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ORGANIC AND INORGANIC METAMORPHISM IN THE TAVEYANNAZ SANDSTONE OF THE SWISS ALPS AND EQUIVALENT SANDSTONES IN FRANCE AND ITALY[1]

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ABSTRACT: The authigenic mineralogy of the Eocene-Oligocene Taveyannaz Sandstone of the Alps and equivalents in France and Italy has been correlated with the coal-rank of the associated humic material. A relationship between fixed carbon (FC), isochemical mineral zonation and illite crystallinity was established as tabulated below:

FC	Characteristic Mineral Assemblage	Illite Crystallinity
55–63	heulandite-montmorillonite-(albite)	>6.6 mm
63–68	heulandite-laumontite-montmorillonite-(albite)	6.6–6.3 mm
68–87	laumontite-prehnite-pumpellyite-corrensite-illite/montmorillonite mixed layers-albite	6.3–4.8 mm
87–95	laumontite-prehnite-pumpellyite-epidote-corrensite-illite-albite	4.8–3.4 mm
95–99	prehnite-pumpellyite-epidote-chlorite-illite-albite	3.4–1.5 mm

Evidence suggests that chemical equilibrium was approached. Therefore a given mineral zone and illite crystallinity is a reliable coal-rank/temperature indicator. Paragenetic, chemical and coal-rank data suggest that the crystallization of the hydrated calcium-silicates and phyllosilicates was mainly controlled by temperature; the formation of the different calcium-silicates resulted from reactions between the clayey matrix and calcium rich solutions. None of the mineral zones represents a metamorphic product of the foregoing stage(s). According to geochronological and mineralogical data, the metamorphism of the Taveyannaz Sandstone took place some 40 million years ago, during the Lepontine Metamorphic Event. The complete spectrum of metamorphic grades was generated by this event, ranging from the low temperature end (the subject of this paper) up to and including the amphibolite stage as found in the Ticino Culmination of the Central Alps.

INTRODUCTION

The development of models of burial diagenesis and low-grade metamorphism correlating coal-rank with petrophysical and mineralogical parameters is receiving increasing attention. Although still poorly developed, these models are necessary for defining the degree of metamorphism of geological units and reconstructing their structural history (Ernst, 1971; Martini, 1972; Weber, 1972).

From the viewpoint of hydrocarbon exploration, these models may help in forecasting reservoir properties if the burial history can be inferred. Furthermore, the large amounts of water released during progressive diagenesis (Fyfe, 1973) could be the driving force for the expulsion of mature hydrocarbons. A knowledge therefore, of the temperature at which such fluid expulsion occurs should allow a prediction of the time of hydrocarbon expulsion and migration (Powers, 1959; Burst, 1969). These waters also have an important bearing on the cementation and leaching of reservoir rocks (Rumeau & Sourisse, 1972).

As recognized by Russian authors (Kossovskaya & Shutov, 1965), different sandstone compositions will require different correlation models; for instance, the mineralogy of quartz-sandstones tends to be characterised by kaolinite/dickite and authigenic quartz (Kulbicki & Millot, 1962), that of feldspathic sandstones by the presence of illite (Stalder, 1973), while sandstones derived from volcanic sources are frequently zeolite-bearing. It has long been realized that coal rank could be used as a reference scale against which to relate various metamorphic

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mineral assemblages resulting from different primary mineralogies. This paper establishes the relationship between the mineralogical/petrophysical characteristics of an andesitic sandstone and the coal rank of the associated humic material.

A wealth of data on the correlating coal-rank to petrophysical/mineralogical parameters has already been published. Very few of these studies comprised a complete correlation model. It was clear that as many parameters as possible should be investigated because of the inherent scatter of any given data type in the low-temperature range. The most complete correlations are certainly those of Kaplan (1971) and v. d. Kamp (1976). Other correlations which have been attempted were: 1) Coal-rank with metamorphic facies and clay mineralogy (Kish, 1966, 1968, 1969, 1971; Castaño and Sparks, 1974), 2) coal-rank with metamorphic facies and illite crystallinity (Frey & Niggli, 1971), 3) temperature and pressure with clay-mineral assemblages (Utada, 1965; Kossovskaya and Shutov, 1965, 1970; Winkler, 1970; Frey, 1969, 1970; Meisl, 1970; Iijima and Utada, 1971; Aoyagi, 1969; Packham and Crook, 1960).

With a few exceptions, coal-rank and inorganic metamorphism were not measured from the same or spatially closely related samples. This can lead to erroneous correlations. Moreover, there is little data on illite crystallinity, index minerals and coal-rank correlation.

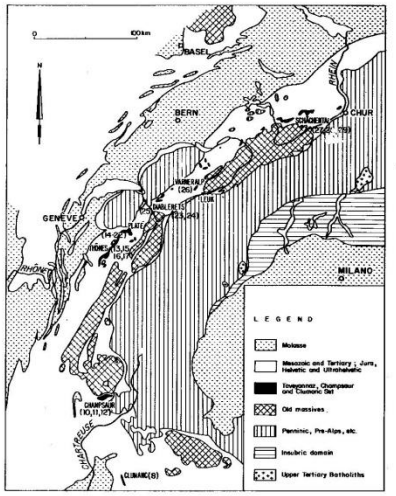

FIG. 1.—Distribution of main "Taveyannaz" Sandstone outcrops in the Swiss and French Alps; sections investigated are provided with name. (numbers in parentheses refer to section numbers of Fig. 3 and Table 1).

ANALYTICAL PROCEDURES

Material Sampling

The material to be investigated was collected from 29 stratigraphic sections spread over the Alpine Arc from Sicily through Switzerland to Southern France, (Figs. 1, 2).

The samples for the different measurements (sandstone, shale, coaly material) were selected where possible at the same location, within a few decimetres or metres.

Within any stratigraphic section none of the measurements made was found to be depth related; average values were therefore used.

Laboratory Analyses

Coal-rank was measured for more than 250 samples using vitrinite reflectance (Mc Cartney and Teichmüller, 1972) and is expressed here as a percentage of fixed carbon (FC) which in turn is derived from the reflectance fixed carbon correlation (Castano & Sparks, 1974; Hood et al, 1975).

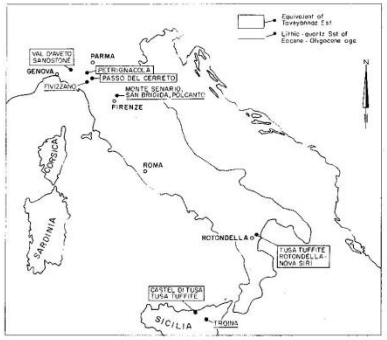

FIG. 2.—Location map of sections sampled in Italy (Apennines).

Porosity and permeability of some 270 samples of sandstones were measured, while 160 *shale-density* measurements were carried out by the "pycnometer" method.

Both *thin-section* and *bulk X-ray examinations* (more than 500) of gravity-separated samples were carried out to identify the critical mineral phases.

Clay-mineral assemblages (460 samples) were investigated by X-ray diffraction in the fraction smaller than 2 microns, using normal, glycolated and heated preparations. For the sake of clarity: 1) Montmorillonite is understood here as a mineral showing a 14 Å peak, decreasing to 10 Å by heating and increasing to 17 Å by glycolating, 2) corrensite has peaks at 14 Å and 28 Å, swelling to 15–16 Å and 31–32 Å respectively by glycolating and collapsing to 28 Å after heating at 550° C (Kübler, 1973b), 3) illite has peaks at 10.5 Å and 3.3 Å (non-swelling), 4) illite-montmorillonite mixed layers were identified using Weaver's method (1956).

The *bulk chemical composition* of 43 sandstone samples was measured by X-ray fluorescence and atomic absorption; their clay-mineral fraction (smaller than 2 microns) was analysed for Na_2O, K_2O and MgO.

Selected crystals of *chlorite, pumpellyite, prehnite* and *laumontite* were analysed by the Mining Department of the Delft Technological University (the Netherlands). The measurements were carried out on a Miniprobe (Siemens spectrometers and electronics) using standards of forsterite, orthoclase and andradite.

