X-ray diffraction intensity ratios of phyllosilicate reflections in cleavage- and bedding-parallel slabs: incipient development of slaty cleavage in the Caledonides of Jämtland, western central Sweden

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ABSTRACT

The ratio of the absolute intensities of a **00l** phyllosilicate X-ray diffraction peak measured on cleavage (C)- and bedding (B)-parallel slabs, or the ratios of the relative intensities of a **00l** lattice plane to that of a **hk0** or **hkl** lattice plane, reflects the relative orientation of the phyllosilicate mineral in clastic rocks showing incipient slaty cleavage. The $I_{10Å}$ and $I_{10Å}/I_{4.46Å-19.9°}$ C/B ratios are used as mica-orientation criteria. The dependence of these ratios on slab sizes below *ca.* 20 mm is minimized when the peaks are measured using suitable divergence/scatter slit pairs. These X-ray orientation criteria were measured on a series of Lower Paleozoic clastic rocks showing incipient slaty-cleavage development from the external Caledonides of Jämtland, western central Sweden. In the external low-grade areas the $I_{10Å}$ C/B and $I_{10Å}/I_{4.46Å-19.9°}$ C/B ratios are smaller than unity in the 'diagenetic' (par)autochthon, and around unity in the low-anchimetamorphic lower thrust sheet. In the more internal anchimetamorphic areas many rocks show a combination of low X-ray orientation ($I_{10Å}$ C/B = 0.3-0.9) with high **c/b** cleavage/bedding fissility ratios. This reflects cleavage-domain development without appreciable mica re-orientation, whereas the increase in the X-ray C/B ratios for essentially similar **c/b** cleavage/bedding fissility ratios reflects increased mica orientation in the cleavage domains and the microlithons at the expense of bedding-parallel micas, particularly in fold hinges. It appears that, at these incipient stages of slaty-cleavage development, the phyllosilicate fabric as expressed by the X-ray orientation is a more sensitive indicator of local variations in strain than the **c/b** fissility ratio - apparently the expression of cleavage-domain development -, which tends to be more uniform over a given area.

Keywords: Slaty cleavage, X-ray diffraction intensities, Fissility, Illite 'crystallinity', Anchimetamorphism, Caledonides, Jämtland.

RESUMEN

Razones de intensidad de difracción de rayos X de filosilicatos en lajas paralelas a la foliación y a la estratificación: desarrollo incipiente de clivaje de pizarra en las Caledonides de Jämtland, Suecia central occidental. La razón de las intensidades absolutas de un pico **00l** de difracción de rayos X de filosilicatos medida en lajas paralelas a la foliación (C) - y a la estratificación (B), o las razones de las intensidades relativas de plano **00l** y planos **hk0** o **hkl**, reflejan la orientación relativa de los filosilicatos en rocas clásticas que muestran incipiente clivaje de pizarra. Las razones $I_{10Å}$ C/B y $I_{10Å}/I_{4.46Å-19.9°}$ C/B se usan como criterios de orientación de las micas. La dependencia de estas razones con el tamaño de estas lajas menores que *ca.* 20 mm es minimizado cuando los 'peaks' son medidos usando pares de divergencia/dispersión adecuados. Estos criterios de orientación por rayos X fueron medidos en una serie de rocas clásticas del Paleozoico Inferior de las Caledonides externas de Jämtland, Suecia central occidental. En las áreas externas de bajo grado las relaciones $I_{10Å}$ C/B y $I_{10Å}/I_{4.46Å-19.9°}$ C/B son menores que 1 en el (para)autóctono 'diagenético', y alrededor de la unidad en la napa inferior con anquimetamorfismo bajo. En las áreas anquimetamórficas más internas, muchas rocas muestran una combinación de baja orientación ($I_{10Å}$ C/B=0.3-0.9) con altas relaciones de fisibilidad **c/b** de clivaje/estratificación. Esto refleja un desarrollo de dominios de clivaje sin una reorientación apreciable de las micas, mientras que el aumento de las razones (C/B) de rayos X para razones de fisibilidad **c/b** de clivaje /estratificación esencialmente similares, refleja un incremento de la orientación de las micas en los dominios de clivaje y en los microlitones, a costa de las micas paralelas a la estratificación, particularmente en charnelas de pliegues. Al parecer, en estos estados incipientes de desarrollo de clivaje de pizarra, la fábrica de los filosilicatos, expresada por su orientación en rayos X, es un indicador más sensible de variaciones locales de la deformación que la razón de fisibilidad **c/b**- aparentemente la expresión de desarrollo de dominios de clivaje- la cual tiende a ser más uniforme sobre un área determinada.

Palabras claves: Clivaje de pizarra, Difracción de rayos X, Fisibilidad, 'Cristalinidad' de illita, Anquimetamorfismo, Caledonides, Jämtland.

INTRODUCTION

As a simple means of quantification of the intensity of incipient slaty cleavages, Durney and Kisch (in press) proposed the cleavage/bedding (**c/b**) fissility ratio, the dimensional ratio of the fissilities developed along the planes of cleavage- and bedding-fabric anisotropy, as measured on fissility fragments of mudrocks in slightly weathered outcrops. The intensity of this cleavage/bedding fissility is a function of several microtextural factors, which include the original bedding fissility of the rock; the spacing, continuity (in the cleavage direction), thickness, and smoothness of the cleavage domains; and the degree of cleavage-parallel orientation of the phyllosilicate minerals, particularly in the cleavage domains. This paper uses a simple X-ray diffraction (XRD) method to quantify one of these factors, the cleavage/bedding orientation ratio of the phyllosilicate minerals- which is often difficult to estimate by microscopic observation- as measured on two rock slabs cut respectively parallel to bedding and cleavage of the rock.

The intensity of the 00l XRD reflections of phyllosilicate minerals as measured on rock slabs cut in different directions reflects both the amount of these minerals and their relative degree of orientation in the

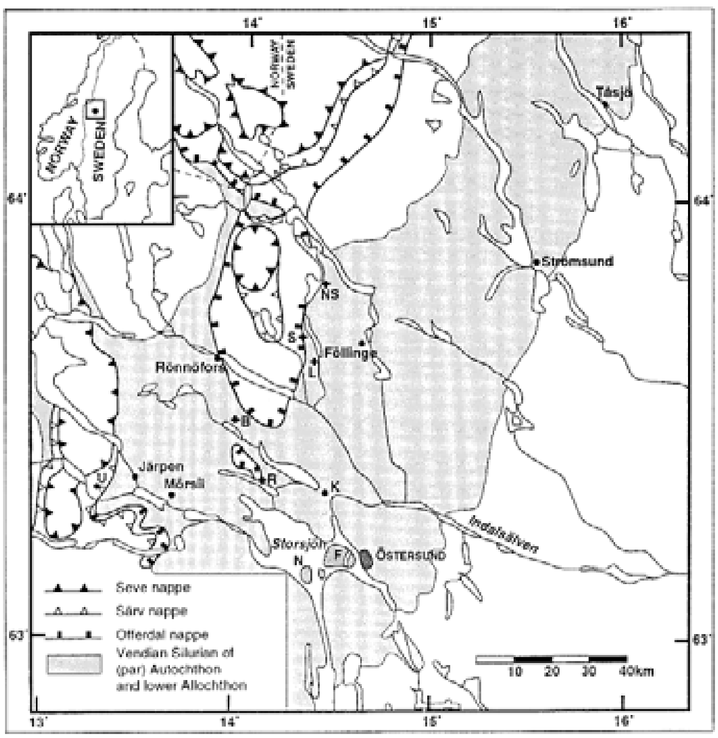

FIG. 1. Geological-tectonic sketch map of the western part of Jämtland county, Sweden. Geological details after Gee (1975, Plate 1) and Gee and Kumpulainen (1980, Plate 1). Abbreviations of some sample localities mentioned in the text: B=Bångasen; F=Frösön; K=Krokom; L=Lillholmsjö; N=Norderön; NS=Norra Skärvangen; O=Offerdal; R=Röde; S=Storholmsjö; U=Undersaker.

slab surface. If two slabs are cut in a rock in different directions, the ratio of the intensities of the same **00l** reflection in these two sections should reflect the relative orientation of the **00l** lattice planes. This approach can be used to quantify the relative orientation of the phyllosilicates in the cleavage (C) and bedding (B) planes of sedimentary rocks showing incipient slaty cleavage, and to assess its relationship to the **c/b** cleavage/bedding fissility ratio.

MATERIAL STUDIED

Polished sections have been prepared parallel to the B and C planes of 50 sedimentary rocks of Ordovician and Silurian age from the Jämtlandian nappes (lower Allochthon) of the external Caledonides of Jämtland province, western central Sweden. The samples were collected from exposures with a large angle between the cleavage and the bedding in most of which, the degree of incipient metamorphism had been studied earlier (Kisch 1980; Padan *et al.*, 1982). Cleavage/bedding fissility ratios were measured in the field on samples collected in 1992, and in the laboratory on some samples collected earlier in 1978. In most of the samples, the 'C' direction is an S_1 cleavage, but in at least three samples the 'C' direction is an S_2 crenulation or crenulation cleavage, and the indicated 'B' direction, a probably bedding-parallel S_1 cleavage, for instance in N92-1A Mörsil, N92-10 Hälland/Undersåker, and N92-23 west of Rönnofors (quartz-poor crenulated slates).

