Metamorphism of the Lower Palaeozoic rocks of the Lochmaben district, southern Scotland, 1:50K Sheet 10W

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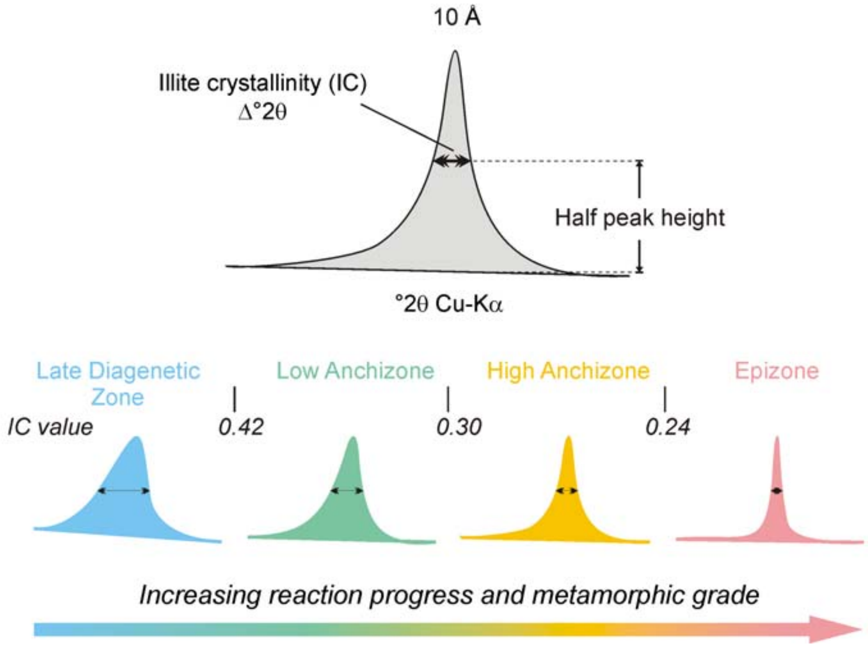

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/01/125

Metamorphism of the Lower Palaeozoic rocks of the Lochmaben district, southern Scotland, 1:50K Sheet 10W

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Key words

Low grade metamorphism, mica (illite) crystallinity, accretion.

Front cover

Illite crystallinity cartoon

Bibliographical reference

MERRIMAN, R J, KEMP, S J AND HIRONS, S R. 2001. Metamorphism of Lower Palaeozoic rocks from the Lochmaben district, southern Scotland, 1:50K Sheet 10W. *British Geological Survey Internal Report*, IR/01/125. 14pp.

Keyworth, Nottingham British Geological Survey 2002

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) and forms part of the Core Strategic (Lands and Resources) Programme.

Acknowledgements

We are grateful to Maxine Akhurst, Andrew McMillan and Jim Floyd (all BGS) for providing a draft geological map and advice on the interpretation of the metamorphic data. Brin Roberts (Birkbeck College) is also thanked for his help and advice.

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Summary

The pattern of regional metamorphism indicated by illite crystallinity has been used to interpret the tectonic and thermal history of the Lochmaben district of southern Scotland. The regional pattern is characterised by the sub-parallelism of isocrysts with the regional strike, and by changes in grade across the strike-parallel, tract-bounding faults. The late diagenetic grade of the oldest Gala Group strata, compared to the low anchizonal grade of the younger Hawick Group strata south of the Lauriston Fault is indicative of regional very low-grade metamorphism resulting from accretionary burial. Similar relationships have been recorded elsewhere along the Lauriston Fault. Uplift and block faulting prior to Permo-Carboniferous basin development is responsible for a restricted area of high anchizonal and epizonal strata in the north-east of the district, and late diagenetic zone strata along the eastern side of the Dumfries Basin.

1 Introduction

Systematic studies of metapelitic grade linked with the geological re-survey of the Scottish Southern Uplands have been used to generate a series of contoured metamorphic map which currently cover nearly two-thirds of the Lower Palaeozoic terrane. These studies have used X-ray diffraction (XRD) measurements of clay mineral reaction progress, particularly *white mica (illite) crystallinity (IC)*, to delineate zones of diagenesis and low-grade metamorphism in the imbricated Ordovician and Silurian strata. Although the regional pattern revealed by *metapelitic grade* shows considerable variations in metamorphic trends, patterns of grade increasing from older into younger strata suggest that accretionary burial was the main cause of regional metamorphism (Merriman & Roberts, 2001). These patterns also reflect the different levels of exhumation of the terrane, by both normal movement on reactivated thrust faults and differential block movement on NNW-trending faults.