Illite crystallinity (Kübler, 1964, 1966, 1968) was measured for 10 Å peaks of at least 5 cm. on air dried specimens. It should be stressed that for lower degrees of diagenesis, the crystallinity index includes illite-montmorillonite mixed layers (Dunoyer de Segonzac, 1970). The illite crystallinity values reported here are closely comparable to those found in published literature (Kübler, 1964, 1966, 1968) as demostrated by a calibration with Kübler's international standards.

GEOLOGY OF THE TAVEYANNAZ AND EQUIVALENT SANDSTONES

The best-known European example of volcaniclastic sandstone is the Taveyannaz sandstone of the Swiss and French Alps. Numerous studies were devoted to its petrography and palaeogeography (de Quervain, 1928; Vuagnat, 1952; Brückner, 1937, 1943; Mercanton, 1963; Martini, 1969; Coombs et al, 1976; Sawatzki, 1972). Lateral equivalents were also found in the Apennines—Tusa tuffites, Petrignacola and Val d'Aveto sandstone—(Ogniben, 1964, 1969; Elter et al, 1969) and in France—Clumanc and Champsaur sandstone (Boussac, 1912; Stanley, 1961a, b; Vuagnat, 1947, 1949; Boeuf et al, 1961; Sawatzki and Vuagnat, 1971; Sawatzki, 1972; Rosset et al, 1971).

Petrography of the Taveyannaz Sandstone and Its Lateral Equivalents

All the sandstones mentioned above have in common a high amount of unstable minerals such as basic plagioclase (40–75%), pyroxenes and hornblende (5–20%) and altered primary glass matrix (10–40%); clastic quartz amounts to 5–20%, in exceptional cases up to 30%. Lithoclasts of andesitic rocks are frequent, and basaltic fragments are more abundant towards the top sequences (for the Taveyannaz sandstones only). The content of plant remains can be high towards the top of the beds.

Shale breaks occur regularly and vary in thickness from a few centimeters to a few tens of meters (occasionally hundreds of meters).

Stratigraphy, Sedimentology, and Palaeogeography

The Taveyannaz, Champsaur and Clumanc sandstones (Fig. 1) show the characteristic features of turbidites and are thought to have been deposited in a basin adjacent to a volcanic andesitic island arc during the Upper Eocene-Lower Oligocene (Trümpy, 1960; Dickinson, 1970). These volcaniclastic sandstones are restricted to the north-helvetic realm (lit. cit.) (Fig. 1) and up to now no other remnant of the volcanic arc has been found.

The thickness of the sandstone sequence varies from a few tens of meters to possibly some thousand meters (Canton Uri, Switzerland). It normally overlies Globigerina shales/marls and in some areas underlies quartz-lithic sandstones referred to as Val d'Illiez, Altorfer and Matt Gruontal Sandstones (Vuagnat, 1952). Tectonically these sandstones occupy either a para-autochthonous or an allochtonous position on the back of Helvetic Nappes (Vuagnat, 1952; Martini, 1968).

The Tusa tuffites, Petrignacola and Val d'Aveto sandstones occur exclusively in the allochthonous eugeosynclinal Sicilide Complex of the Apennines (Ogniben, 1964, 1969; Elter et al, 1969; Abbate & Sagri, 1970; Abbate et al, 1970; Zanzucchi, 1962). They are associated with shales (argille scagliose) and often have the shape of lenticular bodies. Their age ranges from Upper Eocene to Lower Oligocene.

ORGANIC AND INORGANIC METAMORPHISM OF THE TAVEYANNAZ AND RELATED SANDSTONES

Parameters to be Measured: a Discussion

Both the hydrated calcium silicates and clay-mineral assemblages show a consistent world-wide zonality with increasing depth of burial (Weaver, 1967; Dunoyer de Segonzac et al, 1968; Dunoyer de Segonzac, 1970; Kübler, 1964, 1966, 1968; Hay, 1966; Coombs, 1954, 1960, 1961, 1968, 1971; Surdam, 1967).

Data pertaining to the stability field of these mineral assemblages are derived mainly from experiments (Liou, 1971a, b, c, and 1973; Nitsch, 1971) and cannot easily be applied in nature, at least in the low-temperature range (100–250° C). The reasons for this are:

1) At low temperatures, metasomatic reactions are generally the rule. Variations in the ionic composition of interstitial fluids can have a greater influence than temperature on the stability field of the authigenic minerals (Surdam, 1967; Boles and Coombs, 1975).

2) There may be substantial differences between solid and fluid pressure (up to 60%) (Coombs et al, 1959; Hay, 1966). Such pressure differences may lower reaction temperatures considerably (Coombs, 1971).

3) Even if fluid and solid pressures are equal, the activity of water can be lowered by the presence of other components (CO_2, salts). As a consequence less hydrous zeolites can occur at lower temperatures than expected in a chemical environment where water activity is high (Fyfe et al, 1958).

Data from geothermal areas (Muffler & White, 1969; Tomasson & Kristmannsdottir, 1972; Iijima & Utada, 1971) are still too few for general application in metamorphic petrology. However, experience in oil exploration has shown that coal rank can be reliably correlated with temperature and time (Karweil, 1956; Castaño and Sparks, 1974; Teichmüller & Teichmüller, 1967; Connan, 1975; Hood et al, 1975) and is almost independant of the surrounding lithology. Hence, it seems meaningful to extend this correlation to include data relating mineral reactions to temperature-time.

Correlation of Organic and Inorganic Metamorphism, Results and Discussion

The basic data used to construct the correlation chart (Fig. 3) are shown in Table 1. On this correlation chart I have plotted all the authigenic minerals of all the samples associated with a given FC, regardless whether these minerals coexisted or not in the single samples. I think that this procedure is a valid one because the correlation applies to a range, admittedly rather narrow, of sandstone chemical compositions, the small variations of which can account for some minerals to coexist in one sample and not in another one. In other words, the correlation chart displays the maximum amount of possibly coexisting phases at any FC/temperature.

Both the clay-minerals and the hydrated calcium-silicate assemblages show a clear zonation as a function of FC. Furthermore there is also a clear relation to FC of illite crystallinity, shale density and to a lesser extent sandstone porosity. A combination of these yardsticks allows unambiguous determination of coal rank and maximum temperature. The temperature scale in Figure 3 is derived from temperature-coal rank correlations of Hood et al (1975). The effective heating time is thought to be some 5–10 million years during Lower Oligocene (Trümpy, 1973).

From the correlation chart (Fig. 3) we observe that:

1) For the range $55 < FC < 100$, the mineral assemblages can be split into six different zones with boundary temperatures at 125°, 170°, 210°, 250° and 300° C. These temperatures agree well with those reported by Juan (1972), and their coal rank (FC) is

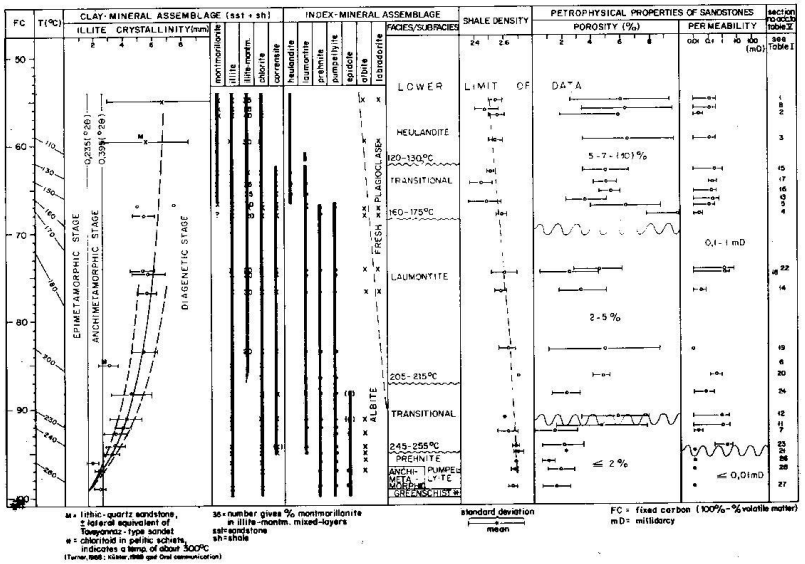

FIG. 3.—Correlation between organic and inorganic metamorphism of Taveyannaz and related Sandstones.

similar to those of Frey & Niggli (1971), Kisch (1968/1974), Kaplan (1971), and Weber (1972).