Most of the samples studied were collected from the Ordovician Föllinge Graywacke Formation, and a few from the overlying Lower-Silurian Bångåsen Shale and Middle-Silurian Röde Sandstone Formations, from two anchimetamorphic areas in the internal part of the 'Föllinge nappe' (Asklund and Thorslund 1935)- the Mörsil-Järpen-Bångåsen area to the south and the Föllinge area to the north (for localities see the sketch map Fig. 1). The degree of metamorphism, as determined earlier (Kisch, 1980) and for the present study, is medium-grade anchizone to anchi-epizone (mainly 0.17-0.28°Δ2θ in the <2 μm fraction) in the Mörsil-Järpen-Bångåsen area and slightly lower-grade, medium- and low-grade anchizone (mainly 0.24-0.33°Δ2θ in the <2 μm fraction) in the Föllinge area.

Two additional samples were studied from the middle-Ordovician 'Ogygiocaris shale' or Andersön shale on Norderön and Frösön islands in the low-grade anchizone of the more external underlying lower thrust sheets of the southeastern Storsjön area- the 'Sunne Nappe' of Thorslund (1940) and 'Frösön Allochthon' or 'Frösön Nappe' of Gee and Kumpulainen (1980, p. 30, 35). Strömberg *et al.* (1984) Jämtland map (also Gee and Kumpulainen, 1980, Plate 1) appeared to correlate northern Norderön- earlier included by Asklund (1960, 1961) in the frontal part of the overlying Föllinge nappe (cf. Gee, 1975, Plate 1; Gee and Kumpulainen, 1980, Fig. 11)- with this Frösön thrust slice. Note that the Jämtlandian nappes, including the above-mentioned Sunne and Föllinge nappes, are part of the lower Allochthon as used here. Three further samples come from the Ordovician of the even more external 'diagenetic' Parautochthon or Lower Allochthon around Östersund and autochthonous Cambrian of Tåsjöberget in the north.

RELIABILITY OF THE INTENSITY OF THE 00l REFLECTIONS: EFFECT OF SLAB SIZE AND OF DIVERGENCE/SCATTER SLIT APERTURES

As a check on the reliability of the intensities of the 10-Å reflections of illite/phengite, their ratios against those of the higher-order 004 5-Å reflections, as measured using the 1° divergence/scatter slit set, were plotted for the C and B sections (Fig. 2). The I_{10A}/I_{5A} ratios in the C and the B sections show no systematic difference, but scatter widely around the 1/1 relation. This scatter appears, to a large extent, to be related to slab size: in the I_{10A}/I_{5A} C *versus* I_{10A}/I_{5A} B plot (Fig. 2), most points with a marked divergence from the 1/1 relationship represent pairs of polished slabs whose sizes in the direction of the X-ray beam differ by more

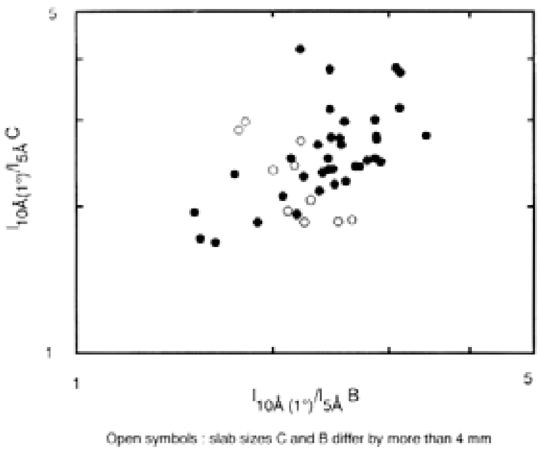

FIG. 2. Intensity ratio of the illite/phengite 10-Å and 5-Å peaks ($I_{10Å}/I_{5Å}$) in the C and B slabs. All intensities measured using the 1° divergence/scatter slit set. Open circles represent pairs in which the C and B slab sizes in the X-ray beam direction differ by more than 4 mm.

than 4 mm, the $I_{10Å}/I_{5Å}$ ratio of the smaller slab being anomalously low. This is evident from a plot of the $I_{10Å}/I_{5Å}$ C/B ratios against the size ratio of the C and B slabs (Fig. 3).

Since many rocks disintegrate along either the C or B direction upon sawing, and the polished C and the B slabs are, therefore, unavoidably of different size, such slab-size dependence of the X-ray intensities used as parameters of the phyllosilicate orientation is undesirable: it is imperative to adopt X-ray settings that will minimize slab size-dependence of these X-ray intensities.

This size dependence must reflect the use of the 1° divergence/scatter slit pair: for the Philips X-ray diffractometer used, the smallest 2θ angle for the full utilization of a 1° beam-*i.e.*, the smallest diffraction angle at which the sample completely intercepts the X-ray beam-for a 20 mm long specimen is 18.4°, corresponding to 4.83 Å for CuKα radiation (Jenkins and De Vries, no date, p. 21). At smaller diffraction angles 2θ, such as 8.85°2θ (10 Å illite), part of the 1° beam will bypass a 20 mm specimen (Fig. 4). This results in a decrease in intensity of these low-angle reflections relative to those of higher-angle peaks, such as 17.75°2θ (5 Å illite), 19.9°2θ (4.46 Å illite) and 20.9°2θ (4.255 Å quartz) in small compared to large specimens that completely intercept the 1° beam at all these diffraction angles, and thus, in a decrease in the $I_{10Å}/I_{5Å}$ and $I_{10Å\ (ill/phe)}/I_{4.26Å\text{-}20.8°\ (qz)}$ intensity ratios. It might, therefore, be preferable to use the intensity of the 5-Å rather than the 10-Å illite peak as the parameter of phyllosilicate orientation, were it not for the fact that the 5-Å peak is much weaker, being less than≈160 cps in several slabs, even using the 1° slit sets.

For a ½° divergence/scatter slit pair, the smallest diffraction angle at which a 20 mm sample completely intercepts the X-ray beam is halved, *i.e.*, equals 9.2°2θ (corresponding to 9.66 Å for CuKα radiation), so that at 8.95°2θ (10Å) the 20-mm specimen almost completely intercepts the X-ray beam (Fig. 4); this increases intensity ratios, such as $I_{10Å}/I_{5Å}$ and $I_{10Å\ (ill/phe)}/I_{4.26Å\text{-}20.8°\ (qz)}$ compared to the 1° slit pair, but at the expense of absolute intensity. Specimen length less than 20 mm in the beam direction at ½° results in a smaller apparent sample surface at 9.2°2θ and a concomitant reduction of the 10-Å intensity, and thus effects a similar relative reduction in the above intensity ratios as do wider divergence/scatter slit pairs.

The effect of the divergence/scatter slit set was tested by running 29 slabs both at ½°-0.2 mm-½° and 1°-0.2 mm-1°. As expected, the intensities of all reflections show a marked decrease at ½° slits, but the $I_{10Å\ (1/2°)}/I_{10Å\ (1°)}$ intensity ratio shows a marked relationship with the slab size: the intensity $I_{10Å}$ in the larger slabs is 0.36-0.52 of that at 1° (Fig. 5a) -this reduction in the intensity $I_{10Å}$ being of the same order as was measured on long slabs, where the intensity of the 10-Å reflection using ½° slits was about 0.37-0.44 of that with 1° slits-, whereas smaller decreases in $I_{10Å}$,

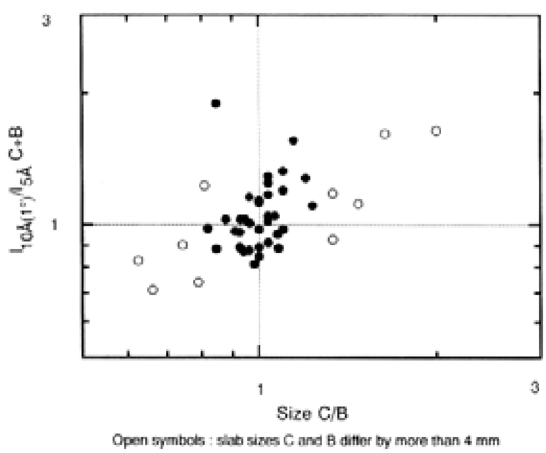

FIG. 3. Relationship between the ratio of the intensity ratios $I_{10Å}/I_{5Å}$ in the C and B slabs ($I_{10Å}/I_{5Å}$ C/B) and the slab-size ratio of the C and B slabs.

