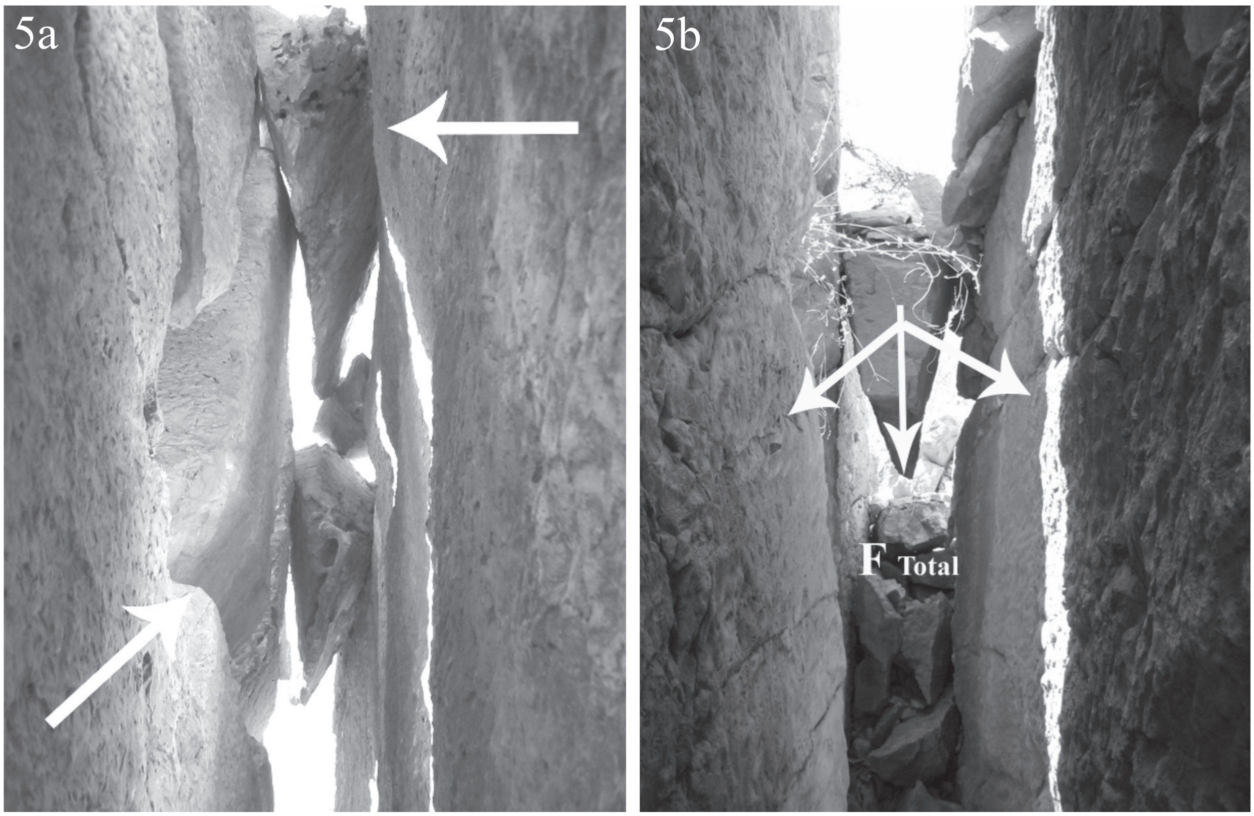

Figure 5 a). Stone wedges were used and the rock was destabilized for separation by creating cracks below the rock. **b)**. Forces were applied gradually in vertical components.

One of the main points to be considered is the size of the pieces. To cause minimal damage, rocks were mined in large pieces, with an average height of ca. 9 to 12 m. To achieve a better result during mining without destructing rocks, a crack with a depth of 10 to 15 cm was dug beneath the rock, which caused it's instability (Fig. 5a). Cracks made the rocks unstable and they could be separated and fell in a predictable direction.

