K-Hilbe

BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION IN FUZHOU GEOTHERMAL FIELD, FUJIAN PROVINCE, CHINA

Zhang Jinzhang*
UNU Geothermal Training Programme,
National Energy Authority,
Grensasvegur 9, 108 Reykjavik,
ICELAND.

*Permanent address:
Geological Bureau of Fujian,
Fujian Province,
CHINA.

ABSTRACT

The Fuzhou geothermal field is located within an extinct Cenozoic-Mesozoic volcanic belt which is a part of the Circum-Pacific Orogenic and Volcanic System. The geothermal field is, however, of a low temperature non-volcanic type. It is mainly situated in the basement rocks of Yenshan granites and Quaternary conglomerates. In the former rock type, fractures and fissures control the geothermal water flow, whereas in the latter, unconformity between the basement rocks and the Quaternary system plays an important role. From mineralogical observations, an alteration scheme for the Fuzhou geothermal field is proposed, where the alteration is divided into three episodes. The alteration minerals are of a very complicated origin and regular zoning is lacking. The alteration minerals thought to be in equilibrium with the present low temperature system (zeolites, calcite, quartz and clay minerals) are mainly found in fractures and pores. Most of the alteration recognized in the Fuzhou low temperature field does not confirm well with the present thermal regime. This can be explained by episodic flow of hydrothermal fluids at different temperatures and with different physical and chemical features. The key issues are therefore to differentiate the alteration minerals associated with the present thermal water from the older alteration and to construct a three dimensional model of the alteration.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Scope of training

The author of this report was awarded an UNU Fellowship to attend the 1984 six months Geothermal Training Programme held at the National Energy Authority in Iceland. The programme included an introductory lecture course (4 weeks) dealing with the various fields of the geothermal sciences. The course included also some field excursions (3 weeks) such as a visit to an extinct and deeply eroded central volcano (Geitafell) and to the Vesturhorn intrusive complex, visits to a number of district heating services, to the power station at Krafla and to many of the low and high temperature resources in the country. Apart from these the author had the unique oportunity to observe a volcanic eruption in the Krafla area, which started at 23:00 the fourth of September, 1984.

The author's specialized training in borehole geology included theoretical and practical aspects of X-ray diffraction (XRD) analyses (2 weeks) and training on a drill site at the Nesjavellir high-temperature area (1 week). Most of the time was, however, spent on studying the hydrothermal alteration of three drillholes (DW1, ZII+2 and ZII-7) from the Fuzhou low-temperature field, Fujian province, China.

This report firstly outlines earlier studies of the senior scholars on the regional geology of the Fuzhou geothermal field (Bureau of Geology and Mineral Resources, 1979; Second Team of Hydrogeology and Engineering Geology, 1980; Wang et al.,1982). Following that comes a description of the hydrothermal alteration observed in three wells in the Fuzhou area. This latter part of the report is based upon the data collected in Iceland which unfortunately is limited due to the very few samples brought to Iceland and to lack of general informations about the area at the time of writing of this report.

1.2 Purpose of study

The relationship between hydrothermal alteration and geothermal activity has been thoroughly studied in many geothermal fields in the world, e.g. in the United States of America, New Zealand, Iceland and Japan (Browne, 1977; Ellis and Mahon, 1977; Steiner, 1977; Kristmannsdottir, 1978; Kristmannsdottir and Tomasson, 1978). These studies have shown that the formation and stability of hydrothermal mineral assemblages are controlled by many factors, such as temperature, fluid composition, original rock composition, permeability, pressure, duration of activity and the rate of water or steam flow.

Some alteration minerals have been oberved to be strongly temperature dependant and have therefore been used as temperature indicators. Amphibole, for instance is thought to reflect temperatures >280°C, whereas the presence of garnet indicates temperatures >320°C and epidote is usually observed at temperatures above 240-260°C (Browne, 1977). Studies of the Icelandic geothermal areas have indicated that a strong relation exists between the hydrothermal mineral assemblages and the rock temperature. As a result, a sequence of mineral assemblages related to increased temperature (and depth) has been observed (Kristmannsdottir, 1976, 1978; Kristmannsdottir and Tomasson, 1978; Franzson, 1983). The progressive alteration in the high temperature areas have lead to the formation of four distinct alteration zones, i.e. a smectite-zeolite zone, a mixed layer clay zone, a chlorite-epidote zone and a chlorite-amphibole zone. In the low-temperature areas, where zeolites and smectite are common, thefollowing four alteration zones have been distinguished; a chabasite zone, a mesolite/scolesite zone, a stilbite zone and a laumontite zone (Kristmannsdottir and Tomasson, 1978).

Pressure existing in the upper parts of active geothermal systems is usually considered to be too low to have any significant effect on the secondary mineral assemblages. However some mineral reactions are pressure-dependant and as pointed out by Browne and Ellis (1970) pressure is an indirect variable as it controls the depth and temperature of boiling, a process that changes the fluid composition (esp. pH) and therefore affects the mineral stabilities.

Former geothermal studies have also demonstrated that permeability and fluid composition are important controlling factors. In poorly permeable rocks for instance equilibrium between the rocks and the circulating fluid is seldom achieved and primary minerals or glass can persist to high temperatures. Fluid compositon has also been shown to affect the mineral assemblages. In Japan, where the pH of the thermal water is near-neutral, quartz, K-mica, heulandite, wairakite, albite and adularia have been observed, while the deep acid fluid produces alunite and kaolinite (Hayashi, 1973). In Iceland the formation of anhydrite has mainly been connected to saline waters (Bjornsson et al., 1970) and zeolites have been observed to be more abundant in hydrothermal areas where the circulating fluid is dilute (Kristmannsdottir and Tomasson, 1978). The concentration of gases like H_2S, CO_2 and O_2 affects also the hydrothermal mineral assemblages (Steinthorsson and Sveinbornsdottir, 1981; Armannsson et al., 1982).

From the above it is clear that much valuable information about thermal areas can be obtained by studying the alteration mineralogy. This has led to the author's interest to study the hydrothermal alteration in the Fuzhou geothermal field. The purpose is to recognize its general and specific characteristics and eventually to compare it to other geothermal fields in the world.

2 THE GEOLOGICAL AND GEOTHERMAL SETTING IN FUJIAN PROVINCE

2.1 Geological setting

The Fujian Province lies astride the Circum-Pacific Orogenic and Volcanic Belt. According to the plate tectonics theory, the area is located at the intersection between the Europe-Asian plate on one hand and the Pacific Plate on the other. The former has been intensively subjected to compression as the Pacific Plate is constantly colliding against it and being subducted below it. The crustal thickness varies (34-39 km), but in general it decreases towards the east (Bureau of Geology and Mineral Resources, 1979).

In the Fujian Province three tectonic events have been recognized (Figure 1):

1. Caledonian upwarded district in NW-Fujian; This tectonic event is evidenced by metamorphic rocks, e.g. schists, gneisses, granulites and Caledonian granites.

2. Varisean depression in SW-Fujian; This event is mainly made up of carbonate rocks, chalk, clastic rocks (along with intermediate-acid volcanic rocks) and Varisean and Yenshanian granites.

3. Cenozoic-Mesozoic volcanic belt in E-Fujian; Rocks belonging to this third event are widely distributed intermediate-acidic volcanic rocks and granites from Jurassic and the Cretaceous periods.

From geological and geophysical surveys, the deep faults in the Fujian area (Fig. 1) are relatively well known. Four of them trend NE and these are intersected by five faults with a NW direction. In addition a few faults have east-westerly direction.These fault-zones form the basic tectonic framework of the Fujian Province, especially the Zhen He - Dapu Fault Belt which is situated near the centre of the Province. These fault-zones are believed to have originated within a subduction zone environment during early Palaeozoic (Caledonian) (Wang et al., 1982; Zhang, 1984). However, it is likely that these were tectonically reactivated at later times.

2.2 The geothermal potential

The distribution of hot springs in the Fujian Province is shown in Fig. 1 (Second Team of Hydrogeology and Engineering Geology, 1980) The springs are of a non-volcanic type, with temperatures ranging from 36-120°C (most commonly 60-100°C). Natural discharge is generally about 1-5 l/sec (the maximum is 15,4 l/sec) and the total output is 1000 l/sec (86400 tonnes/day). Fig. 1 demonstrates that the springs are scattered over most of the area, except were rocks of tectonic unit 3 are situated, but there springs are scarce.

The geothermal manifestations are clearly related to the NE, NW and EW structural zones, and are particularly conspicuous at the intersections between the faults. However, in the coastal regions the hot springs are mainly distributed between the Changle-Shaoan and Fuan-Nangiang Fault Belts.