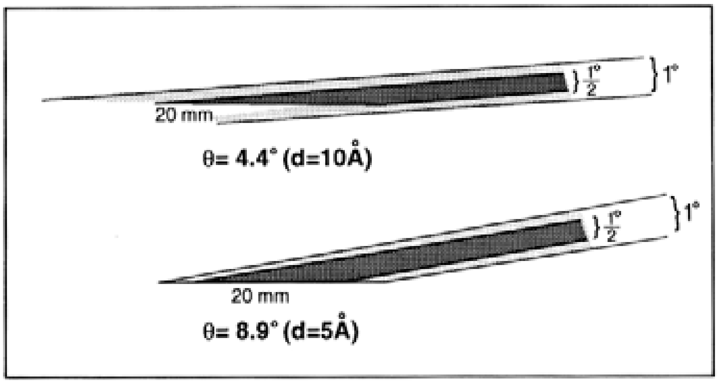

FIG. 4. Interception of ½° and 1° X-ray beams (½° and 1° divergence/scatter slit sets) by a 20 mm specimen at diffraction angles of 8.85° and 17.75°2θ (or 4.4° and 8.9°) for the Philips X-ray diffractometer used, corresponding to the 10-Å and 5-Å diffraction angles of illite/phengite for CuKα radiation. At a diffraction angle of 4.46°θ (10 Å) the specimen almost intercepts the ½° beam, but not at the 1° beam; at 8.8°θ (5 Å) the specimen almost intercepts the 1° beam. In theory, therefore, a diffraction angle of 4.4°- but not at a diffraction angle of 8.9°θ - a larger specimen should intercept a larger proportion of a 1° beam, and therefore, generate a stronger diffraction peak; as a result the intensity ratio $I_{10Å(1°)}/I_{5Å(1°)}$ should increase with sample size. If, on the other hand, the sample is irradiated with a ½° beam at 4.4°θ, and with a 1° beam at 8.9°θ, larger specimens should not intercept appreciably larger proportions of the beams in both cases, and the intensity ratio $I_{10Å(1/2°)}/I_{5Å(1°)}$ should remain unaffected.

i.e., $I_{10Å\ (1/2°)}/I_{10Å\ (1°)}$=0-54-0.69, are restricted to eight slabs of less than 18½ mm in the X-ray beam direction.

At ½° slits the intensities $I_{4.26°Å\text{-}20.8°\ (qz)}$ and $I_{5Å\ (ill/phe)}$ decrease somewhat more than $I_{10Å}$, and are largely 0.26-0.45 of that at 1° (excluding reflections with $I_{5Å\ (1/2°)}$≤80 cps) (Fig. 5b), but the $I_{5Å\ (1/2°)}/I_{5Å\ (1°)}$ and $I_{20.8°\ (1/2°)}/I_{20.8°\ (1°)}$ ratios show very little systematic variation with slab size: $I_{5Å\ (ill/phe)}$ and $I_{20.8°\ (qz)}$ decrease by comparable amounts in large and small slabs.

Some slabs of 18-20 mm show anomalously small values for all three $I_{(1/2°)}/I_{(1°)}$ ratios (N92-6 C; N78-8A C, 47B C, 48 B): $I_{10Å\ (1/2°)}/I_{10Å\ (1°)}$ ratios around 0.4 and $I_{5Å\ (1/2°)}/I_{5Å\ (1°)}$ and $I_{20.8°\ (1/2°)}/I_{20.8°\ (1°)}$ ratios of less than 0.3. These low intensity ratios are considered to reflect slab mispositioning. This was ascertained by plotting the $I_{10Å\ (1/2°)}/I_{10Å\ (1°)}$ and $I_{20.8°\ (1/2°)}/I_{20.8°\ (1°)}$ ratios for the same series of 29 samples, some of which were inserted in two different positions (Fig. 6). The mispositioning is seen to result in a marked reduction of both $I_{(1/2°)}/I_{(1°)}$ ratios. For specimens the size of the ½° beam (*i.e.*, ≈20 mm at 10 Å), this reduction is due, mainly, to reduction of the peak intensity in the ½° beam, since

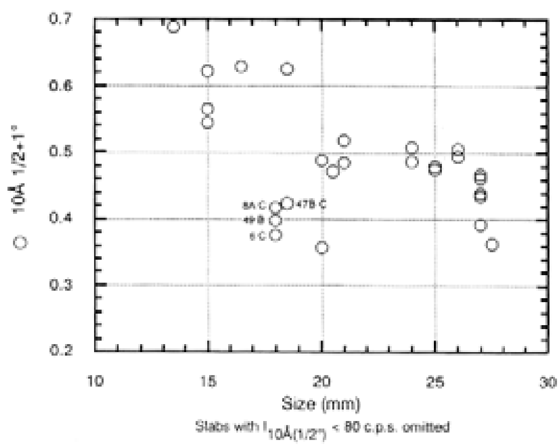

FIG. 5a. Relationship of the intensity ratio of the illite 10-Å reflections as measured with the ½° and 1° slit sets ($I_{10Å}$ ½°+1°) and the slab size for 29 slabs. Note higher intensity ratios for the smaller slabs.

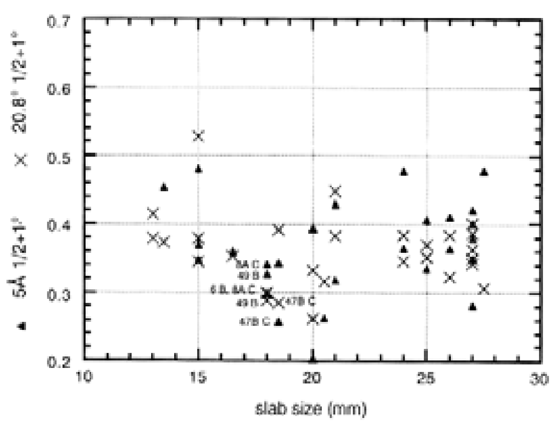

FIG. 5b. As in figure 5a for the intensity ratios of the illite 5-Å ($I_{5Å}$ ½°+1°) and quartz 20.8° ($I_{20.8}$ ½°+1°) reflections. Note lack of variation of intensity ratios with slab size.

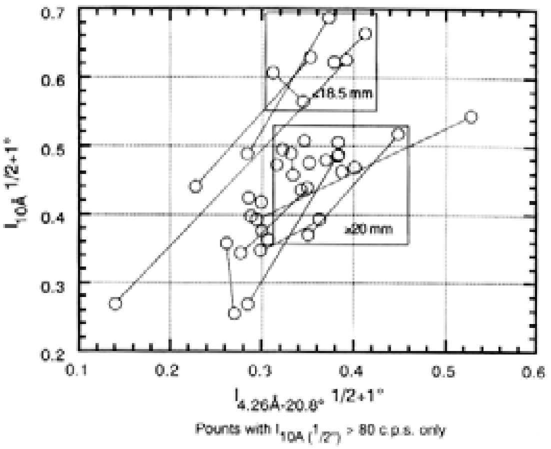

FIG. 6. Relationship of the $I_{(1/2^\circ)}/I_{(1^\circ)}$ intensity ratios for the illite 10-A and the quartz 20.8° reflections ($I_{10A(1/2^\circ)}/I_{10A(1^\circ)}$ and $I_{20.8^\circ(1/2^\circ)}/I_{20.8^\circ(1^\circ)}$ for 29 slabs, some of which were inserted in two different positions. The points for the two insertion positions of the same slab are connected. Mispositioning results in a marked reduction of both intensity ratios for most slabs.

the slab shift upon minor mispositioning will move part of the slab out of the narrower ½°, but not out of the broader 1° beam.

The intensity ratios I_{10A}/I_{5A} at ½° and 1° slit sets have been plotted against the slab size for these 29 slabs (Fig. 7). These plots show that the $(I_{10A}/I_{5A})_{1^\circ}$ ratio tends to decrease much more than the $(I_{10A}/I_{5A})_{1/2^\circ}$ and $I_{10A(1/2^\circ)}/I_{5A(1^\circ)}$ ratios with decreasing slab size, indicating that the $I_{10A\ (1/2^\circ)}$ intensity is much less dependent on slab size than the $I_{10A\ (1^\circ)}$ intensity, and therefore, more suitable as a phyllosilicate-orientation parameter. However, the use of the ½° slits has the disadvantage that many more measurements, particularly of the weaker 5-Å peak, have to be rejected because of poor intensity.

The most practical procedure, therefore, is to measure the intensity at 10Å with ½° slits, and at 5Å (and 4.46 and 4.26 Å) with 1° slits: the $I_{10A\ (1/2^\circ)}/I_{5A\ (1^\circ)}$ intensity ratio (Fig. 7) shows little variation with slab size. However, adoption of ½° instead of 1° slits for measurement of the 10-Å peak intensity has the disadvantage that at 10-Å (8.85°2θ) the beam just covers a 2 cm sample, and that therefore slight differences in insertion position upon repeated insertion, particularly in case of irregular-shaped slabs, will cause major differences in I_{10A}- as confirmed by repeated runs at ½°. Since this insertion position is difficult to reproduce exactly, the measurement of the 10-Å peak with ½° slits and of the higher-angle peak with 1° slits should be carried out in the same insertion position, *i.e.*, without removing the slab.

