Petrography of Indian, Brazilian and Appalachian itacolumites

Hiroyuki Suzuki* and Daikichiro Shimizu**

Abstract  Approximately 200 years has passed already since the discovery of itacolumite, or flexible quartzite, in Brazil. More than 30 papers have been published on lithology, localities, fabric and origin of flexibility of itacolumite. There is a general agreement that the origin of flexibility is the peculiar fabric of itacolumite in which each quartz grain is well interlocked with each other and each grain is separated by narrow intergranular void space. But precise quantitative description of mineral composition, grain size analysis, measurement of porosity and mechanical behavior and so on have scarcely been carried out. So, as a first part of a serial study on itacolumites, the petrography of itacolumite such as mineral composition, grain size distribution, grain fabric, crystal fabric of quartz and porosity was studied quantitatively. Peculiar character of itacolumites is confirmed by comparison with the non-flexible quartzites of same localities. These results show that the Indian itacolumite is a sedimentary quartzite, while the Brazilian and Appalachian itacolumites are metamorphic schistose quartzites. Furthermore, the flexibility of itacolumites is not related to the total volume of intergranular void space but to the uniform distribution of narrow, interconnected void throughout the rock mass.

Key words: itacolumite, flexible quartzite, petrography, mineral composition, preferred orientation, porosity

Introduction

Itacolumites are quartzose rocks which exhibit some flexibility when they are split into slabs (Fig. 1) (Bate & Jackson, 1987). Since the discovery of itacolumite in the 18th century at Mt. Itacolumi in Brazil (Von Eschwege, 1823), it has passed already about 200 years. In the early stage of research, itacolumite had attracted the attention of geologists as a source rock of diamond (Shepard, 1845; 1859; Wetherill, 1867; Derby, 1882). After no genetic relation between itacolumite and diamond was ascertained (Medlicott, 1874; Oldham, 1889), the flexibility of itacolumite has been the main focus of study. Many papers have been published on localities of itacolumites.

Fig. 1. Flexibility of itacolumite. Thin slab of itacolumite bends well with self load (a: India, b: Brazil).
<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Lithology</th>
<th>Age</th>
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<tbody>
<tr>
<td><strong>Igneous Intrusives</strong></td>
<td><strong>Granites &amp; metadiorites</strong></td>
<td>1650 Ma</td>
</tr>
<tr>
<td><strong>Ajabgarh Series</strong></td>
<td><strong>Calcareous schists</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Hornstone Breccia &amp; Kushalgarh Series</strong></td>
<td><strong>Limestones with breccias</strong></td>
<td></td>
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<tr>
<td><strong>Alwar Series</strong></td>
<td><strong>Quartzites with minor argillaceous intercalations</strong></td>
<td></td>
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<tr>
<td><strong>Unconformity</strong></td>
<td><strong>Biotite schists</strong></td>
<td></td>
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<tr>
<td><strong>Raiolo Series</strong></td>
<td><strong>Marbles &amp; basal grits</strong></td>
<td></td>
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<tr>
<td><strong>Unconformity</strong></td>
<td><strong>Phyllites &amp; limestones</strong></td>
<td>2000–2500 Ma</td>
</tr>
<tr>
<td><strong>ARAVALLI SYSTEM</strong></td>
<td><strong>Grits &amp; Gneiss</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Basal quartzites &amp; grits</strong></td>
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</table>

**Fig. 2.** Precambrian stratigraphy in the northern part of India (modified after Wadia, 1961).

Detailed studies of Itacolumites are few and there is a general agreement that the origin of flexibility is ascribed to a peculiar fabric in which each quartz grain is well interlocked with each other and each grain is separated by narrow free spaces. The intergranular spaces give individual quartz grains a certain freedom of movement, and to the rock as a whole a certain degree of flexibility within limit (Wetherill, 1867; Mügge, 1887; Oldham, 1889). This conclusion was obtained through observation under ordinary microscope.