The chemical composition of the thermal water is variable. In the western part of the province the water is predominantly sodium bicarbonate rich and the mineralization of the water is usually lower than 1 g/l. On the east coast, however the mineralization of the water is generally higher than 3 g/l and can be as high as 40 g/l. This is evidently caused by the penetration of sea water into the bedrock thus increasing the concentration of sodium chloride in the thermal water.

The thermal water generally contains 6-10 mg/l of F and the pH of the water is >8. S, K, Na, Cl, SiO_2 and trace elements, such as Mo, Re, Ga, I and gases mainly N_2, CO_2, as well as radioactive radon are commonly present in the thermal water.

The Fujian geothermal area has not been explored by drilling with the exception of the Fuzhou, Zhangzhou and Xiaman fields.

3 THE FUZHOU BASIN GEOTHERMAL FIELD

3.1 Introduction

The Fuzhou Basin Geothermal Field is situated in the eastern part of the Fujian Province (Fig. 1). It is one of the most famous hot springs localities in China and has a long history. In 1959 a reconnaissance survey of the geothermal area was initiated and in 1976 a further research programme was launched in order to evaluate the geothermal potential. Several shallow wells (<600 m) were sunk into the area, but only one well extended down to 900 m depth. The geothermal water has been directly used in agriculture (e.g. crop breeding and nursing young plants), for fishing during winters, industry (such as stogring leather and refrigeration), bathing and swimming.

The geothermal system belongs to the hydrothermal convective type. These occur wherever a fluid circulation is able to develop in sufficiently permeable rocks. The water, which on the grounds of hydrogen isotopic ratios is considered to be of meteoric origin (Second Team of Hydrogelogy and Engineering Geology, 1980) is considered to be either heated by a normal geothermal gradient or some nearby heat source.

3.2 General geology

The geological map of the Fuzhou field is shown in Fig. 2. The stratigraphy based upon surface mapping and well logging (Second Team of Hydrogeology and Engineering Geology, 1980) is summarized below:

1) Nan Yuan formation; This formation is predominantly found in the high mountains around the basin (Fig. 2). It consits of a suite of intermediate and acidic volcanic lavas and volcanoclastic rocks of upper Jurassic age.

2) Metamorphic volcanic rocks; This formation is found in the northern part of the basin. The rock types are blasto-muscovite granite, blasto biotite granulite, blasto chlorite granulite and schistose rhyolite.

3) Quaternary system; Two major stratigraphic units have been recognized within this sequence, i.e. the Pleistocene Series (Long Hai Formation) and the Holocene Series (Chang Le Formation). The rocks are composed of yellow, fine to coarse grained sandstone, dark grey muddy sand, yellow coloured sandy gravel, pebble and clay.

4) Intrusive rocks; The magmatic rocks were intensely intruded during the Yenshan Movement. The granites (which include intermediate, acidic and slightly alkaline rocks) form batholiths, apophysis, dykes and dyke swarms, where the last named generally trend in northeasterly direction. From cross cutting relationships and petrographic studies eight intrusive phases have been distinguished. These are; granodiorites, medium-coarse grained biotite-granite, riebeckite-potash feldspar granite, fine-grained granite, diorite, quartz porphyritic syenite, diorite- and porphyritic diorite.

3.3 Aquifers

The locations of aquifers in drillholes ZK6, ZK3, ZK7, ZK1 and ZK2 are shown in Fig. 3 (Second Team of Hydrogeology and Engineering Geology, 1980). These wells are situated in the center of the Fuzhou geothermal field (see Fig. 2), just to the south of the Chou Dou village. The Figure demonstrates that the aquifers are mainly situated in the fractures between the intrusives and host rocks, along fracture planes and along the boundary between the sandy gravel and the muddy sand of the overlying Quaternary system. In the Fuzhou field the high temperature aquifers are predominantly controlled by the Chou Dou-Wang Zhuang Fault Zone, which is made up of four parallel faults (trending NNW and dipping 65-85° towards east). The total discharge from each well is generally about 15-16 l/sec and the temperatures at the well heads range between 85-94.4°C. As the temperature of the thermal water decreases away from the fault zone the geothermal exploration has been concentrated along it.

3.4 Physical and chemical characteristcs of the thermal water

The exploration of the thermal field (Second Team of Hydrogeology and Engineering Geology, 1980) has shown that the temperature of the thermal waters varies from 40°C to 107°C, but usually lies in the range from 80 to 100°C. The dominant cations are K and Na (80%) wheras Cl and SO_4 are the dominant anions. The pH of the water ranges from 7.9 to 9.0 and the mineralization is less than 1 g/l. With respect to chemistry, the water can be divided into two groups. The water to the north of the Wang Shan-Yu Shan Fault, is of a SO_4-Cl-Na type with mineralization in the range 500-600 mg/l and electric transmission coefficient up to 1.0 to 1.7. On the other hand, to the south of the fault the water is of a Cl-SO_4-Na or Cl-Na type with mineralization and electric transmission coefficient of 900 mg/l and 2.4 respectively. The thermal water commonly contains some radioactive radon which has a zonal distribution decreasing towards ENE. The concentration of radon is inversely related to the water temperature and to the water discharge. The metal elements are mainly Mo, Ti, Cu, Ga. The amount of N_2 is about 80 % of the total gases, whereas O_2 is about 4-10% and CO_2, CO, H_2 are only in minor amounts.

4 BOREHOLE GEOLGY

The wells investigated in this study i.e. DW1, ZII-7 and ZII-2 are located in the northern sector of the geothermal field, approximately 2 km south of Xin Dian village. They respectively reached to the depths of 468 m, 201 m and 160 m. The respective bottom-temperatures in the wells are 83.4°C, 41.9°C and 52°C. Some of the information regarding petrography and alteration is attributed to borehole geologist Chen Chuanyan (personal communication). However, prior to the present study many minerals especially zeolites and clay minerals had never been exactly identified before.

4.1 Analytical techniques

While in China the author selected some core-samples from horizons which showed marked changes in lithology and secondary mineral assemblages. A total of 35 thinsections were studied with respect to alteration minerals and their textural relationship. In order to confirm and complete the identification of the secondary minerals some XRD analyses were carried out. Samples were either taken directly from veins and pores in the hand samples or in the case of sheet silicates by the analytical method described in the Appendix.

4.2 Lithology

A brief petrographical description of the main rock types penetrated by wells DW1, ZII-2 and ZII-7 are given below, and a geological profile of well DW1 is shown in Figure 12. A conspicuous unconformity separates the Quaternary 1) from the underlying rock types 2)-6).

1) Quaternary sandy gravel; The thickness of the Quaternary rocks ranges from 20-50 m.The Quaternary conglomerates are composed of pebbles which are made up of quartz and various rock types such as granite, diabase, diorite-porphyrite and lamprophyre and these are cemented mainly by argillaceous matrix. The pepples vary in size

from 0.4-5.0 cm.

2) Intermediate-coarse grained biotite-granite; The primary minerals of this granite are quartz, orthoclase, perthite, biotite, albite-oligoclase along with accessory minerals such as sphene, apatite, zircon and magnetite. The biotite has frequently been broken down to form chlorite but has preserved its pseudomorphic form. The speckled apperance in the cores of feldspar is caused by fine inclusions of sericite.

3) Acidic porphyry rocks; These rocks were found predominantly in drillhole DW1. The phenocrysts amount to 5-15 % and are composed of feldspar, quartz or both. Accordingly, these porphyritic rocks have been termed; feldspar porphyry, quartz porphyry and fine grained granite porphyry. The textures are micrographic, granophyric and spherulitic. In addion to these textures, the quartz-phenocrysts have been observed to have corrosion rims and glomeroporphyritic textures. Some vesicles have been observed in these rocks, which along with the textures indicate that these rocks may have formed under hypabyssal and ultrahypabyssal conditions.

4) Diabase; It is commonly fine grained or microcrystalline and is characterized by intergranular texture. The primary minerals are mainly augite, amphibole and basic feldspar, but magnetite is an abundant accessory mineral. The ferromagnesian minerals are frequently pseudomorphed to chlorite. From textural studies and modal analyses the rocks have been divided into three subgroups i.e. diabase, quartz diabase and diabase porphyrite with pandiomorphic phenocrysts of plagioclase.

5) Fine-grained diorite porphyrite; This rock is mainly made up of hornblende and andesine with a minor amounts of biotite, augite and quartz. A small amount of interstitial quartz is also present. The rocks has a porphyritic texture, where the phenocryst species being plagioclase. The matrix has a hypidiomorphic granular texture.