2) The crystallinity of illite is a reliable index tool above FC 70. Its standard deviation expressed in FC units is about twice that of the vitrinite reflectance at high FC (Fig. 4).

3) The stable mineral assemblages become simpler as the degree of metamorphism increases.

4) The onset of the anchimetamorphic stage (Kübler 1964, 1966, 1968) occurs at FC ≥ 96 (250° C) and roughly corresponds with the disappearance of corrensite, irregular illite-montmorillonite mixed layers and laumontite. The boundary anchimetamorphism—greenschist facies occurs at FC = 99; the temperature lies around 300° C (Winkler, 1965, Turner, 1968). The anchizone covers 'pro parte' the prehnite-pumpellyite-quartz facies of Winkler (1965).

5) Kübler (1973a, 1973b) and Kübler et al (1974) noted that the association of corrensite and laumontite was indicative of the same degree of diagenetic alteration; this observation is fully corroborated by the present results.

6) The density of shales increases regularly from FC > 70. The rather large scatter is explained by differences in mineralogy (Kaplan, 1971). Shale density can therefore serve as an additional yardstick if used statistically.

7) The petrophysical properties of the volcaniclastic Taveyannaz Sandstone are poor from FC > 55 irrespective of original sorting and grain size. This, however, does not mean that every volcaniclastic sandstone will behave in such a fashion. The petrophysical properties of the Taveyannaz Sandstone have been further influenced by a number of factors, i) tectonic overcompaction related to the Alpine Orogeny; ii) a structural development such that the porosity could not be improved by leaching; iii) metamorphism under low CO_2-pressure; high CO_2-pressure could lead to completely different and more favourable mineral assemblages (Zen, 1961); iv) the Taveyannaz Sandstone is a turbiditic

TABLE 1.—*Data compilation of Taveyannaz sandstone and related formations*

Section	No	Zeolites H	L	Pr	Pu	E	Plg L	A	Clay Min. Mt	I	I/Mt	Ch	Co	Illite Cryst., [mm] x	s	n	FC [%] x	s	n	Shale Dens. (g/cm³) x	s	n	Set Porosity, [%] x	s	n	Permeabil. [mD] x	s	n
Castel di Tusa	1						+	+		+	+	+		6,7	3,8	11	55	5	5	2,5	0,05	8	6,0	3,4	9	0,12	0,24	10
Troina	2									+	+	+					56,6	1,3	7	2,56	0,06	8	5,9	3,98	8	0,05	0,02	8
Mte Senario	3								+	+	+	+		5,6	2,9	12	59,5	1,75	16	2,55	0,05	12	6,5	3,2	31	0,13	0,13	25
Petrignacola	4			+			+	+	?	+	+	+	+	5,5	0,69	7	68	2,16	4	2,59	0,03	4	10,8	2,99	8	0,04	0,02	8
Passo Cerreto	5			+	+		+	+		+	+	+	+	5,0	—	2	67	1,0	3	—	—	—	6,4	2,4	9	0,11	0,23	9
Fivizzano	6		+							+	+	+		3,05	0,20	4	85		2	—	—	—	1,7	—	—	0,03	—	—
Val d'Aveto	7			+	+	+	+	+		+	+	+		3,50	0,87	22	92,8	1,1	14	2,63	0,07	8	1,52	1,46	20	0,03	0,02	16
Clumanc	8									+	+	+	?	—	—	—	56		2	2,48	0,09	3	6,3	3,3	5	0,12	0,12	5
Chalufy	9								+	+	+	+		8,9	0,73	9	61,1	1,1	7	2,56	0,06	4	6,3	3,9	6	0,29	0,27	6
Les Ricoux	10									+	+	+		4,18	0,43	6	94,8	0,8	3	2,63	0,06	4	1,4	0,5	4	0,03	0,03	4
Champoléon	11			+			+	+		+	+	+	+	4,0	0,5	4	92,1	0,74	5	2,55	—	—	4,7	3,1	9	1,1	1,2	8
Tourond	12			+	+		+	+		+	+	+	+	4,2	1,1	3	91	—	2	2,60	—	2	5,8	2,5	8	0,9	2,0	8
Thônes (laum.)	13			+	+		+	+		+	+	+	+	7,5	1,5	6	66,8	2,9	6	2,48	0,11	6	3,7	1,4	19	0,25	0,50	15
Flaine road	14			+	+		+	+	+	+	+	+	+	5,6	0,55	3	76,8	0,6	6	2,58	0,04	4	3,3	1,5	5	0,05	0,04	3
Mt Colomban	15		+	+	+		+	+	+	+	+	+	+	—	—	—	63,4	2,7	8	2,51	0,01	4	5,0	1,6	7	0,30	0,75	7
Thônes (beul.)	16		+	+			+	+	+	+	+	+	+	—	—	—	65,6	1,8	5	—	—	—	5,3	0,70	8	0,13	0,15	8
Thônes (trans.)	17		+	+			+	+	+	+	+	+	+	—	—	—	64,3	2,3	3	2,45	0,08	3	5,0	0,80	4	0,53	0,15	4
Tête Prés Saix	18					+	+	+		+	+	+	+	5,7	1,1	8	74,2	1,6	6	2,61	0,09	7	2,5	2,0	6	1,34	1,7	6
Lac de Gers	19			+	+	+	+	+		+	+	+	+	5,5	0,9	5	83,4	5,5	12	2,63	0,05	5	4,9	3,8	4	0,01	0	4
Les Perrets	20			+	+	+	+	+		+	+	+		5,5	—	1	86,3	1,5	3	2,70	—	1	4,7	0,6	5	0,54	0,34	5
La Vouardaz	21			+	+	+	+	+		+	+	+	+	3,2	0,49	3	95		2	2,70	0,03	3	2,3	—	2	0,01	—	2
Les Carroz	22			+	+	+	+	+		+	+	+	+	5,3	0,8	5	74,4	2,0	4	—	—	—	4,5	1,7	6	1,2	0,1	5
Nant d'Abefet	23			+	+	+	+	+		+	+	+	+	3,45	0,73	10	94,2	1,0	9	2,68	0,02	6	2,1	1,5	6	2,5	2,0	6
Préserman	24			+		+	+	+		+	+	+	+	4,62	1,4	4	88,2	2,5	6	—	—	—	2,3	0,95	7	0,08	0,17	5
Val d'Illiez	25									+	+	+	+	2,65	0,72	5	94,5	0,6	4									
Varneralp	26									+	+	+	+	1,93	0,45	3	96		2	2,68	—	1	1,1	0,39	5	0,61	—	5
Wespen	27									+	+	+	+	2,44	0,36	10	99	—	5	2,66	0,03	7	1,6	1,0	8	0,01	—	8
Chulm	28									+	+	+	+	2,42	0,29	7	97,1	0,65	5	2,67	0,02	4	1,9	0,9	3	0,01	—	3
Fritertal	29									+	+	+	+	2,24	0,24	9	96,8	1,5	6	2,66	0,02	4	1,4	0,3	5	0,01	—	1

Explanations
x = arithmetic mean
s = standard deviation
n = number of measurements
H = heulandite
L = laumontite
Pr = prehnite
Pu = pumpellyite
E = epidote
A = albite
L = labradorite
Mt = montmorillonite
I = illite
I/Mt = illite-montmorillonite mixed layer
Ch = chlorite
Co = corrensite
Illite-crystallinity mean computed from sandstone and shales

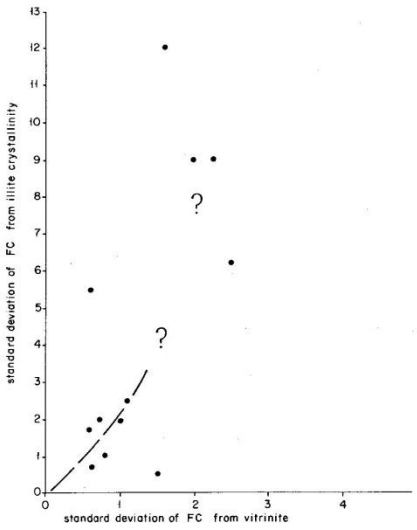

FIG. 4.—Comparison between standard deviation of FC obtained from vitrinite reflectance and that of FC obtained from illite crystallinity (via the correlation displayed in Fig. 3).

sandstone with a high content of fine particles. Other winnowed valcaniclastic sandstones could very likely exhibit higher porosity and permeability at equivalent metamorphic grade.