Other features of itacolumites have been very poorly understood. Lithology of itacolumites has been ill-defined. Itacolumite has been often called “flexible sandstone” (Von Eschwege, 1823; Blake, 1876; Hawkins, 1951; DeVries & Jugle, 1968; Pande & Gupta, 1969; etc.), whereas other authors prefer to use quartzite, usually in the sense of a metamorphic rock (Card, 1892; Derby, 1898; Harder & Chamberlin, 1915; Ginsburg & Lucas, 1949; Carozzi, 1960; Sander, 1970; etc.). The origin of intergranular void spaces is not conclusive. Many authors such as Medlicott (1874), Mügge (1887), Oldham (1889), Ginsburg & Lucas, (1949), Foushee (1954), Perkins (1970) and Verma (1982) have considered that itacolumites are products of chemical weathering at grain boundaries or matrix minerals, whereas Carozzi (1960) and DeVries & Jugle (1968) have proposed mechanical separation of grain boundaries owing to thermal contraction. Quantitative measurements on mineral composition and grain size have never been done. Porosity measurement has been carried out only on the Appalachian (Georgian) itacolumite (Grant, 1950). Reliable physical criteria for comparing the flexibility of itacolumites from various localities are not yet available.

Having been forgotten by modern geologists, itacolumites recently have captured the attention of material scientists who are attempting to find useful “new materials” for technology. The flexibility exhibited by such brittle material as itacolumite may have some suggestion for an invention of ideal “flexible ceramics”, which are eagerly needed in modern industries (DeVries & Jugle, 1968; Dusseault, 1980; Sakanaka et al., 1988). Itacolumites are needed to be reevaluated by scientific method of modern geology and material sciences.

In this article, petrography of Indian, Brazilian and Appalachian itacolumites is quantitatively described and is compared with non-flexible quartzites of same localities. Results of scanning electron microscope and acoustic emission studies on fabric of itacolumites will be presented in a separate paper.
Geologic settings of itacolumites

Indian itacolumite

Itacolumite is known from only one locality, which is situated in the Kaliana Hill, 5 miles to the west of Dadri in Haryana State (Medlicott, 1874; Oldham, 1889). The hill is underlain by a thick sequence of quartzite which belongs to the Alwar Series of Early Proterozoic Delhi System (Fig. 2) (Wadia, 1961). This quartzite has been extensively quarried for millstones. At only one quarry, itacolumite is found as a small mass of about 3 m thick and several tens of meters long in thick layers of non-flexible quartzite which dip vertically (Fig. 3). These quartzite layers have abundant sedimentary structures such as ripple cross- and parallel-laminations. At the present time, this mass of itacolumite is nearly exhausted at the surface outcrop. The specimens of itacolumite used in this study were collected at this quarry by the junior author (D.S.). An additional specimen of itacolumite was donated by the late Dr. D. N. Wadia. A specimen of non-flexible quartzite was also obtained at the same quarry and was examined for the comparison with itacolumite.

Brazilian itacolumite

Itacolumites have been found in several localities in the southern part of Minas Gerais State where thick sequences of quartzite are well developed (Von Eschwege, 1823; Wetherill, 1867; Derby, 1882, 1884). These sequences are called the Carara Quartzite of the Minas Series, and the Itacolomi Series. The latter unconformably overlies the former, and both series belong to the Late Precambrian (Fig. 4) (Oliveira, 1956). The Itacolomi Series is alternatively called the Itacolumn Quartzite (Harder & Chamberlin, 1915). Itacolumite occurs usually in the Itacolumn Quartzite (Bigarella, 1975), but there are some possibilities that some specimens of itacolumite belong to the Carara Quartzite (Derby, 1884). The specimen used in this study was obtained from a geologic supply company and came from Mt. Itacolumn. A specimen of Brazilian non-flexible quartzite was also used for the comparison with itacolumite.

Fig. 3. A quarry where itacolumite had been excavated on the Kaliana Hill in Haryana State, India. a: distant view, b: itacolumite had been excavated only from this narrow zone of the quarry, c: ripple cross-lamination found from non-flexible quartzite layer. (Photographs taken by D.S.)
Appalachian itacolumite

In the Appalachian region, the occurrence of itacolumite is known from several localities of North Carolina, South Carolina and Georgia (Shepard, 1845, 1859; Justice, 1847; Tuomey, 1848; Wetherill, 1867; Grant, 1950; Foushee, 1954; Stuckey, 1958). The geologic settings of these localities are not yet well known. According to Stuckey (1958), the North Carolinian itacolumite is found from the Kings Mountain Group and the Erwin Formation. On the geological map compiled by Bennison (1989), the former belongs to the Upper Proterozoic and the latter to the Lower Cambrian. The specimen used in this study came from Hickory, North Carolina, through a geologic supply company, and so is suggested to belong to the Kings Mountain Group. An additional specimen of itacolumite was obtained from Georgia, and its precise locality is not known.