(6) Rhyolite-porphyry; It is found at 107 m depth in well DW1 but had earlier been named diorite-porphyrite. The rock is grey to green in colour and has a conspicious rhyotaxitic quartz and feldspar phenocrysts, which have a resorption borders or pandiomorphic crystal form. The phenocrysts amount to about 10-15 %. A minor amount of cryptocrystalline biotite and amphibole may be present. Some diabase xenoliths up to 15 mm in diameter are present in the rock.

4.3 Hydrothermal alteration

A wide range of alteration minerals were identified in the Fuzhou drillholes. In order to explore the present thermal system by means of the alteration mineralogy it is necessary to resolve the alteration mineral assemblages with respect to time. This is because only the alteration minerals that are in the closest time relation to the present system are useful for interpreting the present geothermal field. Detailed studies of cross-cutting relationships between mineral veins as well as of infilling sequences in fractures and pores are useful to establish a relative timescale for the alteration (Franzson, 1983; Fridleifsson, 1984). Unfortunately few cross-cuttings were observed in the present study as the available samples were too few and furthermore were not particularily selected with this purpose in mind. However, wherever possible this method was used to attain the relative ages of the mineral sequences, but in most instances microscopic studies of the alteration minerals and their textural relationships hadto suffice.

The following factors are believed to characterize the alteration mineral assemblage that is associated to the present activity:

1. It occurs as fracture- or pore fillings
2. It is unlikely to replace the primary minerals
3. The minerals are in simple textural relationships.

Results from former studies on low temperature areas have also been valuable in establishing the relative time sequence.

In the following section the secondary minerals which are believed to relate to the present thermal regime will be discussed first but followed by description of alteration minerals which are thought to be related to older events.

4.3.1 Alteration minerals related to the present thermal water

Four main groups of alteration minerals are believed to relate to the present system. These are 1) zeolites 2) clay minerals 3) carbonates and 4) quartz:

1) Zeolites; Zeolites are common hydrothermal alteration minerals in the Fuzhou geothermal field. They are seen as a cement material around the quartz pebbles in the Quaternary conglomerates but have also been observed at different depths in the intrusive rocks, mainly between 160-280 m depth in well DW1. Zeolites occur mainly in fractures, vesicles and pores often associated there with calcite and quartz, but do not seem to replace any primary minerals.

Two types of zeolites were identified :

a) Stilbite; In drillholes ZII-2 and DW10 stilbite was found in veinlets that were up to 2 mm in width. It is colourless with glass luster and rhombic prismatic crystal form. Some XRD analyses were carried out and the results are shown in Table 1 and Fig. 4. These results confirm reasonably well with data on synthesized stilbite (Selected Powder Diffraction Data for Minerals, 1974). However some disagreement is observed in peak intensities which could be explained by chemical differences between the natural stilbite and the synthesized one (Table 4).

b) Laumontite; This is the most common zeolite in the Fuzhou field. It was identified in well DW1 between 160-310 m depth and in well ZII-2 between 110-150 m depth. It occurs as fracture- or pore fillings in radiated aggregates, milky white to pink in colour and usually in association with calcite. XRD results for laumontite are shown in Table 1 and in Fig. 5. Conspicuous irregularities were observed in the laumontite structure in samples which showed a strong 2.02-2.05 A peak. Further studies are clearly needed to interpret this behaviour. It is tentatively suggested here that this could be caused either by some impurities in the laumontite structure, or by the presence of an unidentified mineral, which peaks superimpose some of the laumontite peaks.

(2) Clay minerals; The formation of clay minerals is sensitive to temperature, pressure and chemical conditions. This has been found both in nature and in laboratory experiments. Therefore clay minerals are useful to deduce the chemical and thermal conditions of geothermal fields (Kristmannsdottir, 1976; Deer et al., 1963).

The clay minerals of the Fuzhou geothermal field could not been systematically analysed by XRD, because of the limited rock samples brought to Iceland. However, some clay analyses were carried out and the results are shown in Table 2. Clay minerals seem to be present in all rock types and in all the wells. They are however most abundant at 236-350 m depth in well DW1.

Smectite was identified by XRD in well DW1 at 199 and 200 m depth, in well ZII-7 at 76 m, 78 m and 177 m depth and in well ZN+13 at 128 m depth (see Table 2). Correlation with microscopic studies indicates that smectite replaces primary feldspars and glassy groundmass, but has also formed by precipitation in pores. It is most abundant in the fine-coarse grained biotite granites and is generally associated with chlorite.

Illite has only been identified by its optical properties in two thin sections i.e. at 50 m depth in well DW1 and at 177 m depth in well (Z11-7). It is schistose, yellow or brown in colour and shows a slight pleochroism. Inclusions of iron oxides or iron hydroxides are common. The presence of illite should be confirmed by XRD analyses, but probably because of the small quantity of illite in the samples brought to Iceland, this has not yet been possible.

3) Carbonates; Carbonates are the most widely distributed hydrothermal alteration minerals in the Fuzhou geothermal field, especially near the geothermal centre. Calcite is the chief carbonate mineral, but a few crystals of aragonite may be present. Calcite is most commonly found as a cement material in the brecciated rocks or as a fracture or a pore filling together with quartz and zeolites. In addition it is found as a replacement of primary feldspar, pyroxene and amphibole. Calcite veins were found to cross-cut mineral veins of chlorite, prehnite and epidote. This demonstrates that calcite is younger than the other minerals.

4) Secondary quartz; Quartz is a common alteration mineral. It is observed to have formed as an alteration product of the ferromagnesian minerals and feldspars in the groundmass along with albite and epidote, or by direct precipitation from the thermal fluid and is commonly observed as fracture fillings, together with epidote, prehnite, pyrite and calcite. Most of the secondary quartz is probably related to older hydrothermal activity. However, where it occurs in pores and fractures along with calcite and zeolites it can be assumed to be related to the present geothermal activity. Earlier studies (Second Team of Hydrogeology and Engineering Geology, 1980) have shown that opal is also present.

4.3.2 Alteration minerals related to older hydrothermal events

The main hydrothermal alteration minerals which are thought to be related to different pressures and temperatures than are presently active in the Fuzhou field are described below:

1) Albite; Microscopical studies can infer that secondary albite may have formed in three different ways:

Firstly it is found replacing the primary feldspars to form a microperthitic texture.

Secondly, it is found at the margins of the primary feldspars in a variety of a symplectic texture.

Thirdly it is found as an alteration product of the granite-porphyry groundmass together with fine grained quartz and epidote.

2) Epidote; Although epidote is a widespread mineral throughout the Fuzhou field, the amount of epidote varies. Epidote was observed to be in association with albite, prehnite, muscovite, and sphene. However, quartz is the most common associate with epidote.

3) Sphene; Secondary sphene is often observed as a reaction rim around the primary iron ore (magnetite) and is therefore believed to be an alteration product of magnetite.

4) Prehnite; Prehnite was positively recognized both by XRD and through the petrographic microscope. It is mainly found below 228 m depth in drillhole DW1 as well as in well ZII+2. It is most common as a pore or fracture filling, frequently associated with quartz, epidote and calcite. Fig.6 shows the XRD pattern of prehnite.

5) Chlorite; Chlorite was identified at 199 m and 200 m depth in well DW1 in fine grained porphyritic diabase and at 76 m and 107 m depth in well ZII-7 in intermediate-fine grained porphyritic granite and in well ZN13 at 128m depth (Table 2). Chlorite was also observed under the petrographic microscope in the basement rocks. It is light brownish-green or dark green in colour, slightly pleochroic and predominantly found pseudomorphic after primary hornblende, augite and biotite.

4.4 Mineralogical evolution

As mentioned earlier, the alteration mineral asemblage as a whole does not reflect the present thermal regime of the Fuzhou low-temperature field. It is therefore of a great importance to study the alteration history of the field and attempt to resolve the mineral assemblages with respect to time. Accordingly the alteration mineralogy has been divided into three progressive episodes, i.e. autometamorphism of host intrusive bodies; subsequent hydrothermal activity and lastly the present thermal activity (Fig. 7). This classification is based upon distribution of the alteration minerals and their textural relationships.

Some sketches of cross-cutting relationships are shown in Figures 8-11. Fig. 8 is a sketch of the feldspar porphyritic rock at 125 m depth in well ZII-2. The Figure shows a quartz vein which is cross-cut by a younger epidote vein. Also shown on the Figure is epidote that has formed around the iron oxides (magnetite). At the same depth a relationship between prehnite, epidote and calcite was also observed (Fig. 9). The calcite showed in places a relict texture after prehnite and epidote. Consequently, the age relation between these minerals is, from the oldest to the youngest; prehnite, epidote, calcite. Fig. 10 shows a mineral sequence of a vein filling from 307 m depth in well DW1. Prehnite and quartz have first precipitated at the walls of the fracture whereas calcite has formed later and filled the vein. Fig. 11 demonstrates two generations of quartz in the Quaternary conglomerates at 56 m depth in well DW5.