8) As FC increases it appears that the number of montmorillionite layers within the illite-montmorillonite mixed layers decreases. I have not, however, been able to quantify this trend, because of the rather large scatter of the data.

GENESIS OF AUTHIGENIC MINERALS IN THE TAVEYANNAZ SANDSTONE

The mode of occurrence and crystallisation sequence of the authigenic minerals is emphasized because they restrict the number of possible chemical reactions responsible for their formation.

Occurrence of Authigenic Minerals

Chlorite and *corrensite* form the bulk of the clay-mineral fraction depending on the metamorphic stage. They occur both as replacement of detrital components and less frequently as cement.

Albite replaces more basic detrital plagioclases in quantities roughly depending on the degree of metamorphism (for details, see Martini, 1968).

Laumontite may replace almost any detrital component of the sandstone, the clayey matrix being the most and quartz the least affected. Primary laumontite cement is much less widespread and was recorded only in foraminiferal chambers together with chlorite and corrensite.

Pumpellyite mostly occurs as grains of undefined crystallographic boundaries; less frequently acicular crystals can be observed. It usually replaces the matrix of sandstones and the plagioclase fragments. There is no evidence of replacement of laumontite or prehnite by pumpellyite.

Prehnite is never abundant, with the exception of fault-crush zones, where it may fill fissures together with quartz and calcite or epidote and calcite. Its habit is anhedral when associated with pumpellyite (Fig. 6); euhedral crystals were exclusively recorded in the fault zones.

Calcite is widely distributed at every metamorphic stage. The largest amounts occur in the so-called "green facies" of Martini (1969). At least two generations could be recognized: 1) an early one, which cemented the volcanic fragments and clearly prevented further alteration by lowering the sandstone permeability and by producing a CO_2-rich environment unfavourable for zeolite development. For instance the plagioclases within calcite cemented beds of undoubtedly high rank can still be basic and exhibit perfect compositional zonation; 2) and a late calcite generation, corroding all the available detrital and authigenic minerals in all the facies, or occurring as a post-chlorite cement.

In agreement with the thin-section interpretation, the C- and O-isotope composition of calcite from 6 selected samples (free of carbonate lithoclasts) suggest a rather low crystallization temperature (less than 100° C).

For a FC ranging from 74 to 99 (180 to 250° C) δO^{18} varies from −9.8 to −11.6 (SMOW). Such a low isotope gradient bears no relationship to the temperature range inferred from FC. As the composition of the

fluids from which calcite was precipitated is not known, the crystallization temperature can not be directly determined.

The δC^{13} of the same samples varies from −1.8 to −7.3 (PDB), values commonly found in the marine and fresh-water cements (Schwarz, 1969). It is possible that some mixing with CO_2 produced during the coalification of humic material has occurred. Taken together, these results point to a rather low temperature of calcite crystallization: the early generation would have formed before deep burial while the late generation would be synchronous with or postdate the uplift phase. *Sphene/leucoxene* are widespread as replacement products of mafic minerals together with chloritic minerals. *Sericite/illite* very often replace basic plagioclase, as already mentioned by Martini & Vuagnat (1965). Authigenic *quartz* is extremely rare; if present, it overgrows detrital quartz or is produced by alteration of pyroxene. As an only exception, quartz is abundant in cracks in association with prehnite and calcite or with epidote and prehnite.

Sequence of Crystallization

Textural relationships between the different authigenic minerals such as those shown in Figures 5 and 6 lead to the following interpretation of the sequence of crystallization: 1) At low rank (less than about 130° C): calcite-chlorite, albite, heulandite and laumontite; 2) at intermediate rank (130–230° C): calcite-chlorite, pumpellyite-albite, laumontite, prehnite and late calcite; 3) at high rank

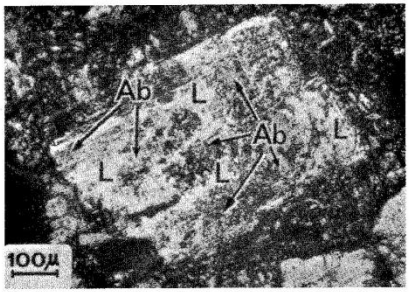

FIG. 5.—Clear-cut case where laumontite (L) replaces albitised (Ab) plagioclase (optically continuous). Champsaur sandstone (Dauphiné, FR).

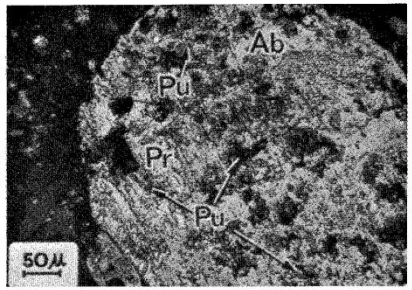

FIG. 6.—Prehnite (Pr) replacing both pumpellyite (Pu) and albitised plagioclase (Ab) is therefore the last phase to have formed. Taveyannaz sandstone from the Schächental (Uri, CH).

(more than 230° C): chlorite, pumpellyite-albite, prehnite and late calcite.

The location of corrensite in the crystallization sequence could not be ascertained microscopically; its formation time, however, is thought to be synchronous with that of laumontite because of their synpathetic relationship (Fig. 3).

Genesis of Authigenic Minerals

The mechanism of formation of the different authigenic minerals occurring at low-grade metamorphism is still unknown. Using thin-sections, field studies and chemical analyses I will attempt to draw some conclusions regarding their genesis. It should be borne in mind that at low temperatures a large number of factors are involved; among the most significant are chemical composition, temperature, pressure, interstitial fluids and reaction kinetics. Of these, only chemical, mineralogical composition, temperature and pressure are directly observable or can reasonably be inferred. The conclusions drawn here are therefore tentative.

The number of possible chemical reactions, however, is restricted insofar as these reactions also have to account for: 1) the sequential order of mineral formation (e.g., chlorite, albite, Ca-silicates); 2) the lack of evidence for mutual replacement of Ca-silicates, a feature caused perhaps by quick temperature rises and 3) the fact that the authigenic minerals occur generally as replacement of detrital components rather than as pore-filling cement.

The genesis of *corrensite* has been discussed by Kübler (1973). As the chemical composition of the sandstones is genrally constant (Table 2) and corrensite occurs only in the presence of laumontite (Fig. 3), the following genesis could be envisaged. The primary matrix/glass content of the sandstones reacts with Ca^{+2} in the interstitial waters to form laumontite; the relative amounts of matrix and available Ca^{+2} determine whether or not corrensite formation is possible. These reactions occur within a temperature range of 125 to 250° C.

The formation of chlorite as pore-filling cement as replacement of glassy matrix and mafic minerals is undoubtedly related to a reaction with the interstitial fluids because more or less well crystallized chlorite occurs over the whole range of temperatures investigated. Mechanisms of leaching and redeposition would be involved for chlorite cement, while the replacements by chlorite can be explained by the relative instability of mafic minerals and glassy matrix with respect to the interstitial fluids. The rather erratic chloritization of the mafic minerals was probably the result of erratic permeability distribution and hence interstitial fluid flow.

Illite occurs as sericite replacement of plagioclase and as a matrix component. In the fraction smaller than 2 microns, it is sporadically present within the stability range of montmorillonite and illite-montmorillonite mixed-layers but occurs almost in all samples as soon as the mixed-layers disappear. This is understandable as illite represents both a detrital component (from shales) and an aggradation product of illite-montmorillonite mixed-layers; i.e., at higher degrees of diagenesis both the illite components always add up to measurable quantities, an interpretation consistent with the rather constant K_2O content of the sandstones. As a consequence the crystallinity of illite could not always be measured at low FC (10 Å peak shorter than 5 cm) while measurements were always possible at high FC (Fig. 3).

In spite of a chemical environment seemingly unfavorable for illite formation (high Na_2O, CaO, MgO, FeO, Fe_2O_3), one can observe a regular increase of its crystallinity from 180–200° C and upwards, while at lower temperatures the scatter of the values nearly obscures the trend. The ternary diagram K_2O + MgO + Na_2O = 100 (Fig. 7) shows that the bulk rock and the clay-mineral fractions do not differ in the relative K_2O content; on the other hand Na_2O is enriched in the bulk rock (in albite) and MgO is enriched in the clay-minerals (in chloritic phases). This is understandable because illite and illite-montmorillonite are the main K_2O-carriers in these rocks; furthermore some K_2O may be released during the process of albitization as fresh labradorites contain 0.5 to 0.9% K_2O (microprobe measurements).