Stone wedges used in these mines have the same size range. The height from top to base was about 1.5 to 3 m. Depending on the volume of the mined rock, the miners probably used wedges with a variable base size. Large amount of force caused by the weight of the wedge and the specific structure of the wedge itself have caused a large amount of isometric force perpendicular to the cut surface of burden, which separated the rock from the pre-weakened points. Forces exerted by the wedge were applied gradually to the rock in two vertical components (Fig. 5b). Judging from all remaining broken stones at the site it seems obvious that the mined rocks were primarily checked and then the cracks and broken parts were separated from the main body, so that cracked and damaged rocks were not used in buildings.

Miners have made a series of stairs for transporting the separated rocks from the stone cutting workshop to the outside. The stairs had a size of about 30 x 30 cm, and the height of each step is 40 cm. These stairs can be seen in all the workshops located in high elevations (Fig. 6).

Figure 6. Stairs used for carrying the mined rocks

Preserving the natural beauty of the mountains was one of the main points that the ancient miners considered in the "Sivand Mines" (a point not to be considered in the modern world). The Achaemenid miners have always made a hallway for each workshop for the mined rocks to have a standard size so that the view of the mountain would not be spoiled, and the workshop itself would be invisible from the outside. More ever, according to their weights, they chose the specific size for the mined rocks to minimize the damage or breakage. The uniquely sized pieces prove this consideration. For the amount of extraction, Achaemenid miners have also considered the slope and stabilities of the walls along with the material as well as the qualities of rocks. They always left a wall in the margins of the mines to retain more stability for the holes that have been dug. These walls are usually oxidized and foliation can be observed on the rock's surface (figs. 7 and 8). Today this matter is also considered for the stabilization and strength of walls in modern mines (Butzer, 1982).

Figure 7. Structures of one of the mining workshops in Mount Almaas Bori. The slope of the workshops have been chosen based on the slope of the mountain

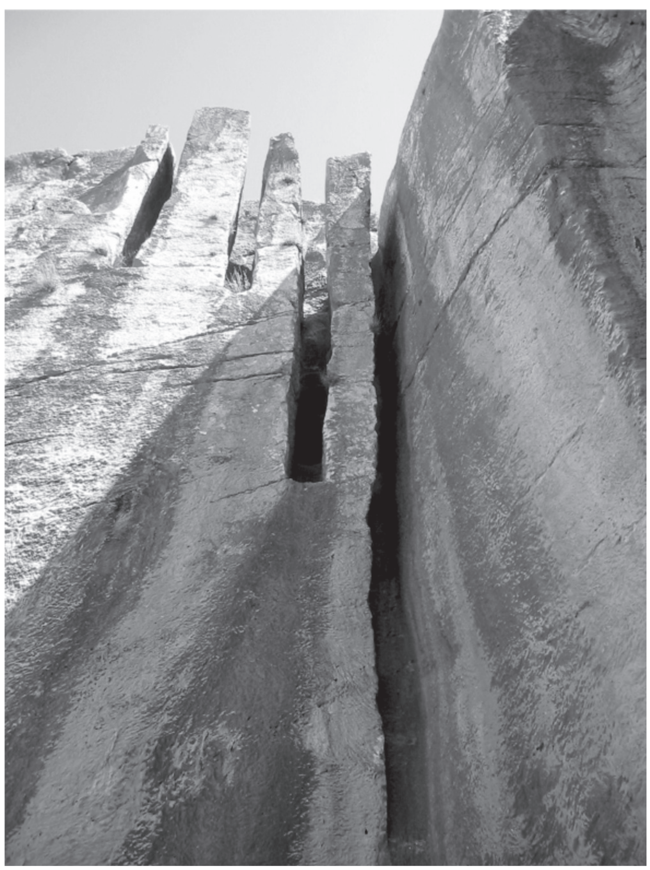

Figure 8. The structure of one of the mining workshops in Mount Almaas Bori. The position of a wedge is shown at the right side of the picture.