A complete progressive time scale based on vein systems is difficult to establish as cross-cutting of mineral veins are rare in the few samples brought to Iceland. However some conclusions can be drawn from the present data. The earliest vein system seems to be composed of sphene, epidote and chlorite and is likely to be related to the autometamorphism period. Upon progressive hydrothermal activity, the precipitates in veins changed to quartz and prehnite and later to epidote, quartz and possibly calcite. The latest vein system is mainly composed of calcite, zeolites including laumontite and stilbite, some quartz and opal. This vein system is thought to be related to the present low temperature activity.

It is necessary to revise the preliminary time sequence described above by further studies of cross-cutting relationship between mineral veins.

5 COMPARISON WITH LOW TEMPERATURE FIELDS IN ICELAND

In Table 3 the characteristics of the low temperature areas in Iceland (Saemundsson, 1979; Fridleifsson, 1979; Palmason et al., 1979) and of the Fuzhou field, China (Bureau of Geology and Mineral Resources, 1979; Second Team of Hydrogeology and Engineering Geology, 1980) are compared . The table demonstrates that these areas are quite different especially with regards to the tectonic settings. However, some similarities can be seen, for instance, both are of hydrothermal convective type where the fluids are of meteoric origin.

In Iceland and some other countries, zonations of hydrothermal alteration minerals have been observed with progressive temperature increase (Miyashiro and Shido, 1970; Liou, 1971; Kristmannsdottir, 1976; Steiner, 1977; Haashi, 1977; Kristmannsdottir and Tomasson, 1978; Franzson, 1983). As mentioned earlier four zeolite zones have been distinguished in the Icelandic low-temperature areas with increasing depth (temperature). In the Fuzhou Basin Geothermal Field the alteration minerals reflect the complex thermal and geological history of the region. They have formed at different time and under different conditions and therefore regular alteration zones are difficult to see (Fig.12). That can, however, stem from the fact that the present study of the Fuzhou field is only preliminary and the present results are based on very limited data. Consequently, much further studies are needed before comparison between the alteration pattern of the Fuzhou field on one hand and thoroughly investigated areas on the other is realistic.

6 FUTURE STUDY PROPOSAL

1) The alteration mineralogy of the Fuzhou field is very complex and regular alteration zones are difficult to recognize. Therefore it is of importance to eliminate the alteration minerals that do not relate to the present activity and concentrate the investigation on the alteration minerals which reflect conditions of the present system.

2) Cross-cutting relationships between mineral veins and infilling sequences in pores and fractures should be used to establish a relative timescale for the alteration. A comparison between the alteration observed in the Quaternary rocks and the alteration identified in older strata could also be helpful in this context.

3) The alteration minerals should be correlated toaquifers that are located during or after drilling (e.g. circulation losses/additions, temperature logging) as the temperature, pressure and water composition of the aquifers can be measured and correlated with the infilling sequences that are found at those locations.

4) Systematical study of the distribution of zeolites and clay minerals should be undertaken, using tecniques like microscopic investgations, XRD analyses, Differential Thermal Analyses (DTA), Infrared Spectrum Analyses (IS) and chemical analyses.

5) Fluid inclusion studies may help in determining the temperatures at which the alteration minerals formed.

7 SUMMARY

1) The Fuzhou thermal area is of a non-volcanic convective type. It is water dominated and earlier hydrogen isotopic analyses have shown that the circulating water is of meteoric origin.

2) Surface thermal manifestations are mainly located along the Chou Dou-Wang Zhung fault especially where it is intersected by fractures of ENE direction.

3) The geothermal reservoir can be divided into two rock formations: a) The basement rocks (mainly acidic intrusives), b) Overlying Quaternary sedimentary strata.

4) Subsurface exploration of the Fuzhou geothermal field has demonstrated that the aquifers are predominantly controlled by intrusives, fractures and faults,in the basement rocks but also by stratification in the overlying Quaternary sequence.

5) The hydrothermal history is tentatively divided into three epsodes i.e. the oldest being the autometamorphism, followed by hydrothermal activity and lastly the present low temperature activity.

6) The alteration minerals that are thought to relate to the present system are; zeolites, carbonates, smectite and quartz.

7) In order to confirm the mineralogical evolution of the hydrological system, additional work, such as cross-cutting relationships, drilling and aquifer data is called for.

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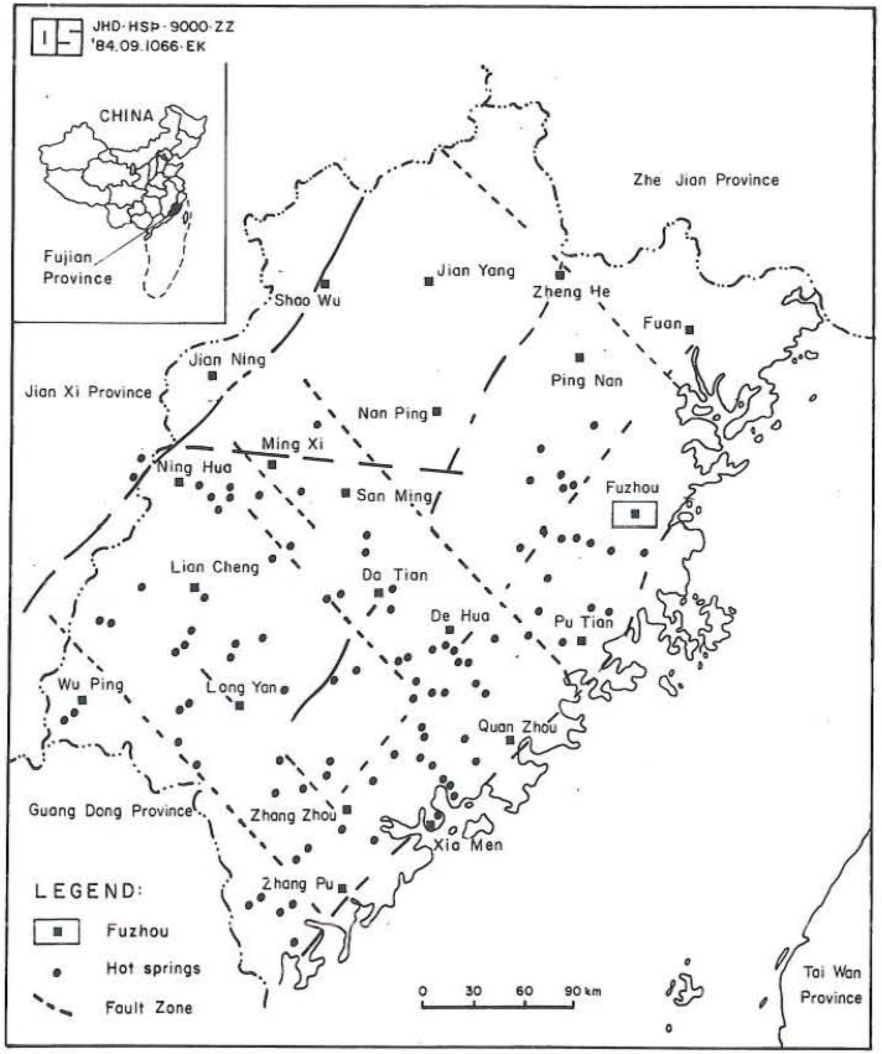


Fig. 1. The location of hot springs and the tectonic features of the Fujian Province, China.