These observations suggest that the gradual formation of illite in these rocks is mainly controlled by increasing temperature and results from changes within the clay-mineral fraction only. The heat energy supplied during burial suffices to squeeze out the water contained in the illite-montmorillonite mixed-layers, in agreement with the experiments of Velde and Bystrom-Brusewitz (1972) and to redistribute the K^+ and Al^{+3} which must be added to form illite (Hower et al, 1976). This conclusion was already drawn for more mature clastics by Kübler (1966, 1968, 1969) and Dunoyer de Segonzac (1970b).

The *albitization* of plagioclase starts at low temperature and becomes more complete as

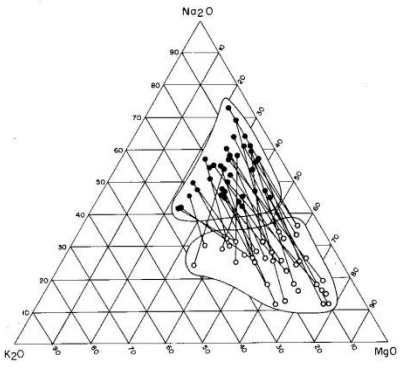

FIG. 7.—Ternary diagram where Na_2O + K_2O + MgO = 100. On an average, the lines joining the bulk-rock projections (black dots) to those of the relevant clay-mineral fraction (open circles) do not show any noticeable K_2O-enrichment in the clay-mineral fraction as compared with the bulk rock.

TABLE 2.—*Chemical composition of selected Taveyannaz sandstones and their clay-mineral fraction*

Sample No.	Chemical Composition of Sandstones in Oxide Percentage											Bulk Sample $Na_2O + K_2O + MgO = 100$			Clay-Mineral Fraction (< 2 micron)						Sample Location
										Ignit. Loss					Percentage % oxide				$Na_2O + K_2O + MgO = 100$		
	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	$^0Na_2O$	K_2O	TiO_2	P_2O_5	SO_3		Sum	Na_2O	K_2O	MgO	Na_2O	K_2O	MgO	Na_2O	K_2O	MgO	
910	58.2	17.34	2.4	2.5	2.8	6.13	4.9	0.63	0.60	0.17	0.00	5.39	101.1	59	7	34	2.6	1.5	4.2	31	18	51	Platé Massive, Savoie, FR
922	55.9	13.65	2.3	3.6	2.7	8.26	5.2	1.31	0.57	0.21	0.20	7.16	101.1	57	14	29	3.0	1.2	11.8	19	8	73	Platé Massive, Savoie, FR
952	57.0	14.89	3.8	4.0	4.0	3.95	6.1	0.84	0.83	0.22	0.20	4.21	100.0	56	7	37	3.8	0.6	6.1	36	6	58	Platé Massive, Savoie, FR
995A	59.9	14.24	2.2	3.0	2.1	7.73	4.4	1.52	0.52	0.19	0.17	4.80	100.9	55	19	26	2.4	1.5	5.7	25	16	59	Schächental, Uri, CH
999	56.0	15.72	1.8	5.1	2.3	6.70	4.0	3.20	0.71	0.27	0.49	3.94	100.2	42	34	24	2.5	2.2	4.8	26	23	51	Schächental, Uri, CH
1001	57.1	16.24	1.7	4.8	2.4	6.95	4.4	1.41	0.65	0.23	0.11	4.19	100.1	54	17	29	2.4	3.8	3.6	24	40	36	Schächental, Uri, CH
1002	52.6	14.61	1.6	4.4	2.1	9.91	5.2	1.82	0.61	0.21	0.41	7.51	101.0	57	20	23	3.1	2.6	4.0	32	27	41	Schächental, Uri, CH
1016	56.2	16.03	1.8	5.1	2.7	4.74	5.4	1.67	0.70	0.27	0.13	4.28	99.1	55	17	28	2.6	2.3	5.0	26	23	51	Schächental, Uri, CH
1019	60.0	14.87	1.6	4.4	2.6	4.16	5.8	1.30	0.59	0.20	0.17	5.04	100.8	60	13	27	3.3	1.2	5.2	34	12	54	Schächental, Uri, CH
1041A	53.3	15.25	2.3	6.3	4.2	6.73	4.9	1.68	0.76	0.22	0.02	2.55	98.2	45	16	39	2.6	2.3	5.3	25	23	52	Leuk, Valais, CH
1043	56.4	17.67	2.0	5.6	3.5	4.94	6.9	0.95	0.78	0.23	0.12	3.15	102.1	61	8	31	3.6	0.9	6.3	33	8	59	Diablerets, Vaud, CH
1049A	53.2	16.41	2.0	5.6	3.6	5.99	6.8	1.33	0.80	0.23	0.05	3.87	99.9	58	11	31	2.4	2.7	4.5	25	28	47	Diablerets, Vaud, CH
1058	54.8	16.66	1.9	5.2	3.3	6.90	5.1	0.64	0.73	0.22	0.09	4.93	100.4	57	6	37	2.0	0.9	5.0	25	11	64	Diablerets, Vaud, CH
1080	54.8	13.23	1.7	4.7	3.3	5.74	5.2	1.45	0.69	0.19	0.07	4.84	99.2	52	16	33	2.1	1.0	5.5	24	12	64	Diablerets, Vaud, CH
1081A	56.9	16.25	1.7	4.7	2.4	4.83	8.3	0.70	0.72	0.22	0.10	2.82	99.7	73	6	21	3.8	0.6	6.1	36	6	58	Diablerets, Vaud, CH
1082	58.1	16.66	1.9	5.0	3.3	2.84	6.7	1.53	0.83	0.25	0.06	2.56	99.7	58	13	29	2.9	1.8	5.6	28	17	55	Diablerets, Vaud, CH
1092B	54.4	15.18	1.8	5.1	3.4	6.38	6.7	1.96	0.74	0.21	0.03	5.03	101.0	55	17	28	1.8	1.1	5.4	22	13	65	Diablerets, Vaud, CH
1113	59.2	14.65	1.9	5.3	4.3	5.98	4.5	1.98	0.76	0.19	0.15	3.31	102.2	42	18	40	2.4	1.8	4.9	26	20	54	Varneralp, Valais, CH
1114B	56.4	15.94	2.2	6.0	3.9	2.42	5.2	2.36	0.91	0.21	0.06	3.40	99.1	45	21	34	1.6	1.2	4.6	22	16	62	Varneralp, Valais, CH
1116	57.5	15.30	2.0	5.5	4.2	5.14	5.3	2.64	0.78	0.21	0.16	2.85	101.5	44	21	35	3.0	2.7	4.7	29	26	45	Varneralp, Valais, CH
1240	57.5	16.98	2.1	3.1	2.7	4.38	5.4	1.73	0.76	0.18	0.19	4.26	99.2	55	7	28	0.8	1.2	2.2	19	29	52	Castel di Tusa, Sicily, I
1311	55.4	16.49	2.4	3.4	2.9	3.85	5.8	0.72	0.75	0.20	0.10	5.11	99.1	69	6	25	1.3	2.4	6.1	13	25	62	Rotondella, Lucany, I
1395	55.9	15.54	1.7	4.7	3.6	3.70	6.7	0.65	0.77	0.27	0.42	5.08	99.1	61	6	33	2.1	1.7	7.8	18	16	66	Petrignacola, I
1399	56.4	14.81	2.5	3.6	3.0	5.47	6.5	0.59	0.72	0.27	0.27	6.04	99.7	64	6	30	1.3	1.3	5.3	16	16	68	Petrignacola, I
1419	50.6	14.18	2.1	5.7	4.6	9.29	4.9	0.86	0.96	0.23	0.26	6.26	100.0	47	9	44	1.3	1.0	8.2	12	10	78	Passo del Cerreto, I
1423	50.2	14.40	2.8	3.0	3.3	11.12	4.8	2.03	0.71	0.21	0.12	8.50	101.2	47	20	33	1.3	2.5	6.8	12	24	64	Passo del Cerreto, I
1445	57.2	16.45	1.5	4.3	3.2	7.59	3.7	1.31	0.65	0.16	0.14	4.63	100.9	45	16	39	2.9	3.2	5.5	25	18	47	Val d'Aveto, I
1451	58.7	15.11	1.5	4.2	2.8	8.12	4.1	0.70	0.76	0.19	0.11	4.27	100.7	54	9	37	2.6	2.3	16.6	12	11	77	Val d'Aveto, I
1462	58.7	17.14	1.8	4.7	1.2	6.39	2.3	0.99	0.76	0.22	0.09	3.99	98.3	51	22	27	2.1	2.6	6.8	18	23	59	Val d'Aveto, I
1488	49.6	11.48	2.0	2.9	2.7	14.90	3.2	1.55	0.54	0.17	0.12	11.73	100.9	43	21	36	1.0	1.4	10.1	8	11	81	Clumanc, southern FR
1489	48.5	13.42	1.6	2.3	2.2	14.95	3.3	1.44	0.57	0.23	0.09	11.14	99.8	48	20	32	1.3	0.8	5.9	16	10	74	Clumanc, southern FR
1574	64.0	14.13	2.4	2.6	2.1	3.52	3.9	2.60	0.58	0.15	0.06	3.57	99.6	46	30	24	2.4	2.1	2.5	34	30	36	Champsaur/Dauphiné, FR
1576	64.6	14.61	1.5	2.6	2.2	3.16	4.2	2.38	0.60	0.16	0.13	3.65	100.8	48	27	25	2.7	2.4	3.9	30	27	43	Champsaur/Dauphiné, FR
1585	58.5	15.04	2.5	2.7	2.7	7.03	3.7	1.66	0.56	0.17	0.04	5.74	100.4	46	21	33	2.0	1.5	3.7	28	21	51	Champsaur/Dauphiné, FR
1606	66.6	13.72	0.9	2.4	1.4	3.15	3.4	2.88	0.48	0.10	0.04	3.81	99.1	44	18	18	3.1	3.2	4.3	29	30	41	Champsaur/Dauphiné, FR
1610	70.5	12.91	0.9	2.5	1.8	2.33	3.3	2.74	0.44	0.09	0.02	2.85	100.3	42	35	23	3.1	2.5	4.2	31	25	44	Champsaur/Dauphiné, FR
1613	60.6	14.63	1.5	4.1	3.4	4.81	4.9	1.80	0.59	0.14	0.10	4.10	100.3	50	18	32	1.8	1.1	8.8	15	9	76	Thônes, Savoie, FR
1634	55.2	16.57	2.6	3.7	3.1	5.97	3.9	1.09	0.56	0.18	0.30	4.99	98.3	47	12	41	2.2	0.8	8.7	19	7	74	Thônes, Savoie, FR
1658	56.4	15.97	3.0	4.4	3.4	5.90	3.7	1.16	0.78	0.18	0.21	4.86	99.9	45	14	41	2.2	1.2	8.6	18	10	72	Thônes, Savoie, FR
1667	61.8	15.45	2.4	2.5	2.1	4.11	4.6	1.66	0.51	0.16	0.01	4.09	99.3	55	20	25	2.8	1.5	4.5	32	17	51	Thônes, Savoie, FR
1673	57.5	15.54	2.7	2.8	1.9	6.76	4.1	2.20	0.66	0.20	0.05	4.86	99.4	50	27	23	2.4	2.3	4.3	27	25	48	Thônes, Savoie, FR
1694	52.0	16.54	3.4	4.9	3.6	4.96	5.4	0.76	0.87	0.23	0.21	5.24	98.1	55	8	37	2.9	1.0	7.2	26	9	65	Thônes, Savoie, FR
1697	57.5	15.08	2.3	2.4	2.3	7.03	5.4	0.75	0.49	0.16	0.03	6.28	100.0	64	9	27	2.8	1.1	4.9	32	12	56	Thônes, Savoie, FR
Average	57.01	15.27			2.91	6.16	4.85	1.52	0.69	0.20													