When this has not been done, *i.e.*, I_{10A} has been measured with ½° slits at an slab insertion position different from the measurements at 1° slits, the value of intensity ratio $I_{10A(1/2^\circ)}/I_{10A(1^\circ)}$ can be used as an approximate indication of mispositioning: if it is much lower than befits the slab size, this probably indicates an anomalously low $I_{10A\ (1/2^\circ)}$ due to wrong sample positioning with respect to the goniometer axis. This can be checked by re-measuring the 10-Å peak with ½° and 1° slits after careful re-insertion of the slab and **without** moving it between measurements; much stronger intensity at ½° and higher $I_{10A(1/2^\circ)}/I_{10A(1^\circ)}$ ratio than obtained earlier, indicates a formerly low intensity of the peak as measured with ½° slits due to wrong slab positioning.

A possible alternative approach is measurement of all intensities using beams **wider** than the broadest slabs used (28 mm) -*i.e.*, the 10-Å peak with 1° slits and the higher-angle 5-Å, 4.46-Å (19.9°2θ) and 4.26-Å (20.8°2θ) peaks with 2° slits- and dividing all intensities by the slab size. This gives higher absolute intensities, but peak-intensity ratios similar to that obtained by the method followed here.

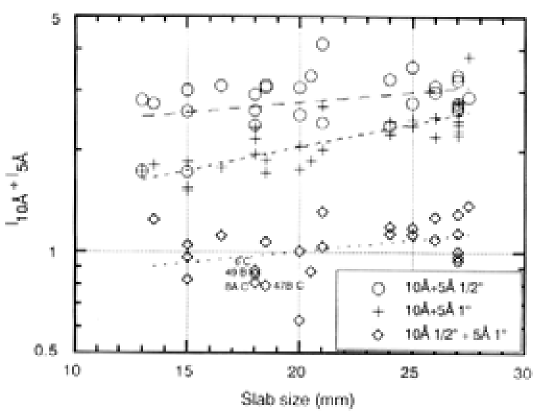

FIG. 7. The intensity ratio I_{10A}/I_{5A} as measured; **a**- both peaks measured with the 1° slit set ($I_{10A}/I_{5A\ 1^\circ}$); **b**- both peaks measured with the ½° slit set ($I_{10A}/I_{5A\ 1/2^\circ}$), and **c**- the 10 -A peak measured with the ½° slit set and the 5-A peak with the 1° slit set ($I_{10A1/2^\circ}/I_{5A\ 1^\circ}$), against the slab size for 29 slabs. Four anomalous slabs discussed in the text are numbered. $I_{10A}/I_{5A\ 1^\circ}$ decreases with decreasing slab size, whereas $I_{10A}/I_{5A\ 1/2^\circ}$ and $I_{10A1/2^\circ}/I_{5A}$ Department of Geology and Mineralogy, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva 84 105, Israel, show almost no marked systematic variation.

CHOICE OF ORIENTATION CRITERIA

Two types of intensity ratios can be used to assess the relative orientation of the **00l** lattice planes of phyllosilicates:

- the ratio of the **absolute intensities** of the same **00l** XRD reflection in the cleavage- and bedding-parallel slabs (hence referred to as the C and B slabs).
- the ratio of the **relative intensities** of the reflection of a **00l** lattice plane to that of a **hk0** or **hkl** lattice plane in the C and B slabs.

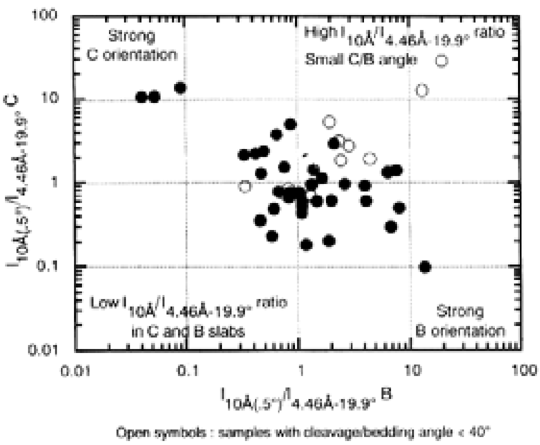

FIG. 8. Ratio of the intensity ratios of the 10-A and 4.46-A-19.9° peaks of illite in the C and the B slabs. Note the relationship between the divergence from the inverse relationship between $I_{10Å(.5)}/I_{4.46Å\text{-}19.9°}$ C and B and the angle between the C and B directions.

The strongest **00l** reflections of the phyllosilicate minerals, *i.e.*, the 002 reflection of illite/phengite at 10Å and the 002 reflection of chlorite at 7Å, were selected for study. The strong $\bar{1}11$ reflection at 4.46 Å (19.9° 2θ at CuKα) was taken as representative of the **hk0-hkl** lattice planes.

Very weak XRD peaks with <120 cps (<1 ½ cm at 2,000 cps full scale) were not considered.

The orientation parameters of the second type, such as the $I_{10A}/I_{19.9°}$ C/B ratio of the relative intensity of the reflection of this **00l** lattice plane to that of the **hkl** lattice plane at 4.46 Å (19.9° 2θ at CuKα), are virtually unaffected by differences in the quartz content (see below). Admittedly, since the $I_{19.9°}$ intensity in a C slab is at a maximum when the B fabric is orthogonal to it and *vice versa*, the $I_{10A}/I_{19.9°}$ ratios in both the C and B slabs will increase as a function of divergence of the angle between these directions from the perpendicular (Fig. 8). However, this increase is the same for the C and B slabs, and will, therefore, cancel out in the $I_{10A}/I_{19.9°}$ C/B ratio of these relative intensities.

The absolute intensities of the **00l** reflections, used in criteria of the first type should be strongly affected by lithological inhomogeneities: since many of the rocks have an inhomogeneous bedding lithology, the C section of such samples unavoidably traverses lithologies slightly different from the more uniform lithology in the B slab, as evident from the markedly different intensities of the reflections of quartz (and to a lesser extent calcite and feldspar) in some of these slab sets. In order to show the effect of different quartz content in the C and B slabs on the C/B ratios of the uncorrected I_{10A} intensities, these were plotted against the $I_{10A}/I_{19.9°}$ C/B ratio of the relative intensities of the reflection of this **00l** lattice plane to that of the **hkl** lattice plane at 4.46 Å (19.9° 2θ at CuKα) in the C and B sections (Fig. 9a). A good linear relationship with a correlation coefficient of 0.994 is obtained, whereby the slab sets with markedly different quartz contents, as evident from $|I_{20.8 (qz)}$ C-B$|$>400 cps (marked by their sample numbers) show the widest- although still minor- divergences from the regression.

In principle, the absolute intensities of the phyllosilicate reflections could be normalized to those in quartz-free samples by correcting them with reference to the intensity of a quartz X-ray reflection. For this purpose, the quartz content of the sample has to be estimated with respect to X-ray diffraction intensities, measured on standard slabs of known quartz content, such as a pure quartz sandstone. Since the strongest quartz reflection at 3.343 Å (26.64° 2θ at CuKα) usually is not resolved from the strong illite 006 reflection at 3.33 Å, the second strongest quartz reflection at 4.255 Å (20.86° 2θ at CuKα) must be used. A similar $I_{10A}/I_{19.9°}$ C/B *versus* I_{10A} C/B plot using quartz-corrected I_{10A} intensities (Fig. 9b) shows a distinct, but subordinate improvement of the correlation. However, in view of optical evidence that the quartz itself tends to become c-axis reoriented in the course of cleavage formation, thereby, relatively enhancing the intensity of the prismatic $10\bar{1}0$ reflection at 4.255 Å (20.86° 2θ) in the C slab, uncorrected I_{10A} values were used.

Both types of orientation parameters, I_{10A} C/B and $I_{10A}/I_{19.9°}$ C/B, were used interchangeably.

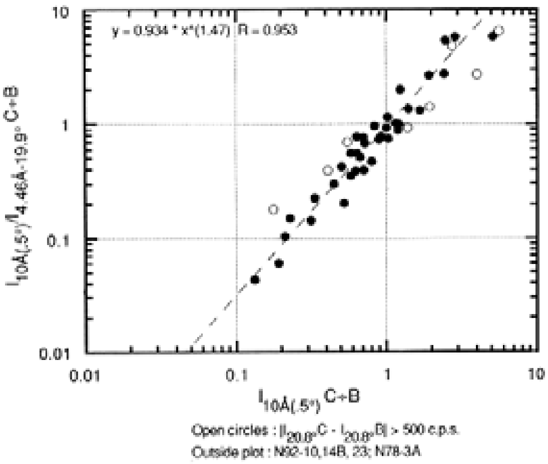

FIG. 9a. Relationship between the orientation parameters, *i.e.*, a- the ratio of the intensity ratio $I_{10Å(.5°)}/I_{19.9°}$ in the C and B slabs ($I_{10Å(.5°)}/I_{19.9°}$ C/B) and b- the intensity ratio of the 10-A peak as measured with the 1/2° slit set in the C and B slabs ($I_{10A\,.5°}$ C/B). Samples with major differences in quartz content between the C and B slabs as apparent from the difference between the intensities of the quartz 20.8° peaks ($|I_{20.8°C}-I_{20.8°B}|$>500 cps) show the widest divergence from the linear relationship. The regression given includes the four points outside the plot.