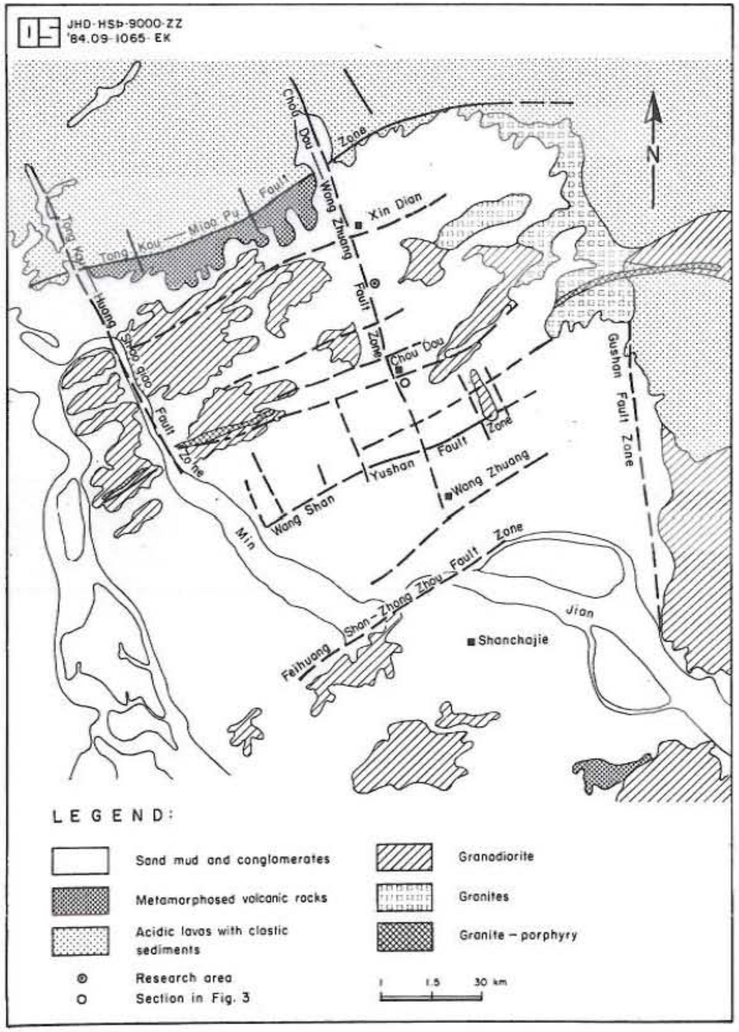


Fig. 2. Geological map of the Fuzhou Field.

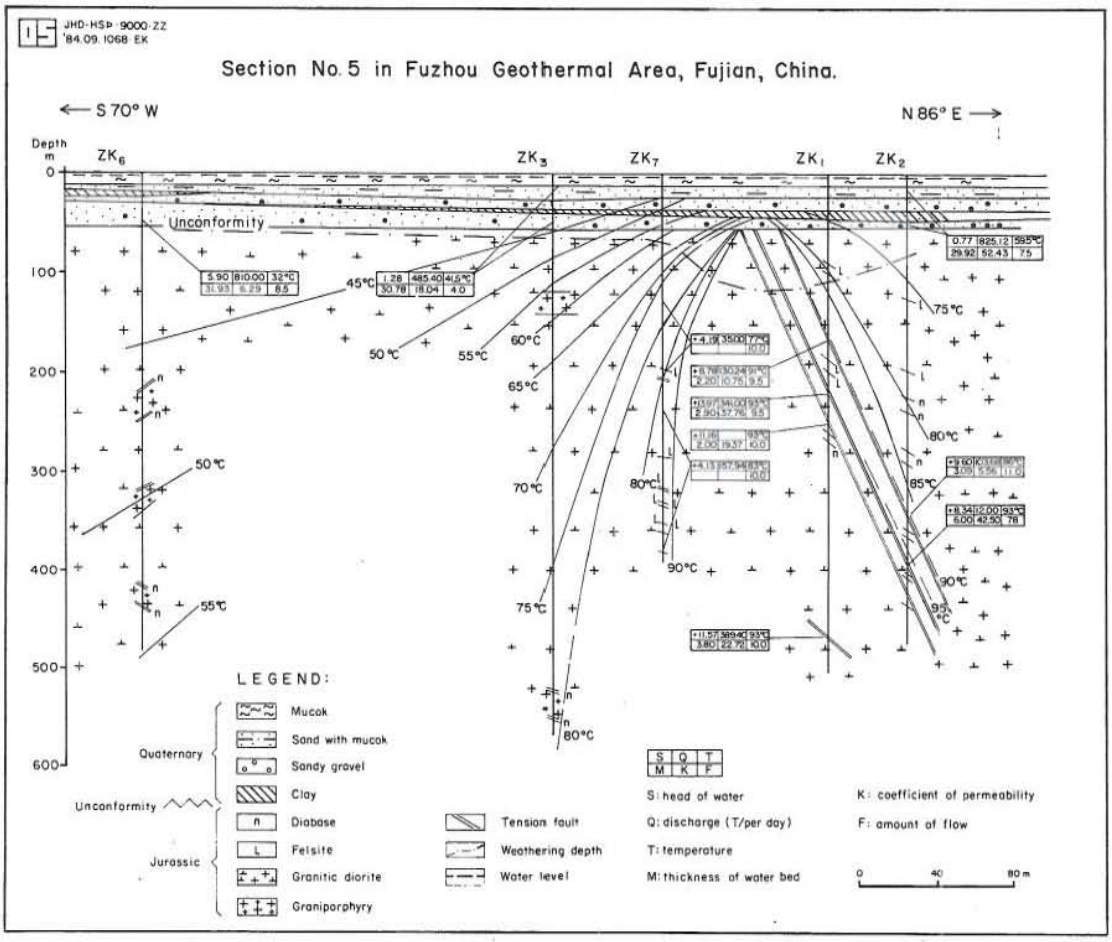


Fig. 3. Geological cross-section of the Fuzhou Field.

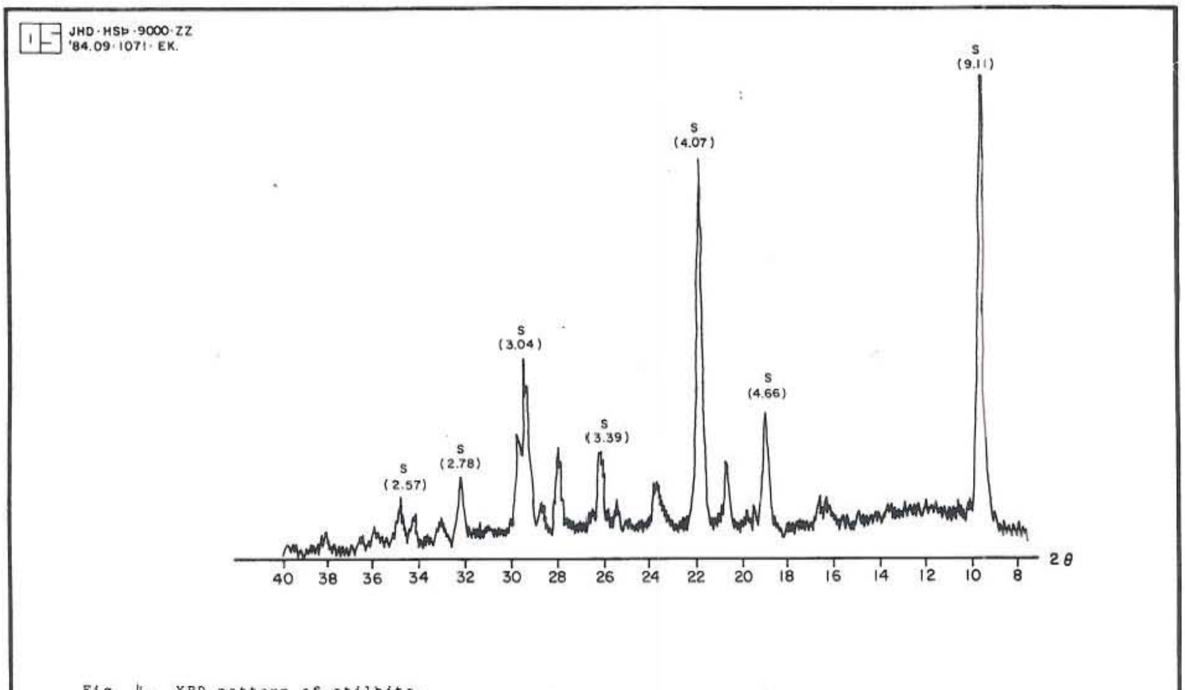


Fig. 4. XRD pattern of stilbite.