Preparation of thin section

For preparing the thin section of itacolumite for microscopic observation, a rather larger block (4x4x4 cm) of specimen was cut out with a diamond saw, and cyanoacrylate resin was penetrated into the intergranular void space. Then only the central part (1x1x1 cm) of the now rigid block was again cut out with a diamond saw and thin section was made from this part. This treatment was used for preventing the artificial enlargement of intergranular void space due to the vibration of diamond saw. For clarifying the existence of void space, cyanoacrylate resin being mingled with red dye was forced to permeate into the void space of some specimens in a vacuumized bottle.

Mineral composition

Under microscope, 500 points were selected at constant intervals in each thin section and were counted for the analysis of mineral composition. Thin sections of the Indian and Brazilian non-flexible quartzites, which are suggested to be the mother rock of itacolumite, were also inspected in similar way for the analysis of mineral composition. The results are shown in Fig. 5. Quartz, the main constituent of itacolumites, occupies 80 to 90% of total volume. The Indian itacolumite shows a remarkable difference from the Brazilian and Appalachian (North Carolinian) itacolumites in having a lesser amount of muscovite and a greater amount of matrix which consists of clay minerals. It
should be noted that the total void space of itacolumites is about twice as large as that of non-flexible quartzites. When itacolumite is compared with non-flexible quartzite in mineral composition, it has a lesser amount of muscovite and a greater amount of void space.

**Grain size and preferred orientation**

The same thin section as used for the analysis of mineral composition, was employed for grain size and fabric analyses. The apparent longest diameter and its orientation of 400 quartz grains were measured for each thin section which was cut parallel to the bedding plane (Indian itacolumite) or foliation plane (Brazilian and Appalachian itacolumites). The results are shown as histograms and cumulative curves of grain size distribution (Fig. 6). Median diameter, mean diameter and sorting coefficient were calculated for each specimen. These data are not converted to those by sieving method. The Appalachian (North Carolinian and Georgian)
Fig. 7. Orientation diagrams of quartz grains of itacolumites. (The abscissa is arbitrarily chosen on the bedding or foliation plane.)

Itacolumite is the most fine-grained. The Indian itacolumite is the most coarse-grained and has the largest value of sorting coefficient.

As shown in Fig. 7, the preferred orientation of quartz grains is clearly observed in the Appalachian and Brazilian itacolumites, whereas it is obscure in the Indian itacolumite.

Furthermore, using a universal stage, the orientation of optical axes of 300 quartz grains was measured for each thin section of itacolumite. The orientation data were plotted on a Schmidt equal-area projection net and contour diagrams were drawn as shown in Fig. 8.

The Brazilian and Appalachian (Georgian) itacolumites indicate a strongly-preferred orientation of optical axis. The orientation diagram of the Appalachian itacolumite shows a single maximum encircled by a girdle pattern with maxima situated on a small circle. That of the Brazilian itacolumite shows a girdle pattern with maxima situating on a large circle. The orientation pattern of the Indian itacolumite is rather widely scattered except some concentration in a single maximum.

Porosity

Small (4–8 cm³) cubic blocks of itacolumites were cut out and dried in an oven at 95 degrees centigrade for 48 hours. Using a helium-gas-displacement pycnometer, the apparent solid volume of the block was measured. Then, the surface of the block was coated with thin film of cyanoacrylate resin to prevent air from
Table 1. Effective porosity (in percent) of itacolumites and non-flexible quartzites measured by helium-gas-displacement method

<table>
<thead>
<tr>
<th>ITACOLUMITE</th>
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<tbody>
<tr>
<td>India</td>
<td>15.20, 17.32, 18.63</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>5.79, 6.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Carolina</td>
<td>10.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td>8.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NON-FLEXIBLE QUARTZITE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>6.43, 11.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>4.75</td>
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</table>

Percolating into void space, and the bulk volume was also measured with the pycnometer. Effective porosity was calculated from these two values. For the comparison with itacolumite, the effective porosity of the Indian and Brazilian non-flexible quartzites was also measured in the same way. The results are shown in Table 1. The effective porosity of itacolumites has values ranging from 6 to 19%, and that of the Brazilian itacolumite is twice or three times as large as that of the Brazilian and Appalachian itacolumites. While the effective porosity of the Indian itacolumite is 1.5 to 3 times as large as that of the Indian non-flexible quartzite, that of the Brazilian itacolumite is 1.2 to 1.5 times as large as that of the Brazilian non-flexible quartzite.