[0]Measured by atomic absorption; all other elements determined by X-ray fluorescence.
Standard rocks used for control: GR, GA, GH and BR of Roubault et al. (1966).
Analyst: H. Baak of Kon. Shell Exploratie en Produktie Laboratorium, Rijswijk (NL).

the degree of metamorphism increases (Fig. 3). The normative plagioclase, computed from the chemical analyses by the Niggli method (Burri, 1959), contains on the average a 30% mol. anorthite, and has therefore an andesine to oligoclase composition, as shown in Figure 8, which reflects a mixture of fresh and albitized plagioclases. Thus as albite replaces more basic plagioclases at constant volume, Na_2O must be added to the system. I have tentatively assumed that the source of this additional Na_2O is connate sea-water and compaction fluids.

That Na_2O was probably added to the system can be concluded from another line of evidence. If one compares the average chemical composition of the 43 Taveyannaz sandstones analysed with the average Cenozoic andesite conposition of Chayes (1969), a striking similarity can be observed except for the Na_2O which is almost double in the Taveyannaz Sandstone indicating an extraneous source (Table 3).

It has already been mentioned that the formation of *laumontite* followed that of chlorite. The formation of laumontite could therefore very well be linked with the reaction of Ca^{+2}-rich interstitial fluids with the chloritic material in the follwing way: clay-minerals + $Ca^{+2} \rightarrow$ laumontite + corrensite. The Ca^{+2} content of the interstitial fluids would originate from the albitization of basic plagioclase, as already suggested by Coombs (1952) and later by Otalora (1964). The antipathetic relationship between fresh plagioclase and laumontite indeed substantiates this view.

As Taveyannaz Sandstones of almost the same chemical composition can occur in two different "facies," namely a laumontite-corrensite facies and a "green facies" characterised by chlorite-albite (-calcite) (Martini, 1968, this study), we must assume that another parameter controls the development of laumontite. A reasonable assumption would be that the interstitial fluid compositions differed in CO_2-pressure (Zen, 1959, Coombs, 1971). This CO_2-pressure build-up, which prevented the formation of laumontite, could be related either to CO_2-release during the coalification of associated plant remains (Teichmüller and Teichmüller, 1967) or to CO_2-release during deep burial of underlying calcareous shales or to both mechanisms simulataneously. It is not yet clear why CO_2 would be trapped preferentially in certain parts of the sequence and not in others; permeability barriers (poor sorting and/or small grain-size, shale breaks) could perhaps be the explanation as the development of the "green facies" is related to its association with shales (Martini, 1968).

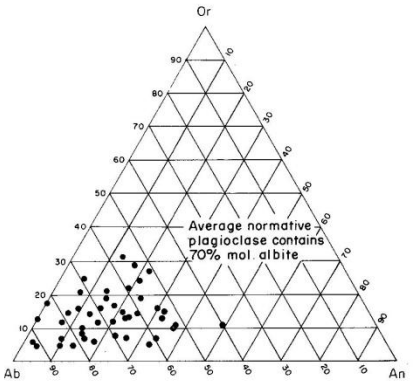

FIG. 8.—Normative plagioclase composition (for explanation see text). The Or (orthoclase) occurs within the plagioclase, as a detrital mineral and in the clay-mineral fraction. This plots shows that the average normative plagioclase contains about 70% mol.Ab (albite).

TABLE 3.—*Comparison between the average chemical composition, in oxide percentages, of the Cenozoic Andesite of Chayes (1969)[A] and of the 43 analysed Taveyannaz sandstones.[B] The excess of Na_2O in the latter is obvious and suggests extraneous origin.*

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5
A:	58.17 ±4.06	17.26 ±1.56	3.07 ±1.38	4.18 ±1.62	3.24 ±1.24	6.93 ±1.63	3.21 ±0.72	1.61 ±0.75	0.8 ±0.35	0.21 ±0.15
B:	59.7 ±4.5	18.1 ±1.4	6.5 ±1.3		3.0 ±0.8	6.4 ±2.9	5.1 ±1.5	1.6 ±0.7	0.7 ±0.1	0.2 ±0.05

The analyses have been recalculated on a water-free basis.

Prehnite occurs either at high rank or as fissure-filling mineral at relatively low rank. The association with fissures tends to indicate that the fluid pressure might have been low, which would enhance the formation of prehnite rather than laumontite (Coombs, 1971).