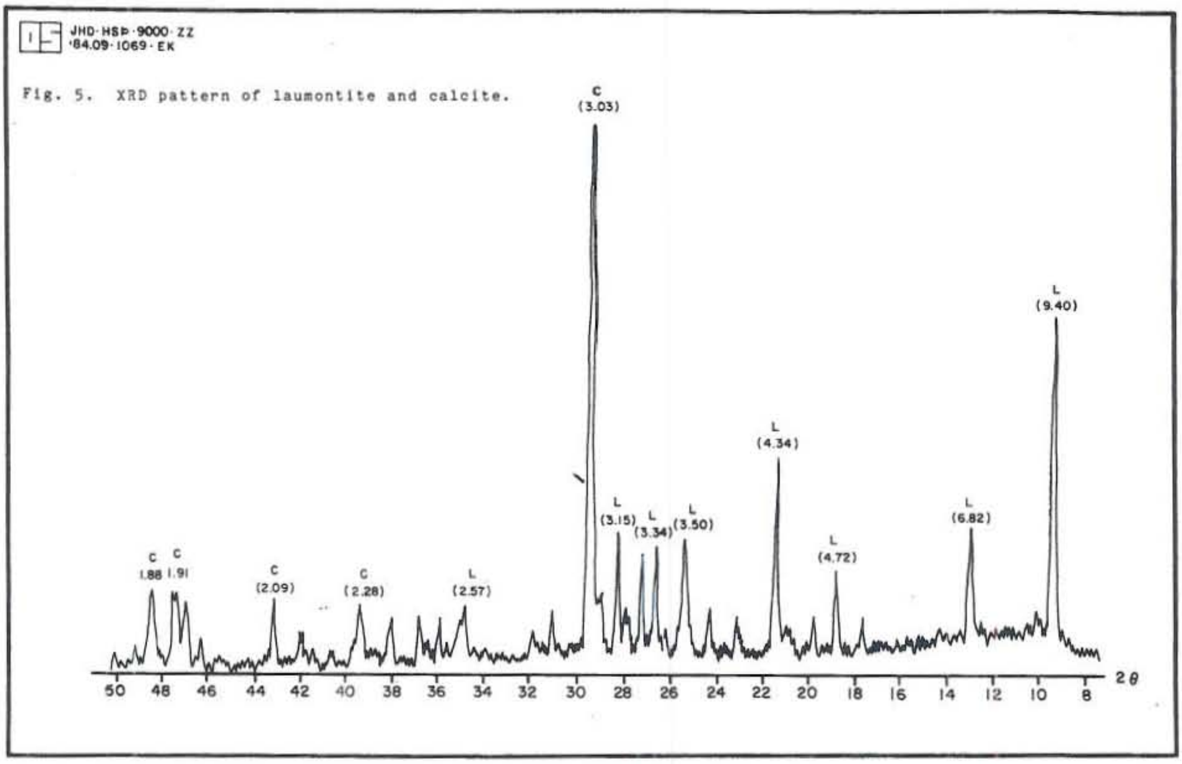


Fig. 5. XRD pattern of laumontite and calcite.

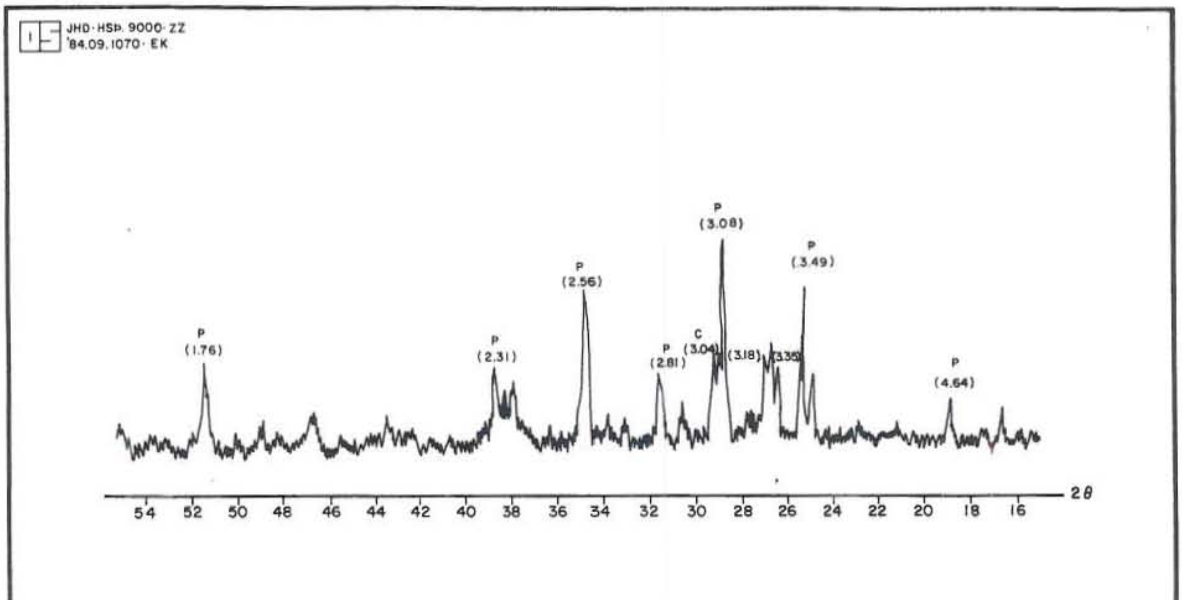
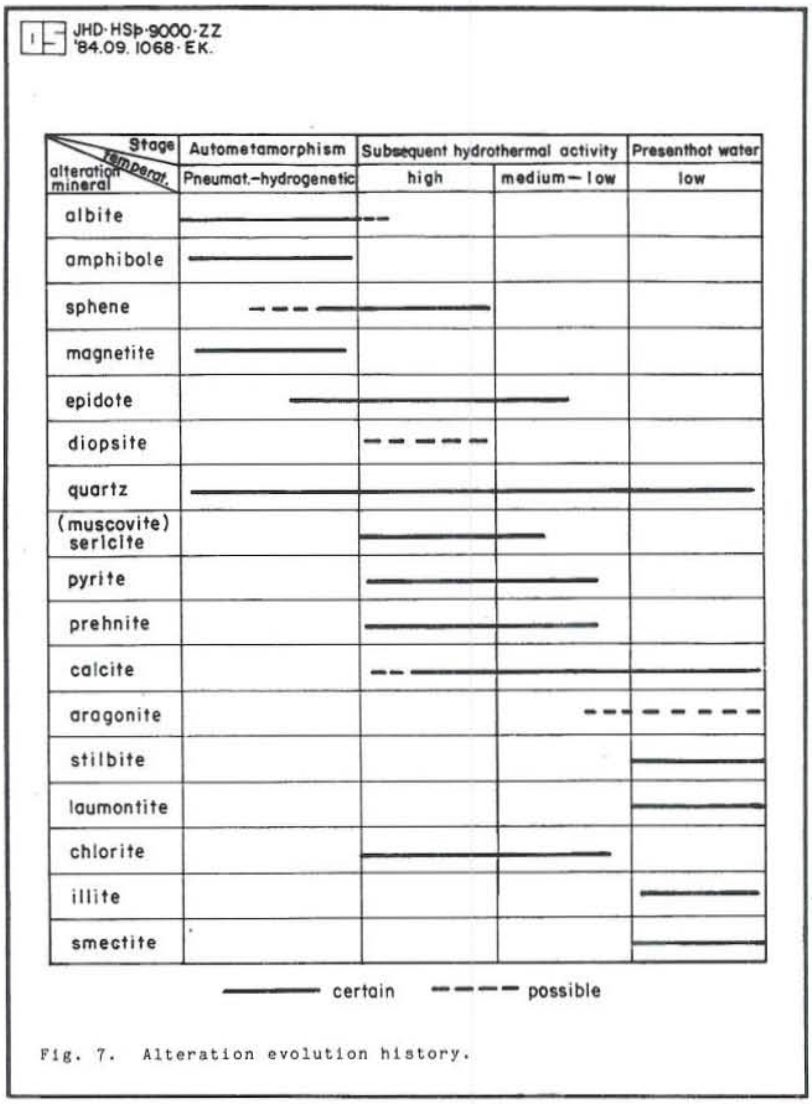


Fig. 6. XRD pattern of prehnite, calcite and quartz.



Stage / temperat. / alteration mineral	Autometamorphism	Subsequent hydrothermal activity		Presenthot water
	Pneumat.-hydrogenetic	high	medium – low	low
albite	—	- -		
amphibole	—			
sphene	- - —	—		
magnetite	—			
epidote	—	—	—	
diopside		- - - -		
quartz	—	—	—	—
(muscovite) sericite		—	—	
pyrite		—	—	
prehnite		—	—	
calcite		- - —	—	—
aragonite			- -	- - - -
stilbite				—
laumontite				—
chlorite		—	—	
illite				—
smectite				—

—— certain - - - - possible

Fig. 7. Alteration evolution history.