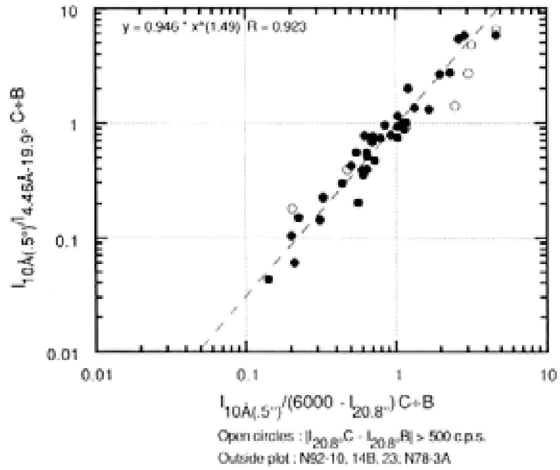

FIG. 9b. As in figure 9a for the quartz-corrected diffractograms, the $I_{10Å(.5°)}/(6000-I_{20.8°})$ C/B ratio being used as the X-axis parameter instead of $I_{10Å(.5°)}$C/B. Note the reduction of the divergence of the samples with major differences in quartz content between the C and B slabs. The regression given includes the four points outside the plot.

RESULTS

X-RAY PHYLLOSILICATE ORIENTATION AND ITS REGIONAL VARIATION

The I_{10A} and $I_{10A}/I_{19.9°}$ C/B ratios in all samples studied, range respectively from 0.04 to 29 and from 0.007 to 198 (Table 1); the ranges are 0.13-5.6 and 0.04-6.4 in all, except four samples (N92-10 with lower, N92-14B, 23; N78-3A with higher values).

The five samples from the external low-grade areas show low I_{10A} C/B ratios and $I_{10A}/I_{19.9°}$ C/B ratios of, respectively, 0.22-1.0 and 0.10-1.15, less than unity in the 'diagenetic' parautochthon at Östersund (samples N78-65B and N78-66B) and autochthon of Tåsjöberget (sample N78-19), and around unity in the low-anchimetamorphic lower thrust sheets (samples N78-59A and N78-63). The differences between the ranges for the various areas are rather smaller than expected from the differences in metamorphic grade as determined using illite 'crystallinity' (IC).

In 13 of the 22 samples from the more internal, medium-anchimetamorphic to anchi-epimetamorphic Mörsil-Järpen-Bångåsen area to the west, the range of the X-ray C/B ratios is rather similar, with I_{10A} C/B between 0.29 and 1, and $I_{10A}/I_{19.9°}$ C/B between 0.14 and 1.15. Exceptions are N92-3, 5A, 5B and 10 with lower ratios I_{10A} C/B<0.20 and $I_{10A}/I_{19.9°}$ C/B mostly ≤0.06, and the siltstone and silty mudstone N78-47A, 48A, and the siltstone N92-9A from close to the thrusts of the Särv and Seve nappes, with higher ratios I_{10A} C/B=2.5-5.6 and $I_{10A}/I_{19.9°}$ C/B=5.4-6.4.

The ratios in 17 of the 20 samples from the medium- and low anchimetamorphic Föllinge-Skärvången area cover a slightly higher range, with I_{10A} C/B between 0.34 and 4, and $I_{10A}/I_{19.9°}$ C/B between 0.23 and 4.75. One sample (N92-15H) has somewhat lower ratios, and the samples Storholmsjö N92-14B, collected 2 km east of the thrust of the overlying Offerdal thrust sheet, and N78-3A have much higher I_{10A} C/B ratios of 27-29, and $I_{10A}/I_{19.9}$ C/B well over 100.

TABLE 1. LOCALITIES AND DATA FOR THE STUDIED SAMPLES: CLEAVAGE/BEDDING FISSILITY RATIOS, SLAB SIZES, PHYLLOSILICATE ORIENTATION PARAMETERS $I_{10Å(.5°)}$ C/B AND $I_{10Å(.5°)}/I_{4.46Å-19.9°}$ C/B, AND PHENGITE/ILLITE 'CRYSTALLINITIES' (10-Å HALF PEAK-HEIGHT WIDTHS) MEASURED ON THE SLABS.

Sample No.	Locality	c/b (morphology)	Size (mm)		$I_{10Å(.5°)}$	$I_{10Å(.5°)}/I_{4.46Å-19.9°}$	B' (hphw) (°Δ2θ)		
			C Slab	B Slab	C/B	C/B	C Slab	B Slab	mean wtd
Mörsil-Järpen-Bångåsen area									
N92-1A-crenulated slate	W Mörsil	1.50	26.0	27.0	0.526	0.204	0.180	0.180	0.180
N92-2-silty mudstone	W Mörsil	1.00	25.0	27.0	0.721	0.681	0.160	0.195	0.181
N92-3-silty mudstone	Järpen	1.50	26.0	27.0	0.177	0.181	0.145	0.140	0.141
N92-4B-silty mudstone	E Mörsil	1.75	28.0	26.0	0.896	0.737	0.180	0.190	0.185
N92-4C-silty mudstone	E Mörsil		28.0				0.195		
N92-5A	E Mörsil	0.67	27.5	24.0	0.192	0.061	0.157	0.170	0.167
N92-5B	E Mörsil	0.50	21.0	26.0	0.132	0.043	0.195	0.162	0.166
N92-6-siltstone	E Mörsil	3.00	18.0	22.0	0.584	0.557	0.185	0.180	0.182
N92-7	Röde	1.00	27.5	25.0	1.41	1.36	0.210	0.200	0.206
N92-8-siltstone	Röde	1.00	27.0	26.0	0.555	0.699	0.187	0.210	0.201
N92-11B	Bångåsen	2.50	26.0	28.0	0.644	0.554	0.195	0.185	0.190
N78-42	Bångåsen		25.0	27.5	1.02	1.15	0.205	0.195	0.200
N78-43	Bångåsen		27.5	25.0	0.507	0.424	0.185	0.160	0.169
N78-44A-sandstone	E Järpen				1.02				
N78-44B-silty mudstone	E Järpen	0.67	18.5	18.5	0.799	0.470	0.142	0.142	0.142
N78-46A	E Järpen		27.0	13.5	1.00	0.929	0.164	0.170	0.166
N78-47A-siltstone	Mörsil-Järpen	2.00	28.0	28.0	2.47	5.36	0.192	0.203	0.196
N78-47B	Mörsil-Järpen	0.67	18.5	28.0	0.316	0.144	0.162	0.172	0.170
N78-48A-silty mudstone	E Mörsil	2.00	27.5	28.0	5.59	6.44	0.181	0.220	0.188
N78-49	Mörsil-Mattmar	1.00	26.5	18.0	0.582	0.353	0.175	0.177	0.176
(near thrust of Seve nappe)									
N92-9A-siltstone	Undersåker	3.00	27.5	26.5	2.88	5.76	0.145	0.155	0.148
N92-10-crenulated slate	Undersåker	0.34	20.5	26.0	0.042	0.007	0.210	0.150	0.153
Föllinge-Skärvången area									
N92-15B	W Föllinge	1.00	20.0	27.0	0.672	0.511	0.220	0.220	0.220
N92-15D	W Föllinge	2.00	28.0	21.0	1.20	0.885	0.210	0.210	0.210
N92-15E	W Föllinge	2.00	22.0	26.0	0.412	0.393	0.215	0.200	0.205
N92-15F-silty mudstone	W Föllinge	2.00	28.0	27.0	0.705	0.767	0.260	0.250	0.255
N92-15G	W Föllinge	2.50	28.0	27.0	1.68	1.33	0.220	0.280	0.242
N92-15H-silty mudstone	W Föllinge	1.00	29.0	28.0	0.229	0.152	0.230	0.195	0.205
N92-17A	NW Föllinge	2.00	18.5	15.0	0.451	0.300	0.225	0.215	0.218
N92-18A	Föllinge-Skärvången	2.50	25.0	27.0	0.709	0.396	0.218	0.215	0.216
N92-18B	Föllinge-Skärvången	2.50	15.0	24.0	2.43	2.75	0.205	0.210	0.207
N92-20	Föllinge-Lillholmsjö	1.75	25.0	25.0	0.335	0.226	0.230	0.210	0.215
N78-3A	Krokom-Föllinge		27.0	13.0	28.9	198	0.256	0.245	0.256
N78-4A	W Föllinge	4.00	27.0	25.0	1.93	2.67	0.252	0.250	0.252
N78-5	W Föllinge	1.50	27.0	16.5	0.923	0.788	0.246	0.225	0.238
N78-7-siltstone	Föllinge-Lillholmsjö	1.25			1.39	0.927	0.200	0.198	0.199
N78-8A	NW Föllinge	1.00	18.0	15.0	1.24	2.01	0.250	0.322	0.278
N78-11B-silty mudstone	Skärvången		26.5	28.0	4.00	2.71	0.190	0.180	0.188
N78-14	Föllinge-Skärvången	6.00	28.0	21.0	1.16	1.02	0.230	0.220	0.226
N78-16A	Lövsjön		28.0	28.0	1.21	1.00	0.250	0.230	0.240
(near thrust of Offerdal nappe)									
N92-14B	Storholmsjö	3.00	26.0	13.0	26.8	149	0.225	0.265	0.226
N92-14C	Storholmsjö	3.00	29.0	28.0	2.76	4.75	0.210	0.230	0.215
Eastern low-grade areas									
N78-19	Tåsjöberget		28.0	28.0	0.836	0.961	0.290	0.290	0.290
N78-59B	N Norderön	1.00	24.0	25.5	1.03	0.746	0.237	0.233	0.235
N78-63	N Frösön	1.00	22.0	20.0	0.637	0.780	0.225	0.338	0.299
N78-65B	N Östersund		22.0	26.0	0.212	0.104	0.262	0.271	0.269
N78-66B	Brännasen		25.0	28.5	0.629	0.389	0.240	0.230	0.234
Northwest of Tåsjön									
N78-27	Sjoutälven tunnel	1.00	24.5	23.0	5.11	5.78	0.190	0.177	0.188
West of Rönnöfors									
N92-23	W Rönnöfors		27.0	28.0	24.2	258	0.160	0.220	0.163
N92-24	Djupsjön	3.00	27.0	28.0	1.95	1.42	0.130	0.160	0.140