As a high rank metamorphic mineral prehnite is always the last phase to have crystallised. It replaces, for example, albitized plagioclases from the outside towards the inside suggesting that its formation could be linked with the reaction between interstitial fluids and minerals. No example where laumontite is transformed to prehnite was encountered.

The crystallisation of *pumpellyite* requires SiO_2, Al_2O_3, CaO, FeO, Fe_2O_3 and MgO. Its presence within plagioclase indicates that there was introduction of iron and magnesium, and in many cases pumpellyite could have replaced chloritized glass droplets which frequently occur in volcanic plagioclases. As there is no evidence of a laumontite stage preceding that of pumpellyite it is tempting to explain the pumpellyite formation by some reaction between clay minerals and Ca^{+2}-rich fluids/solids. Arguments in favor of this point are differences in habit and absence of secondary quartz, which is a by-product of this type of transformation (Coombs, 1961).

CORRELATION AND CHEMICAL EQUILIBRIUM

The correlation model developed here should have application in any other similar system provided that the diagenetic mineral products are in chemical equilibrium. Without this assumption, the model fails.

Chemical equilibrium can be tested in several ways such as absence of incompatible phases, non-violation of the phase-rule and partition of elements between coexisting minerals (Zen, 1963; Kern and Weisbrod, 1964; Fonteilles, 1965; Turner, 1968). The tests mentioned above were applied to the reaction series within the Taveyannaz Sandstone. It could be established that there are no incompatible phases and no violations of the phase rule.* Because of the very small size of the minerals it was impossible to measure the composition of all the relevant coexisting phases in the same thin-section: partition-coefficient diagrams could therefore not be constructed. It was possible, however, to show that the minerals investigated, although possibly of rather variable composition, have a very constant composition at thin-section scale (Fig. 9). This suggests that chemical equilibrium was at least partially attained in spite of the presence of relictic pyroxene, amphibole and labradorite.

Further evidence of chemical equilibrium is provided by the fact that at similar gross chemical composition: 1) there is a regular increase in illite crystallinity and a clear zonation of the other authigenic minerals when FC increases; 2) this zonation is meaningful with respect to the geological frame (Fig. 12) and 3) secondary mineral assem-

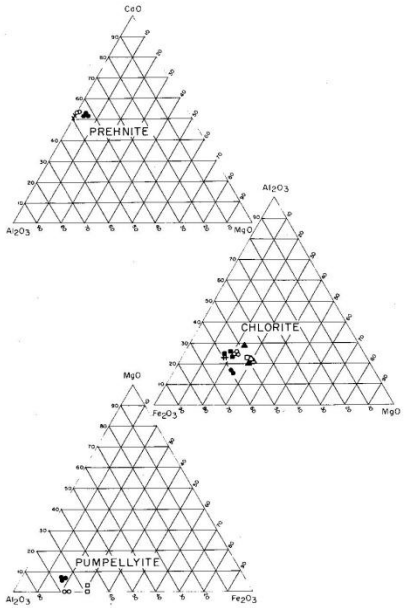

FIG. 9.—Compositions of prehnites, chlorites and pumpellyites from Taveyannaz sandstones. Identical symbols refer to minerals of the same sample. Note the constant composition within a single sample.

*If SiO_2, Al_2O_3, Fe_2O_3/FeO, CaO, MgO, Na_2O, K_2O and H_2O are the necessary components, we can see on Figure 3 that the number of coexisting phases never exceeds that of the components.

blages can be accounted for by chemical composition (Fig. 10).

We can, therefore, conclude that chemical equilibrium was approached and that the correlation model presented in this paper is a reliable tool for estimating the degree of metamorphism and the relevant temperatures.

PRESSURE AND TEMPERATURE DURING METAMORPHISM OF THE TAVEYANNAZ SANDSTONE FROM THE ALPS

General Considerations

We can safely assume that the main mineralogical changes encountered in the Taveyannaz Sandstone result from changes in the intensity of the metamorphism because: 1) the chemical composition of the sandstones is fairly constant (Table 2) and generally accounts well for the presence of a given set of minerals at a given degree of metamorphism (Fig. 10); 2) the mineralogical zonation displayed by the sandstones is similar to that observed in many other parts of the world; 3) the correlation between illite crystallinity and FC/temperature is quite good (Fig. 3) and 4) the mineralogical zonation is meaningful with respect to the geological megaframe of the Alps (see below).

Minor superimposed mineralogical variations can probably be accounted for by activity of interstitial fluids which is a common feature in very low- and low-grade metamorphic rocks. As the correlation of, mineralogy with FC is quite good, and as FC is rather insensitive to pressure, it can be concluded that in this particular case mineralogy is also a good temperature indicator.

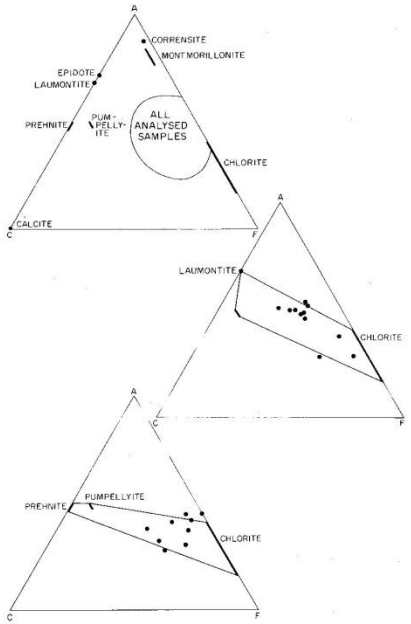

FIG. 10.—ACF-projections of the Taveyannaz sandstone samples analysed. The points lie within the triangle having as apexes the metamorphic minerals. A, C and F as defined in metamorphic petrology (Winkler, 1965).

Pressure-Temperature Regime and Facies Sequence

The pressure-temperature relationships involved in the metamorphism of the Taveyannaz Sandstone are still poorly understood. It is hoped to shed some light on this problem with the results presented below.

1. *Facies Sequence.*—The facies sequence or sequence of mineral assemblages in the sense of Miyashiro (1961 and 1967) is a very useful concept for the determination of the temperature-pressure relationship. Compilation works by Seki (1969), Coombs (1968, 1971) and Miyashiro and Shido (1970) have shown that the facies sequences were well defined even for very low- and low-grade metamorphisms. Consequently the temperature-pressure relationship for the Taveyannaz Sandstone metamorphism can be estimated by comparing its facies sequence with the data of Seki (1969) and Coombs (1971). By combining the results of this study with those of other authors (Martini and Vuagnat, 1965, 1970; Sawatski and Vuagnat, 1971; Kübler, 1973; Bocquet, 1971; Coombs et al, 1976), the following sequence of mineral assemblages was established (in order of increasing metamorphic intensity):

laumontite-heulandite-montmorillonite-corrensite
laumontite-pumpellyite-corrensite-illite/montmorillonite mixed layers
laumontite-pumpellyite-prehnite-

corrensite-illite/montmorillonite mixed layers
pumpellyite-prehnite-illite-chlorite
pumpellyite-actinolite-mica-chlorite

This sequence can be well accommodated into the facies sequence characteristic of an intermediate pressure-temperature regime as quoted by Seki & Coombs, i.e., reflecting a normal geothermal gradient.

2. *Other Considerations.*—Five samples of shales associated with the Taveyannaz Sandstone, exhibiting different degrees of diagenesis/metamorphism, were dated by the K-Ar method. The results obtained so far (Table 4, Fig. 11) indicate that the highest-rank samples were metamorphosed at an age slightly younger than 40 million years, while the least altered samples display metamorphic ages resulting from a mixture of hercynian and alpine ages. This age of 40 million years matches very well the Main Alpine Metamorphic Phase at 38 million years (Hunziker, 1969; Jäger, 1970, 1973; Trümpy, 1973) and therefore suggests that the Lepontine Phase which metamorphosed the Ticino Nappes in the amphibolite facies is also responsible for the alterations undergone by the Taveyannaz Sandstone. Such a relationship of the metamorphism of the helvetic sediments in Eastern Switzerland with the thermal culmination of the Lepontine Nappes is also considered possible by Frey et al (1973) and Kübler at al (1974).