Microscopic texture of itacolumites

Quartz grain
Quartz is the main constituent mineral of itacolumites. Quartz grains of the Indian itacolumite are more irregularly shaped and look more dusty or cloudy than those of the Brazilian and Appalachian one (Plates I and II). One grain is commonly composed of one crystallographic entity, though some grains exhibit wavy extinction. It should be noted that some quartz grains of the Indian itacolumite exhibit faint remnant of dust rims of original clastic grains (Fig. 9). Grain boundaries of quartz in the Brazilian and Appalachian itacolumites often meet at triple junctions with interface angles of about 120 degrees.

Muscovite grain
Although rare muscovite crystals of the Indian itacolumite are irregularly shaped, those of the Brazilian and Appalachian itacolumites are fresh, clear and usually occur between quartz-quartz boundaries. Basal planes of muscovite run nearly parallel to each other and produce distinct foliation in the Brazilian and Appalachian itacolumites (Plates I-2 and II-1). It is noted that some muscovite crystals are completely or partly replaced by cyanoacrylate resin (Fig. 10). This fact indicates that these muscovite crystals were chemically dissolved and the intergranular space was not caused by mechanical separation of grain boundary.

Other accessory minerals
Tourmaline and zircon are rarely but consistently found in the Indian and Brazilian itacolumites. Zircon grains are well rounded and some of them are purplish in color. A small...
quantity of iron minerals is found in the Appalachian itacolumite.

Matrix

Interstitial matrix occupies a wider area in the Indian itacolumite. The X-ray diffraction analysis of the Indian itacolumite showed that the clay minerals constituting the matrix is dickite, a member of the kaolinite group. It is noted that, in the Brazilian and Appalachian itacolumites, matrix minerals are scarcely observed.

Intergranular void space

When itacolumite is compared with non-flexible quartzite in thin section under plane polarized light, the existence of uniform intergranular void spaces in itacolumite is easily ascertained (Plates I and II). Owing to lack of intergranular void, the grain boundary of quartz in non-flexible quartzite cannot be well ascertained in plane polarized light (Plate II-2,3). The common feature of all itacolumites is that all quartz grains are separated from each other by narrow intergranular void space. The intergranular void space in the non-flexible quartzite usually exists as an isolated small patch (Plate II-2).

Fig. 10. Photomicrograph of Brazilian itacolumite which suggests chemical dissolution of muscovite crystals. (1: completely dissolved, 2: partly dissolved, 3: not yet dissolved) The void was replaced with cyanoacrylate resin for this study. (In plane polarized light. Width of photomicrograph is 0.94 mm long).

Discussion

Fabric of itacolumites

As previously described repeatedly in many literatures, the common feature of itacolumites is the peculiar grain-to-grain fabric in which quartz grains are interlocked and separated by narrow intergranular void space. The void is not isolated but consistently interconnected with each other. This fabric produces the flexibility of the rock.

In the case of the Brazilian and Appalachian itacolumites, DeVries & Jugle (1968) pointed out that the intergrowth of muscovite and quartz contributes to the rigidity of rock. Although it might have a role in some part, some muscovite flakes were completely or partly dissolved away and open spaces are left as shown in Fig. 10. Hence, their role is not so significant.

Because observation of fabric in thin section is only limited to two-dimensional view, three-dimensional observation under scanning electron microscope will be needed for further studies.

Porosity of itacolumites

According to Grant (1950), porosities of Georgian itacolumite are 19.7 to 24.2 %. These values are not precise because they were simply
calculated from bulk density of itacolumite and density of quartz on the assumption that itacolumite was solely composed of quartz. In this study, porosities of itacolumites are 6 to 19% as shown in Table 1, and these values are larger than those of non-flexible quartzites. Transformation of non-flexible quartzite to itacolumite may be accompanied by an increment of porosity. According to Pettijohn et al. (1972), most Phanerozoic sandstones that form petroleum reservoirs commonly have porosities of 5 to 20%. These sandstones do not exhibit any flexibility. This fact suggests that the flexibility of itacolumite is not related to the total volume of void space but to the uniform distribution of narrow, interconnected void throughout the rock mass.