DIFFERENCES IN MINERALOGY IN THE CLEAVAGE AND BEDDING DIRECTIONS

Differences in phyllosilicate mineral ratios

It is of interest to assess whether the illite/phengite and chlorite are reoriented into the cleavage direction to a different extent, *i.e.*, if their ratio in the C and B sections of the same sample are different, and if this difference changes as cleavage development intensifies.

To this purpose, the parameter $I_{10A(ill/phe)}/I_{7A(chl)}$ C/B ratio was investigated. When plotted against the $I_{10A(ill/phe)}$ C/B ratio parameter of increasing cleavage development (Fig. 10), the $I_{10A(ill/phe)}/I_{7A(chl)}$ C/B ratio shows a distinct tendency to increase with the degree of preferential orientation of phyllosilicate, from 0.4-0.8 at $I_{10A(ill/phe)}$ C/B<0.4 to *ca.* 0.9-2 at $I_{10A(ill/phe)}$ C/B>1.1. The C sections in samples with poorly developed cleavage-parallel phyllosilicate orientation thus have lower illite-phengite/chlorite ratios (are relatively more chlorite rich) than the corresponding B sections, whereas with increasing cleavage-parallel phyllosilicate orientation this relation becomes reversed, the C sections having higher illite-phengite/chlorite ratios than the corresponding B-sections. Apparently, the phyllosilicate to be initially re-oriented or newly formed in the cleavage direction is predominantly chlorite, becoming gradually more illite-predominant as cleavage-parallel orientation intensifies. Illite-phengite thus becomes reoriented more than chlorite as the cleavage-parallel orientation intensifies- presumably with increasing deformation.

Differences in chlorite compositions in the cleavage and bedding direction

In order to assess whether there are measurable differences between the compositions of chlorite preferably oriented in the cleavage and bedding directions, the $I_{7A(chl\ 002)}/I_{4.7A(chl\ 003)}$ ratio, which rises with Fe/Mg content of chlorite (Brindley 1961; Kepezhinskas 1965; Bailey 1972), was investigated in the C against the B sections.

In order to verify if the $I_{7A(chl)}/I_{4.7A(chl)}$ C/B ratio possibly varies with degree of cleavage development, it was plotted against the $I_{10A(ill/phe)}$ C/B ratio, the parameter of increasing cleavage development (Fig. 11). No distinct correlation was observed: the weak tendency for the $I_{7A(chl)}/I_{4.7A(chl)}$ C/B ratio to be somewhat smaller than unity, *i.e.*, slightly more Mg-rich chlorite compositions in the C sections, appears to be independent of the degree of cleavage development.

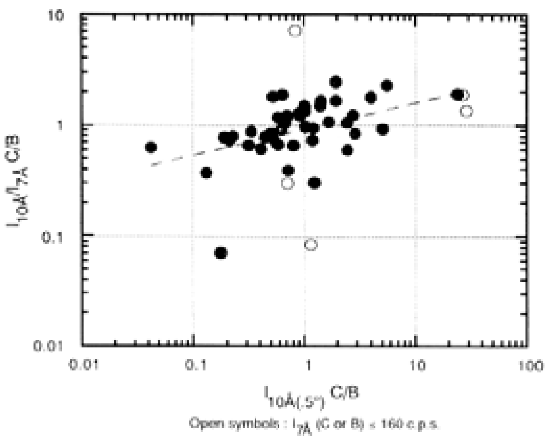

FIG. 10. Relationship between the illite/chlorite ratio as expressed by the $I_{10Å}/I_{7Å}$ ratios in the C and B slabs, and the orientation parameter $I_{10Å(.5°)}$ C/B. The C slabs in samples with poorly developed cleavage-parallel phyllosilicate orientations are relatively chlorite-richer than the B slabs ($I_{10Å}/I_{7Å}$ C/B ratios < 1); with increasing cleavage-parallel phyllosilicate orientation this relationship tends to reverse.

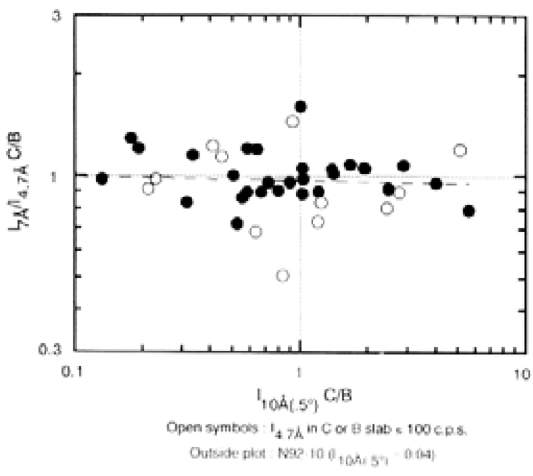

FIG. 11. Relationship between the Fe/Mg ratio in chlorite in the C and B slabs as expressed by the $I_{7Å}/I_{4.7Å}$ ratio, and the orientation parameter $I_{10Å(.5°)}$ C/B. The chlorites of the C slabs tend to have very slightly lower Fe/Mg ratios.

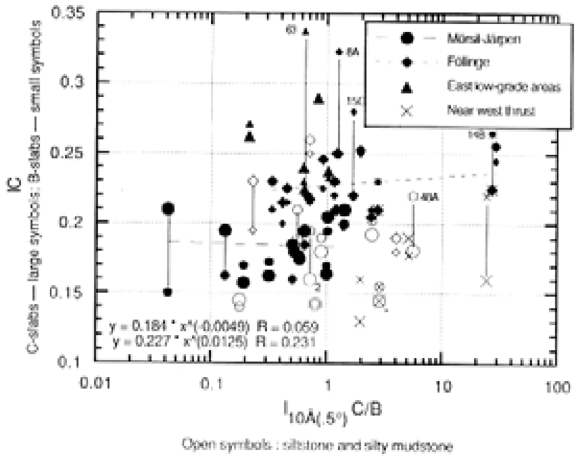

FIG. 12. Relationship between the illite 'crystallinity' measured on both the C and B slabs and the orientation parameter $I_{10Å(.5°)}$ C/B. Where necessary for clarity, the points representing appreciably different illite 'crystallinities' of the C and B slabs of the same sample have been connected by vertical lines. Sample numbers are given for some samples discussed in the text. The two regressions refer to the C slabs of the mudstones of the Mörsil-Järpen (long dashes) and the Föllinge (short dashes) areas.

Difference in illite 'crystallinity' between the cleavage and bedding direction

Illite 'crystallinity' was measured on the slabs in order to detect systematic differences. In figure 12, the 10-Å half-height peak widths are shown for both, the C and B slabs of each sample; the regional variations are better illustrated by the weighted mean peak widths of both slabs, *i.e.*, the sum of peak width times peak height in each of the C and B sections, divided by the sum of the peak heights (Fig. 13).

Due to the predominance of clastic micas, the 10-Å peaks are much narrower than in the separated <2 µm fractions. The differences measured between the C and B slabs were small, exceeding 0.03°Δ2θ only in ten slab sets. In most samples of all areas, the IC values in the C slabs are only between 0.025°Δ2θ broader and 0.01°Δ2θ narrower than in the B slab (Fig. 12). This reflects the predominant orientation of the more crystalline coarse clastic mica in the B direction, and a tendency to deterioration of its 'crystallinity' in the cleavage direction, presumably as a result of growth of less 'crystalline' anchimetamorphic micas. Nevertheless, small but consistent differences in slab-measured illite 'crystallinity' between areas, and a distinct relationship with the degree of C-parallel fabric were detected.