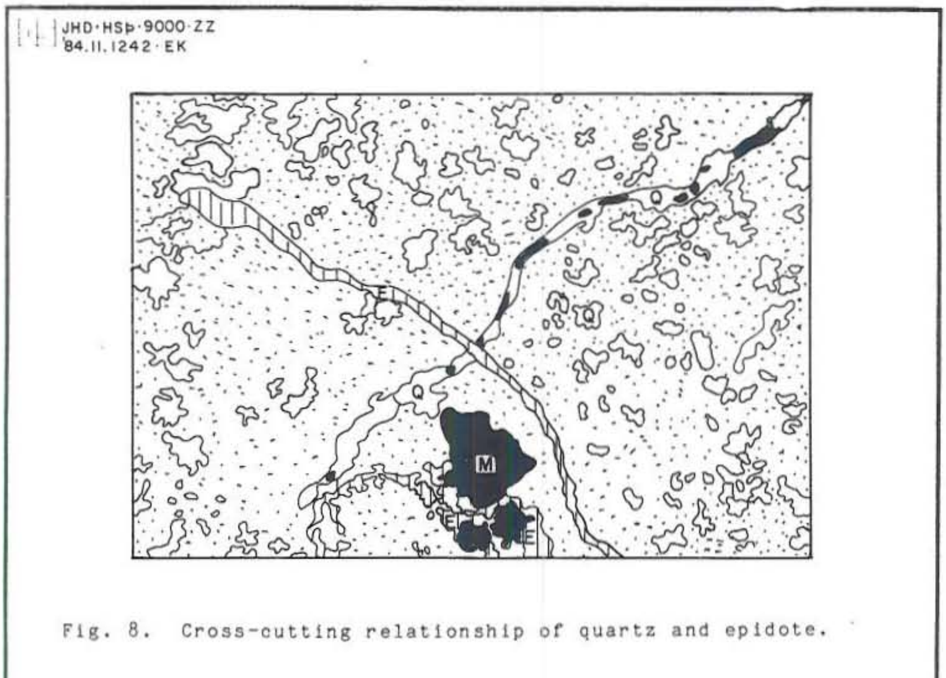


Fig. 8. Cross-cutting relationship of quartz and epidote.

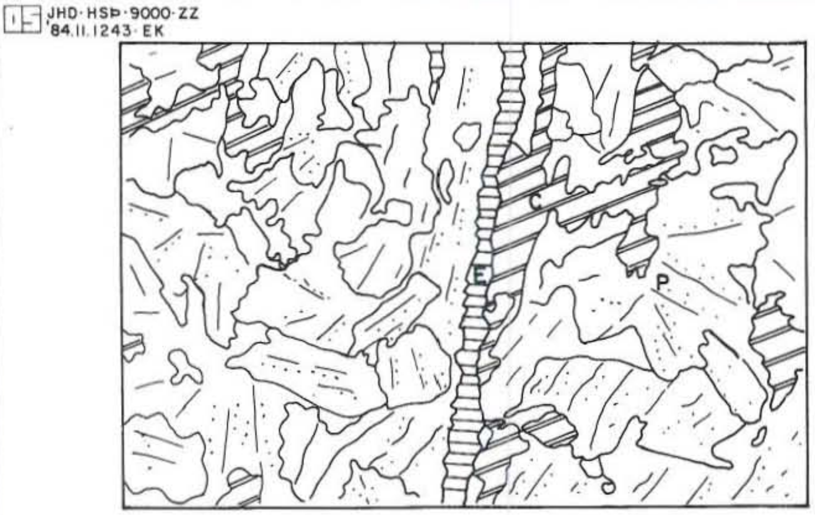


Fig. 9. Cross-cutting relationship of prehnite, quartz and calcite.

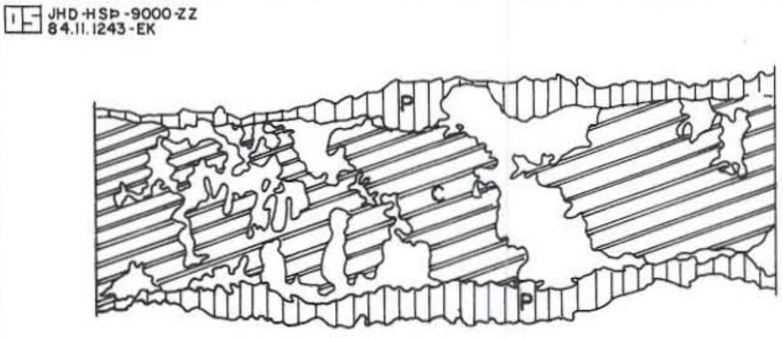


Fig. 10. Fracture filling of prehnite, quartz and calcite.

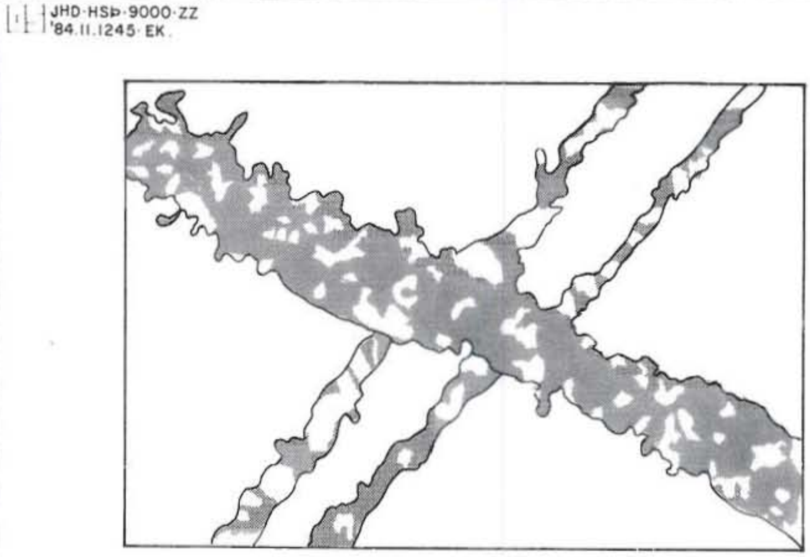


Fig. 11. Cross-cutting of two quartz veins.

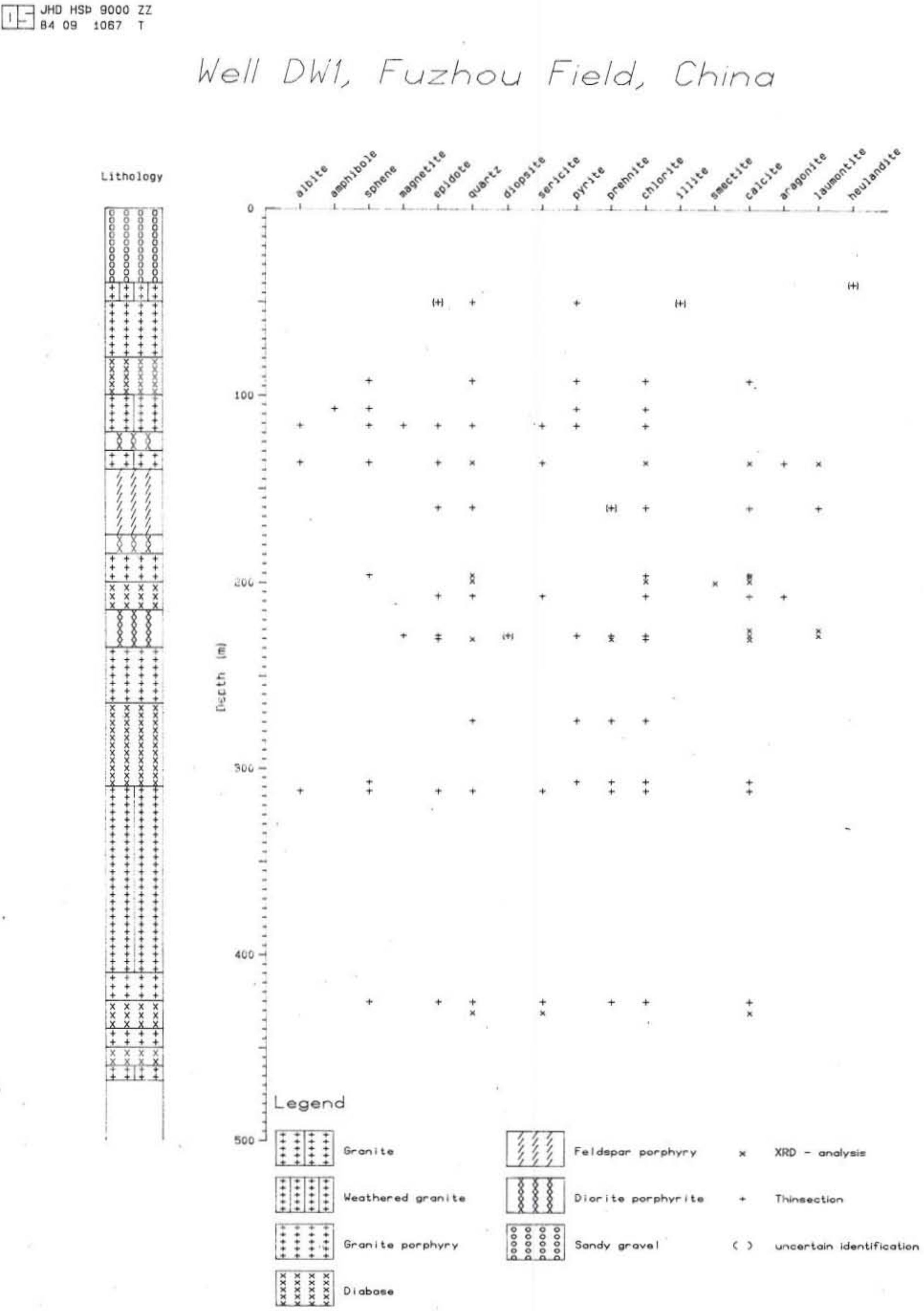


Fig. 12. Qualitative distribution of hydrothermal minerals in well DW1.