TABLE 4.—*Analytical results of the age determination of five shale samples associated with Taveyannaz sandstones, using the K-Ar method.*

	Sample	Na (%)	K (%)	Argon (10^{15} atoms/g)	Age (10^6y)	Illite crystallinity (mm)
Bulk rock	SL 1000	1.6	2.73	0.135	45 ± 5	1.8
	SL 1111	1.3	3.40	0.150	41 ± 6	1.5
	SL 1056	0.7	3.59	0.210	74 ± 6	2.6
	SL 938	0.4	2.80	0.275	89 ± 9	4.1
	SL 1615	0.9	3.28	0.320	90 ± 5	9.4
Fraction < 2μ	SL 1000	0.8	3.56	0.194	50 ± 8	2.5
	SL 1111	0.9	4.27	0.200	43 ± 5	2.4
	SL 1056	0.4	3.48	0.290	76 ± 7	3.3
	SL 938	0.4	4.25	0.360	77 ± 7	5.5
	SL 1615	0.4	3.77	0.361	88 ± 3	10.0
Fraction 2–8 micron	SL 1000	1.6	2.74	0.195	66 ± 4	1.5
	SL 1111	0.5	3.37	0.190	52 ± 4	1.5
	SL 1056	0.9	2.83	0.225	73 ± 7	2.2
	SL 938	1.2	3.36	0.265	73 ± 3	2.2
	SL 1615	0.8	2.30	0.400	155 ± 10	1.8

Origin of samples
SL 1000 Schächental, Uri, Switzerland.
SL 1111 Varneralp, Valais, Switzerland.
SL 1056 Diablerets, Vaud, Switzerland.
SL 938 Platé, Savoie, France.
SL 1615 Thônes, Savoie, France.

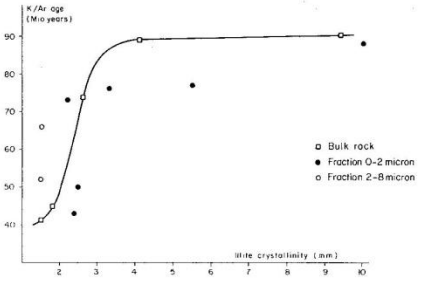

FIG. 11.—K/Ar-age of shales associated with Taveyannaz sandstones plotted against relevant illite crystallinity. Curve defined by bulk-rock ages reflects a metamorphic phase at 40 million years for higher degrees of metamorphism, responsible for all the mineral alterations dealt with in this study. The plateau at 90 million years observed for low degree of metamorphism results very likely from the mixing of hercynian ages (detrital muscovites) and alpine tertiary rejuvenation.

One may also conclude that a common mechanism of metamorphism was involved and that the amphibolite facies and the low-/very low-grade Taveyannaz Sandstone represent the two extremes of the same facies sequence. Such a facies sequence is typical of intermediate pressure-temperature relationship (Fyfe et al, 1958; Turner and Verhoogen, 1960; Turner, 1968). The greenschist facies situated between these two extremes occurs for instance in the Central Massives (von Raumer, 1969 and 1974) and in the Penninic Nappes (Frey, 1969; Niggli, 1970).

If one plots on a tectonic map of the Central Alps the average illite crystallinity at the relevant locations and contours the illite-crystallinity isograds (Fig. 12), it becomes apparent that the latter intersect the Alpine Trend and lie parallel to the outlines of the area metamorphosed in the amphibolite facies (Ticino Nappes). This suggests also that the amphibolite facies and the Taveyannaz Sandstone low-grade metamorphism represent the two extremes of a single metamorphic event. One could argue that the Hevetic Nappes were emplaced after their metamorphism (Trümpy, 1960) and that the course of the isograds was disturbed. Never-

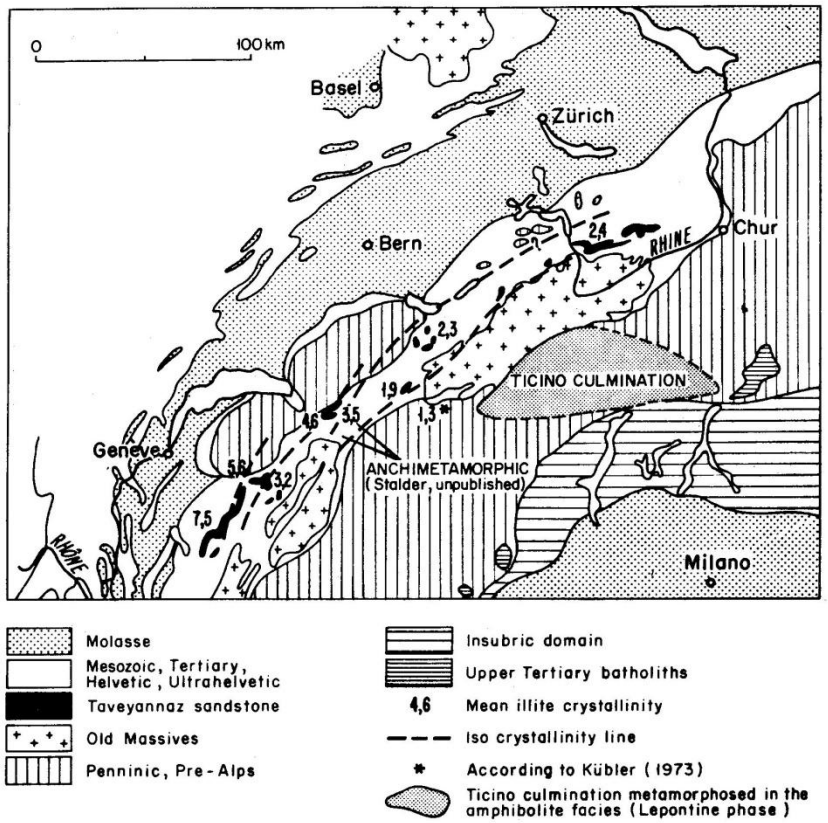

FIG. 12.—Distribution of the mean illite crystallinities (mm) in the Western and Central Alps. The tentative isocryatallinity lines cut the Alpine trend in the West and run more or less parallel to the outlines of the Ticino Culmination; this suggests a genetic relationship for mechanism and age of metamorphism.

theless, the nappe of more internal origin (Diablerets Nappe) shows higher illite crystallinity than those of more external origin (Morcles Nappe and Paraautochtonous), which suggests that the relative sequence of the iosgrads before nappe emplacement was similar to the present one.

3. *Conclusions.*—The evidences shown above suggest that the pressure-temperature relationship of the Taveyannaz Sandstone metamorphism was of normal type (except for intensively tectonized areas) and that the metamorphism itself took place during the Lower Oligocene some 38 million years ago (Lepontine Event). It is stressed that these conclusions are tentative and should be tested with more data points. A high-pressure metamorphic event such as that postulated by Ernst (1971) was not established in the Taveyannaz Sandstone metamorphism, although its existence is well established elsewhere in the Alps (Frey et al, 1974).

CONCLUSIONS

The results so far obtained in this study are fairly encouraging. In spite of some scatter in the data, it has been shown that:

1) The coal rank (vitrinite reflectance) and the mineral assemblages (clay minerals, zeolites, etc.) of the volcaniclastic Taveyannaz Sandstone correlate in a systematic manner (Fig. 3).

2) The observed sequence of mineral assemblages with increasing degree of diagenesis/metamorphism agrees well with that found in other parts of the world.

3) The temperature—coal rank relationship of Hood et al (1975) allows one to assign temperatures in the range of 110° C to 300° C to the appearance and/or disappearance of the characteristic mineral assemblages.

4) With this correlation chart it should be possible to predict on the basis of the burial/temperature history of given formations when the main phases of water release occurred with all the attendant ramifications on cementation processes and hydrocarbon expulsion and migration.

5) The model presented here will contribute data, together with those of other authors, to fill in the gap which still exists in our knowledge of very low-grade metamorphism especially in regard to reaction temperatures; because of the scatter in the data this model should be used in a statistical manner, working with mean figures (e.g., illite crystallinity, shale density, etc.). On the other hand, I think that there are sufficient interrelated yardsticks to reach a unique solution;

6) The Taveyannaz Sandstone diagenesis/metamorphism can be integrated into the general frame of the Central Alpine Metamorphism and seems to represent the low temperature end of a metamorphic facies sequence radiating from the Ticino Thermal Culmination.

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