In the five mudstones of the eastern low-grade areas, with I_{10A} C/B invariably <1, the weighted mean peak widths were 0.23-0.30°Δ2θ, with differences of only up to 0.01°Δ2θ between the C and B slabs, except for one particularly quartz-poor calcareous sample from Frösön (N78-63), in which the IC in the C section, is appreciably narrower (0.225°Δ2θ) than in the B section (0.348°Δ2θ).

Very narrow mean weighted peaks of 0.14-0.20°Δ2θ were measured on slabs of the ten Mörsil-Järpen-Bångåsen mudstones with low I_{10A} C/B ratios ≤1, and on all siltstones and silty mudstones, indicating the predominance of clastic micas. In the cases where IC on the <2 µm fractions had also been determined, these values were 0.20-0.27°Δ2θ-0.05° to as much as 0.1°Δ2θ broader- confirming the above conclusion.

Slabs of the eight Föllinge mudstones with similarly low I_{10A} C/B ratios of <1 consistently yielded somewhat broader mean weighted peaks of 0.20-0.22°Δ2θ, in two cases around 0.24-0.25° (N78-5, N92-15F). The IC

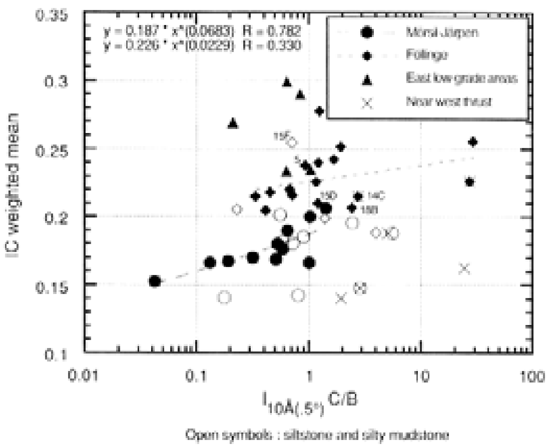

FIG. 13. Relationship between the weighted mean illite 'crystallinity' of the C and B slabs and the orientation parameter $I_{10Å(.5°)}$ C/B for samples from the various areas. The mean weighted peak width equals the sum of half-height peak width times peak height in each of the C and B sections, divided by the sum of the peak heights. Sample numbers are given for some samples discussed in the text. The two regressions refer to the mudstones of the Mörsil-Järpen (long dashes) and the Föllinge (short dashes) areas. Note the distinctly better illite 'crystallinities' (narrower 10-A peaks) in the Mörsil-Järpen area than in the Föllinge area. The deteriorating illite 'crystallinity' with increasing cleavage-parallel phyllosilicate orientation in both areas, reflects the increasing formation of metamorphic at expense of the clastic micas.

values on the C slabs of these slates were largely similar or up to only 0.02°Δ2θ broader than in the B slabs (Fig. 12), indicating relatively little newformation of 'anchimetamorphic' mica in the cleavage direction. Although mostly somewhat broader mean weighted peaks within the range 0.205-0.255°Δ2θ were measured on nine of the ten Föllinge slates with $I_{10Å}$ C/B ratios of >1 (one sample, N78-3A, has≈0.28°Δ2θ), the IC values on the C slabs of most of these slates were also almost invariably similar or broader by up to 0.02°Δ2θ than in the B slabs (except in three samples with very poorly 'crystalline' mica, IC ≥0.26$_5$°Δ2θ, in the B slab, N92-14B, 15G; N78-8A); this reflects the increased recrystallization and new formation of new micas (with 'crystallinities' poorer than those of the clastic micas) in the C fabric.

In two silty-mudstone samples from the Mörsil area (N92-2, N78-48A) IC was **appreciably narrower** (by 0.035-0.04°Δ2θ) in the C than in the B slab; one of these has an unusually high $I_{10Å}$ C/B ratio of more than 5. IC was also much narrower (by 0.04°Δ2θ) in the C than in the B slab in one sample (N92-14B) with an exceptionally high $I_{10Å}$ C/B ratio of 26, from west of Storholmsjö, west of the Föllinge area; this observation and the exceptionally broad, but weak 10Å peak (0.265°Δ2θ) in the B slab of this sample reflects the high $I_{10Å}$ C/B ratio.

The distincly narrower IC values of both the C slab and the weighted mean of mudstones in Mörsil-Järpen-Bångåsen area than of those in the Föllinge areas (see regressions in figures 12, 13) reflect the higher degree of anchimetamorphism in the former area. Despite this difference in metamorphic grade, both areas show the same tendency for the weighted mean IC values as measured on the slabs to broaden towards those of the less 'crystalline' metamorphic mica, with increasing cleavage-parallel phyllosilicate orientation (Fig. 13), reflecting the increased formation of anchimetamorphic at the expense of the more 'crystalline' clastic micas.

PHYLLOSILICATE ORIENTATION, MICROFABRIC AND FISSILITY MORPHOLOGY

Note: this section refers only to the N92 series and 13 N78 samples on which cleavage/bedding fissility data were obtained.

There exists a rather crude correlation between the cleavage/bedding fissility ratio introduced by Durney and Kisch (1991) and the parameters of phyllosilicate orientation (Fig. 14): the samples with cleavage/bedding fissility ratios of <1 mostly have $I_{10Å\,(ill/phe)}$ C/B ratios of less than 0.4 ($I_{10Å}/I_{19.9°}$ C/B <0.2), whereas samples with higher cleavage/bedding fissility ratios have $I_{10Å(ill/phe)}$ C/B ratios of 0.4 to as high as 27 ($I_{10Å}/I_{19.9°}$ C/B=0.2-150).

Seventeen Föllinge samples, fourteen slates, two silty mudstones, and one siltstone show relatively high **c/b** fissility ratios of 1-6 (no reliable measurements are available on three samples, N78-3A, 11B and 16A). Seventeen Mörsil-Järpen samples, eight slates and siltstones and nine silty mudstones-excluding the Hålland/Undersåker sample N92-10 from near the thrust of the Särv and Seve nappes to the west- yielded somewhat lower **c/b** fissility ratios of 0.50-3 (no reliable measurements are available on five samples, N78-42, 43, 44A and 46A, and N92-4C).

However, in most of the samples with the most common intermediate **c/b** cleavage/bedding fissility ratios of 0.67-3 from both areas, these values are not apparent from the rather low XRD intensity ratios-$I_{10Å}$<0.92 and $I_{10Å}/I_{19.9°}$ C/B<0.78.

Petrographical inspection of thin sections shows that most B-predominant slates and interbedded fine

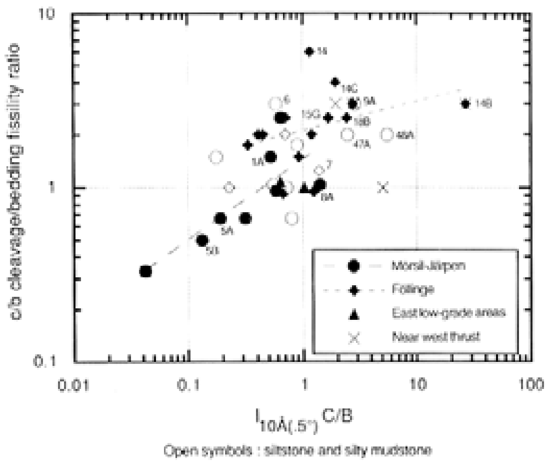

FIG. 14. Relationship between the cleavage/bedding fissility ratio and the orientation parameter $I_{10Å(.5°)}$ C/B. Sample numbers are given for some samples discussed in the text. The two regressions refer to the mudstones of the Mörsil-Järpen (long dashes) and the Föllinge (short dashes) areas. Note the higher cleavage/bedding fissility ratios in the Föllinge area compared to the Mörsil-Järpen area, even for samples with similar values of $I_{10Å(.5°)}$ C/B despite the somewhat lower anchimetamorphic grade from the <2-μm illite 'crystallinities' in the Föllinge area.

mudstones with this combination of relatively good cleavage/bedding fissility ratios of 0.67 to 3 with $I_{10A\,(ill/phe)}$ C/B intensity ratios less than unity have either:

- discrete crenulation cleavages, *e.g.*, N92-1A (weathering in long pencils with l/C=10), or
- domainal cleavages with poor to reasonable continuity (length/spacing ratio 5:1, or<0.2 mm), *e.g.*, N92-11B, 15B, 15E, 17A, 18A, 20, N78-47B.

In both cases there is no significant mica development in the cleavage domains or C-parallel mica reorientation in the microlithons, and there is abundant bedding-parallel clastic mica. The good cleavage/ bedding fissility ratios thus reflect the development of cleavage domains.

Two Mörsil shales with low **c/b** fissility ratios of 0.5-0.7, N92-5A and 5B (same exposure as N78-48), incidentally, are those with the strongest B-predominance of mica (I_{10A} C/B=0.1-0.2) of the sample series from these areas; the thin section of N92-5B shows weak microfolds without development of cleavage domains.