Table 1. D-values (in A) and oberseved intensities (#) of secondary minerals from the Fuzhou Field by X-Ray diffraction.

No	D1	D2	D3	D4	D5	I1/IO	I2/IO	I3/IO	I4/IO	I5/IO	Mineral
DW10	9.11	4.07	3.04	4.66	3.39	89	75	40	31	24	stilbite
DW1 196	3.03	1.87	1.90	2.28	2.09	100	32	30	26	24	calcite
	3.35					20					quartz(1)
	3.07*	1.93				18	16				unknown
DW1 199	3.03	1.90	1.87	2.28	2.09	100	41	37	34	34	calcite
	7.13	1.93	3.19	2.83	3.56	19	18	16	15	14	unknown
DW1 136	3.04	1.87	1.90	2.29	2.10	100	27	26	25	24	calcite
	3.35					19					quartz(1)
	2.03	8.84	7.56	3.10	6.19	18	18	17	14	15	unknown
DW1 225	3.03	1.88	1.91	2.28	2.09	98	18	18	17	17	calcite
	9.40	4.14	6.82	3.15	3.50	67	42	30	29	28	laumontite
	1.92	3.07*				17	19				unknown
DW1 228	3.04	1.89	1.91	2.29	2.10	74	18	19	19	18	calcite
	9.60	4.18	6.82	3.16	3.51	25	20	19	15	22	laumontite(1)
	2.03	2.34	6.91	4.		18	83	29	23	22	unknown
DW1 230	3.03	1.88	1.92	2.29	2.09	100	26	28	28	24	calcite
	3.08*	2.56	3.48	3.53	2.81	44	41	39	29	28	prehnite
	3.34	1.66	1.53			40	19	21			quartz
	3.06	3.30	3.27	2.07	9.25	48	32	29	22	24	unknown
DW1 431	3.04	1.90	1.87	2.09	2.27	100	40	35	35	32	calcite
	3.35					22					quratz(1)
	10.1	3.35	2.58			21	22	12			muscovite(1)
	1.92	1.93	3.07*	5.03		15	16	17	15		unknown
Z11+2 102	3.03	1.90	1.87	2.27	2.09	100	24	23	23	21	calcite
	9.46	4.14	6.83	3.49		57	34	32	23		laumontite
	9.10	4.05	3.04	1.83		26	17	15	7		stilbite
	3.66	1.92				15	11				unknown
Z11+2 102 (b)	3.04	1.91	1.89	2.27	2.10	57	25	25	23	24	calcite
	9.50	4.17	6.87	3.49	2.08*	40	38	36	31	25	laumontite(1)
	2.05	1.43	1.22			100	32	25			unknown
Z11+2 125	3.08	2.56	3.49	1.76	3.28	49	40	39	27	28	prehnite
	3.04	1.90	1.86	2.09		28	15	17	15		calcite
	3.35					26					quartz(1)
	2.90	2.69	5.03	3.21		21	18	15	18		epidote
	2.57*	3.31	3.			55	36	30	25		unknown
Z11+2 151	3.34	1.81	4.24	2.13	1.53	100	30	27	16	19	quartz
	9.40	4.15	6.85	3.48	3.25	33	29	22	30	26	laumontite
	3.02	1.90	1.87			26	10	11			calcite
	2.02					30					unknown
Z11-7 177	3.34					40					quartz
	3.20	3.21	3.24	4.04		35	30	29	23		unknown
	3.78	4.04	4.27	3.67	3.48	23	22	23	22	22	

#calculated from bottom of paper; *shoulder peak; (1) possible

Table 2. D-values (in A) and observed intensities of sheet silicates from the Fuzhou Field

No	Air-Dried ($CaCl_2$,H_2O)	Glycol	Heated(550-600°C) for 1 Hour	Mineral
DW136	14.47(5) 7.13(7)	7.13(9)	14.47(3) 7.13(10)	chlorite
DW1 199	16.66(38) 7.13(9)	16.66(35) 7.13(8)	13.79(4) 9.60(6)	smectite chlorite(tr)
DW1 200	16.66(64)	16.66(66) 14.01(5)	9.60(9)	smectite chlorite(tr)
Z11-7 76	16.66(9) 7.13(8)	7.13(8)	no peak	chlorite smectite(tr)
Z11-7 78	16.66(30)	16.66(25)	9.81(5)	smectite
Z11-7 107	16.98(10) 7.13(8)	16.98(10) 7.13(9)	9.70(7) 7.13(4)	smectite chlorite
Z11-7 177	16.66(16)	16.66(12)	9.6(5)	smectite
ZN13 128	16.05(5) 7.13(9)	7.13(10) 16.05(2) 14.01(2)	8.92(6) 9.5(5) 10.04(4)	smectite(tr) chlorite

(tr) trace

Table 3. Comparison of geological characters between low-temperature fields in Fuzhou and Iceland

Character	Iceland	Fuzhou
Architectonic unit	Astride the Mid-Atlantic Ridge	Circum-Pacific orogenic and volcanic system
Regional location	On both sides of the neovolcanic zone	Cenozoic-Mesozoic Era extinct volcanic zone
Strata	Quaternary Tertiary volcanics	Quaternary Yenshanian granite
Control structure	Dykes, fractures, faults, sub-horizontal, stratification boundaries	Intrusions, faults, stratification boundaries
Present igneous activity	None	None
Temperature	<150°C	<110°C
Type of system	Water-dominated	Water-dominated
Composition of water	High CaO low H_2S slightly alkaline	High Na_2O, radon, low H_2S slightly alkaline
Alteration minerals	Opal, chabazite, levyn, scolcite mesolite, gismondin, thomsonite, stilbite, heulandite, epistilbite, mordenite, laumontite, analchime, calcite, quartz, smectite, mixed-layer clay, chlorite.	Opal, laumontite, stilbite, smectite, illite, calcite, quartz.
Alteration zonation	Have four alteration zones (upper to lower) chabazite zone-mesolite/scolecite zone-stilbite zone-laumontite zone	Not presently known
Heat source	Regional heat flow	Regional heat flow
Topography	Lowland, fjord, valley	Lowland basin
Surface magnifestation	Zeolization , sinter	Sinter

Table 4. XRD-values (dA) and relative intensities (%) for stilbite and laumontite from the Fuzhou Field compared to standards.

Minerals	No	d1 (I1)	d2 (I2)	d3 (I3)	d4 (I4)	d5 (I5)	Location
Stilbite	10.7	9.11(100)	4.07(84)	3.04(45)	4.66(35)	3.39(27)	Fuzhou
		9.04(100)	4.07(95)	3.04(70)	4.65(40)	3.40(20)	*
	DW225	9.40(100)	4.14(45)	6.82(45)	3.15(43)	3.50(42)	
	DW228	9.60(100)	4.18(80)	6.82(76)	3.16(60)	3.51(88)	
	Z11+2 102	9.46(100)	4.14(64)	6.82(60)	3.49(43)	2.08(34)	Fuzhou
Laumontite	Z11+2 102(b)	9.50(100)	4.17(90)	6.87(90)	3.49(77)	2.08(63)	
	Z11+2 151	9.40(100)	4.15(88)	6.85(67)	3.48(91)	3.25(79)	
		9.49(100)	4.16(60)	6.86(35)	3.51(30)	3.03(25)	*

* Selected powder diffraction data for minerals (18)

APPENDIX I

XRD-analytical procedure.

The following procedure is an extract from the NEA XRD-procedure (Hardardottir, 1984).

1) The sample was placed into a glass tube and shaken for approximately 5-6 hours, some for 10-12 hours in order to get sufficient samples.

2) The tube was placed on a table for approximately 2-3 hours to let the largest particles deposit from the water, then 3-4 drops of the water which contained the finest particles were placed on a numbered glassplate.* The samples were then dried overnight at room temperature in a desiccator containing $CaCl_2$ solution.

3) The dublicate of each sample was made and placed in a desiccator containing glycol solution and stored there for a minimum of 48 hours at room temperature.

4) The samples dublicates were run from 2-17 degrees on the XRD-goniometer.

5) The next stage of the analytical procedure was to heat the samples (not the glycol treated ones) in an oven (550-600°C) for one hour; followed by cooling and finally the samples were run individually from 2-17 degrees.

* Each sample was made in dublicate.