**Sedimentary rock or metamorphic rock?**

Itacolumite has been obscurely described as either sedimentary or metamorphic rock. In spite of being similar quartzose rocks and having analogous grain-to-grain fabric, the Indian itacolumite is distinct from the Brazilian and Appalachian itacolumites in the following features; 1) more irregular grain shape, 2) coarser grain size, 3) lesser sorting, 4) dusty appearance of quartz, 5) existence of remnant of dust rims, 6) lacking of preferred orientation of grain shape and optical axis of quartz, 7) lesser amount of muscovite, and 8) greater amount of matrix.

These features exhibited by the Indian itacolumite will be ascribed to those of sedimentary quartzite which experienced secondary overgrowth of quartz due to pressure solution during profound diagenesis (Skolnick, 1965). The Indian itacolumite is lithologically defined as quartzose sandstone.

On the other hand, the Brazilian and Appalachian itacolumites have common features as follows; 1) equigranular grain shape, 2) triple junction of grain boundaries, 3) finer grain size and greater sorting, 4) clear appearance of quartz, 5) distinct preferred orientation of grain shape and optical axis of quartz, 6) straight boundary between quartz and muscovite, and 7) scarcity of matrix minerals.

These features are very similar to those of "polygonal microstructures" which are observed in metamorphic quartzites (Skolnick, 1965; Wilson, 1972). Quartz-rich part of metacherts has also similar "polygonal microstructures" (Masuda et al., 1991) but quartz-poor part of metachert exhibits microstructures dissimilar to itacolumite. Therefore the Brazilian and Appalachian itacolumites must be lithologically called micaceous schistose quartzites.

**Conclusion**

For clarifying the petrography of itacolumites (flexible quartzites), thin sections of the Indian, Brazilian and Appalachian itacolumites were observed under optical microscope. Quantitative measurements on mineral composition, grain size, orientation of grain shape, optical axis of quartz and porosity were also carried out. Peculiar character of itacolumites was ascertained by comparison with the non-flexible quartzites of same localities.

Common features of all itacolumites are peculiar grain-to-grain fabric in which quartz grains are well interlocked and separated from each other by narrow intergranular void spaces.

The intergranular void spaces are not so voluminous as those of reservoir sandstones but they are uniformly narrow and are interconnected throughout the rock mass.

The Indian itacolumite is distinct from the Brazilian and Appalachian itacolumites in grain shape, grain size, sorting, orientation of grain shape and optical axis, quantity of muscovite and matrix, mode of grain junction, etc. The Indian itacolumite is lithologically defined as sedimentary quartzite (quartzose sandstone), whereas the Brazilian and Appalachian itacolumites are metamorphic quartzites (micaceous schistose quartzites).

**Acknowledgements**

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References


Foushee, E. D., 1954, A report of the flexible sandstone or itacolumite of Stokes County, North Carolina. Compass (Sigma, Gamma, Epsilon), 31, 78–80.


Hawkins, A. C., 1951, Flexible sandstone. Mineralogists, 19, 34.


(in Japanese with English abstract)


(要旨)


イタコルマイト（構造型コートサイト）の構造性の成因を現代的手法で解明する基礎として, その岩石学的特徴を明確するために, ブラジル, インドおよびアラチア産のイタコルマイトおよびその母岩を対象に, 華下での観察とともに鉱物組成, 粒度组成, 石英粒子の形態および光軸方位の固定配列, 空隙率の測定を行った。各イタコルマイトの組織に共通する特徴は, 結晶の石英粒子がよくかみ合っていること, 各石英粒子の間に狭いような隙間が存在することである。その一方で, インド産イタコルマイトとブラジルおよびアラチア産イタコルマイトの間には, 粒子の形態, 粒径および淘汰度, 粒子および光軸の固定配列の程度, 基質の量, 粒子の接合様式などに明らかな相違が存在する。この相違は前者が岩石学的には堆積性コートサイト（石英質砂岩）, 後者が変成コートサイト（雲母片状コートサイト）に分類されることを示している。

Explanation of Plates

Plate I (Each photomicrograph is 3.4 mm in width)

Plate II (Each photomicrograph is 3.4 mm in width)
2. Photomicrograph of Indian non-flexible quartzite, in plane polarized light.
3. Photomicrograph of Brazilian non-flexible quartzite, in plane polarized light.