Several silty mudstones and quartz-rich siltstones show a similar combination of relatively good cleavage/ bedding fissility ratios with a low $I_{10A(ill/phe)}$ C/B intensities (Mörsil N92-2, 3, 4B, 6, N78-44B; Röde N92-8; Föllinge N92-15F, H). The quartz-rich siltstone N92-6 from a fold hinge, with a good cleavage/bedding fissility ratio of 3, but a low $I_{10A(ill/phe)}$ C/B intensity ratio of 0.58, has distinct sharp, but discontinuous cleavage domains and a poorly marked bedding fabric. Several other silty mudstones and quartz-rich siltstones with similar or somewhat higher $I_{10A\,(ill/phe)}$ C/B intensity ratios of 0.55-0.80, but lower cleavage/bedding fissility ratios of 0.7-2, show only irregular jagged cleavage domains, *e.g.*, the silty mudstones Mörsil N92-2 (same exposure as N78-47), N92-4B and N78-44B, and Föllinge N92-15F (I_{10A} C/B = 0.7-0.9), or no cleavage domains at all, *e.g.*, Röde N92-8 (I_{10A} C/B=0.55). The retarded development of cleavage domains in these coarser-grained rocks at relatively high I_{10A}C/B ratios probably reflects the scattered phyllosilicate distribution and the poor bedding-parallel fabric prior to deformation.

In virtually all these samples the illite/chlorite ratio I_{10A}/I_{7A} in the C slab is similar or lower than in the B slab, indicating relative predominance of chlorite in the poorly developed cleavage domains (as noted before).

Markedly stronger C-parallel XRD mica orientations, with 1_{10A} C/B>1, were measured in samples from fold hinges and in siltstones and silty mudstones:

- the fold-hinge Föllinge slates N92-15G, N92-18B, N78-8A, N78-14 (I_{10A}C/B=1.68, 2.43, 1.24, 1.16) and quartz-siltstone N78-7 (I_{10A} C/B =1.39);
- the Mörsil quartz-siltstone N78-47A and fine-silty mudstone N78- 48A (I_{10A} C/B=2.47, 5.59);
- the fold-hinge Hålland/Undersåker quartz-siltstone N92-9A(I_{10A} C/B =2.88), collected close to the thrusts of the Särv and Seve nappes, and
- the Storholmsjö slates N92-14B (I_{10A} C/B=27) and 14C (I_{10A} C/B=2.76) collected close to the thrust of the Offerdal nappe.

In these slates and fine-silty mudstones, these are also evident in thin section, the fine mica being predominantly parallel to C, mostly strongly domainal, virtually without coarse mica in the bedding (except in the quartz-siltstones N92-9A, N78-7 and N78-47A), but not markedly in the similar or slightly higher cleavage/bedding fissility ratios of 1-3-6 in one sample (N78-14). In one sample (Röde N92-7), the higher I_{10A} C/B=1.41 is not evident in either.

The increased I_{10A} C/B ratio thus, mainly reflects increasing orientation of the mica in the cleavage domains and in the microlithons in the slates and mudstones, and mica orientation with poor cleavage-domain development in the siltstones, without a marked concomitant increase in the **c/b** cleavage/bedding fissility ratio.

The phyllosilicate fabric thus, appears to be a more sensitive indicator of local increases in strain, for instance in the fold hinges, than the **c/b** cleavage/ bedding fissility ratio, which is more uniform over a given area.

CONCLUSIONS

The I_{10A} C/B and $I_{10A}/I_{19.9}$ C/B ratios as measured on cleavage- and bedding-parallel slabs can be used as phyllosilicate orientation parameters. The **c/b** cleavage/bedding fissility ratios increase in a very general way with the I_{10A} C/B and $I_{10A}/I_{19.9}$ C/B ratios, but several rocks show high **c/b** cleavage/bedding fissility ratios for rather small I_{10A}C/B and $I_{10A}/I_{19.9}$ C/B ratios, reflecting presence of poor or moderate cleavage domains without significant illite development, and microlithons with only minor C-parallel mica reorientation and abundant bedding-parallel clastic mica; markedly higher I_{10A} C/B and $I_{10A}/I_{19.9°}$ C/B ratios were measured, particularly, in samples from fold hinges, reflecting development of a strongly domainal fabric with a predominant cleavage-parallel mica orientation and very little bedding-parallel coarse mica in the microlithons.

Thus, stages of cleavage formation characterized by intermediate cleavage/bedding fissility ratios- apparently the expression of cleavage-domain development- are not necessarily accompanied by marked cleavage-parallel phyllosilicate orientation; strong phyllosilicate orientations are developed mainly in fold hinges and close to thrusts of the overlying metamorphic nappes in association with similar or only slightly higher cleavage/bedding fissility ratios.

Comparison of the I_{10A} C/B and $I_{10A}/I_{19.9°}$ C/B ratios with indicators of the intensity of incipient cleavage, such as the **c/b** cleavage/bedding fissility ratio, and the extent of authigenic phyllosilicate formation, such as illite 'crystallinity' as measured on the polished slabs, yields distinct differences between areas. In each of these areas, the illite 'crystallinities' as measured on polished slabs tend to change from clastic to anchimetamorphic values with increasing cleavage-parallel phyllosilicate orientation, as the degree of mica orientation and recrystallization increase. However, two individual anchimetamorphic areas show distinctly different values of both **c/b** cleavage/bedding fissility ratio and illite 'crystallinity' for similar ranges of I_{10A} C/B ratios.

These regional differences are thought to reflect differences in the relative effects of deformation and recrystallization on cleavage formation in these areas.

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REFERENCES

Asklund, B. 1960. The geology of the Caledonian Mountain Chain and of adjacent areas in Sweden. *Sveriges Geologiska Undersökning*, Serie Ba, No. 16, p.126-149.

Asklund, B. 1961. The extension of the Serv Nappe in the Scandinavian Mountain Chain. *Sveriges Geologiska Undersökning*. Serie C, No. 584, Arsbok 55, No. 584, 28 p.

Asklund, B.; Thorslund, P. 1935. Stratigrafiska och tektoniska studier inom Föllingeområdet i Jämtland. *Sveriges Geologiska Undersökning*, Serie C, No. 388.

Bailey, S.W. 1972. Determination of chlorite compositions by X-ray spacings and intensities. *Clays and Clay Minerals*, Vol. 20, No. 6, p. 381-388.

Brindley, G.W. 1961. Chlorite minerals, Chapter 6. *In* The X-ray identification and crystal structure of clay minerals (G. Brown.; editor). *Mineralogical Society*, p. 242-295. London.

Durney, D.W.; Kisch, H.J. 1991. A field classification and quantification of cleavage. *In* The Geometry of Naturally Deformed Rocks. *The John Ramsay Meeting, Mitteilungen aus den Geologischen Institut ETH Zürich, Neue Folge, Abstracts*, No. 239b, p.131 -132.

Durney, D.W.; Kisch, H.J. (In press). A field classification and intensity scale for first-generation cleavages. *Australian Geological Survey Organization* (AGSO), *Journal*. Canberra.

Gee, D.G. 1975. A geotraverse through the Scandinavian Caledonides-Östersund to Storlien. *Sveriges Geologiska Undersökning*. Serie C, No. 717, Årsbok 69, No.9, 66 p.

Gee, D.G.; Kumpulainen, R. 1980. An excursion through the Caledonian Mountain Chain in central Sweden from Östersund to Storlien. *Sveriges Geologiska Undersökning*, Serie C, No. 774, Årsbok 74, No. 2, 66 p.

Jenkins, R.; de Vries, J.L. (No date). An introduction to X-ray powder diffractometry. N.V. Philips Goeilampenfabrieken, 40 p. Eindhoven, Holland.

Kepezhinskas, K.B. 1965. Determination of chlorite composition from their physical properties [in Russian]. Doklady Akademia Nauk S.S.S.R., Vol. 164, No. 3, p. 658-661 (English translation. *in Doklady Earth Science Sections*, Vol. 164, No. 1-6, p. 126-129).

Kisch, H.J. 1980. Incipient metamorphism of Cambro-Silurian clastic rocks from the Jämtland Supergroup, central Scandinavian Caledonides, western Sweden: illite crystallinity and 'vitrinite' reflectance. *In* Deformation and Metamorphism in the Caledonian Orogen (W.E.A. Phillips.; M.R.W. Johnson.; editors). *Journal of the Geological Society*, Vol. 137, No. 3, p. 271 288. London.

Padan, A; Kisch, H.J.; Shagam, R. 1982. Use of the lattice parameter b, of dioctahedral illite/muscovite for the characterization of P/T gradients of incipient metamorphism. *Contributions to Mineralogy and Petrology*, Vol. 79, No.1, p. 85-95.

Strömberg, A.G.B.; Karis, L.; Zachrisson, E.; Sjostrand, T.; Skoglund, R. 1984. Karta over berggrunden i Jämtlands Län utom förutvarande Fjällsjö K:n, 1:200.000. *Sveriges Geologiska Undersökning*. Serie Ca, No. 53.

Thorslund, P. 1940. On the Chasmops Series of Jemtland and Södermanland (Tvären). *Sveriges Geologiska Undersökning*, Serie C, No. 436, 191 p.

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