There is no clear evidence on the paths and methods of transportation used by the miners. The only indirect evidence remaining is the cone-shaped natural path in the foothills of Mount Rahmat, which was used for transportation. It should be considered that the topographical shape of Marvdasht has changed so much during the centuries.

These kinds of changes are not only seen in Sivand, but can also be recognized in other places in Marvdasht. Research and study on these mines show that this method of mining, using of the stone wedges, was also used in most other mines in this region. There are also two other methods that have been used for mining in lower-volume stonecutting workshops. These methods are:

-Mining by creating sets of parallel caverns in one row on the surface and filling the hollows with wood chips, and macerating the wood chips. The pressure caused by the expansion of the macerated wood chips creates a strong power able to break the rock into pieces along the weak points.

-Using animal skins, such as goat or sheep, filled with wood chips and water causing expansion of the skin, which creates an almost isometric hydrostatic pressure on the walls that will break the rock very symmetrically.

Geoarchaeological data help us to find clues of the techniques that Achaemenians used to provide the raw materials to construct their enormous structures, in such place as Pasargadae, Persepolis, and Naghsh-e Rostam.

Conclusion

The Achaemenian´s culture developed from around 550 B.C. until the capture of the empire by Alexander the Great in 330 B.C. The technology of Achaemenid and the usages of natural and raw materials were widespread for more than 7 countries. The technology of stone cutting and ancient metallurgy at this time is almost a matter of speculation.

The ancient mining activities and rock cutting in the Marvdasht Plain in Fars Province of Iran are examples of the mining activities in this region and in this period of time. Calmeyer (1990) discusses the dating of the material. As before, the technique of excavation and refining of the material remains speculative. Based on what is seen in relieves, there are two methods of rock cutting and processing in this area. The first was to excavate the stones as very huge blocks, and the second process was to keep the stone in finish touch for any purposes.

The term 'Cost surface analysis' is used as the generic name for a series of GIS techniques based on the ability to assign a cost to each cell in a raster map, and to accumulate these costs by travelling over the map. Cost surface analysis is rooted in traditional site catchments analysis, introduced to archaeology by Vita-Finzi & Higgs (1970), who wanted to study the economic basis of prehistoric life by looking at optimal foraging models of resources available within a catchments area or territory associated with a settlement. The resulting cumulative cost surface is a continuous raster map that may use any number of values and subsequently to provide 'cut-off points' or boundaries to the catchment or territory. Calculation of cumulative travel time is a basis for constructing 'accessibility catchments' which are then used as an input variable in a predictive settlement model. Accumulated surfaces will be used for modelling least-cost paths to find most probable ancient routes. These paths will perhaps lead us to find new ancient locations.

There are no metallic materials or something like sledge in this area, and the only aspect of the usage of such tools are the traces of sledge on the walls as parallel lines. These lines prove the high workability of the rocks and the continuity of rock cuttings at this mine. After petrological observations of the rock forming minerals and the comparable stones from some parts of Takht-e Djamshid some similarities can be found.

To obtain an exact interpretation of the originality of materials which are used in Persepolis, it is necessary to carry on a systematic geochemical and isotopic analyses of these materials. Stones have different behaviours against corrosion and weathering depending on their structures. Such investigations could have an authentic interpretation after study and survey of the rock deformations in the original place.

Acknowledgment

The author is grateful to Dipl.-Ing. B. Yaghmai for supporting the GIS field research and for carrying out the GIS analyses, as well as to Professor Siegfried Siegesmund, GWDG Göttingen, and to Professor Pierfrancesco Callieri, Università di Bologna, Italia for their thoroughful review. The author wishes also to thank all colleges at the Parsa-Pasargadae Research Foundation for their encouragements and cooperative relationships.

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