During the recent re-survey of the Lochmaben district, metapelitic rocks representative of the main tectonostratigraphical units were collected and used to determine white mica (illite) crystallinity indices. This report gives details of the methods used and presents the results as a contoured metamorphic map which is used to interpret the metamorphic history of the district.

2 Techniques and laboratory methods

2.1 TECHNIQUES

Burial of unconsolidated clays in basinal sequences causes progressive compaction and lithification resulting in typical shale and mudstone lithologies. The clay mineral reactions that accompany lithification transform authigenic minerals, such as smectite and kaolinite, to assemblages dominated by illite and chlorite. Tectonic deformation of these pelitic lithologies results in further progressive changes in clay mineral assemblages and the development of metapelites with a *slaty cleavage microfabric*. Progress of late diagenetic and very low grade metamorphic reactions in buried and tectonized pelitic sequences can be monitored by measuring changes in the illite–muscovite (white mica) reaction series as thicker crystallites develop in response to progressive recrystallisation (Merriman *et al.*, 1990, 1995). The *Kubler index (KI in $\Delta°2\theta$)* measures small reductions in the half-height width of the mica ~10 Å X-ray diffraction (XRD) peak which occur when the crystallite population thickens. In pelitic rock sequences the Kubler index is used to define the limits of a series of metapelitic zones of very low– and low-grade metamorphism: late diagenetic zone KI>0.42; lower anchizone KI 0.30–0.42; upper anchizone KI 0.25–0.30; epizone KI<0.25 (Merriman & Peacor, 1999).

For this study, 68 metapelites were collected from within Sheet 10W. A further 29 samples from the adjacent sheets (8 from Sheet 10E to the east, 7 from Sheet 16W to the north, 12 from Sheet 9E to the west and 2 from Sheet 6W to the south) were also included to allow more accurate contouring of the illite crystallinity values along the margins of Sheet 10W. Although 68 samples represents a relatively small suite of samples compared to some previously reported sheet studies (e.g. Kemp and Merriman, 2000), a large proportion of Sheet 10W is covered by the Permo-Carboniferous basins at Lochmaben and Dumfries, and Devonian to Carboniferous strata in the south-east of the district. A sampling density of approximately 1 metapelite per 4 km^2 was therefore achieved for the area covered by Palaeozoic strata. All samples were prepared and analysed by XRD techniques in order to determine the Kubler Index (KI) of white mica (illite) crystallinity.

2.2 SAMPLE PREPARATION

After removing any surface contaminants with a wire brush, a representative 50 g portion of each sample was hand-ground, using a hammer mill followed by an agate pestle and mortar, until granules passed 72-mesh sieve. Care was taken to subject the sample to short bursts of milling in order to reduce the chance of over-grinding delicate *phyllosilicate* grains.

A representative 4 g portion of the crushed sample was then placed in a boiling tube and distilled water added to a predetermined level. Each sample was then shaken thoroughly, subjected to ultrasound for 5 minutes and allowed to stand for 3 hours. Where flocculation occurred, 0.5 ml of 0.1M sodium hexametaphosphate was added and the dispersion process repeated. After 3 hours, a nominal <2 µm fraction was removed and centrifuged at maximum speed for 20 minutes. The clear supernatant was then removed and the <2 µm fraction re-dispersed in ~1 ml distilled water with a glass rod and minimal ultrasound. The <2 µm fraction slurry was then pipetted onto the surface of a frosted glass slip and allowed to dry overnight at room temperature.

2.3 X-RAY DIFFRACTION ANALYSIS

The majority of the <2 µm fractions were analysed in the Geology Department, Birkbeck College, using a Philips PW1710 series diffractometer equipped with Ni-filtered Cu-Kα radiation and operating at 40kV and 30mA (see Roberts *et al.*, 1991). The KIs of the samples were calculated from the mean of two scans over the range 7.5-10.5 °2θ at a speed of 0.5 °2θ/minute using the machine conditions recommended by Kisch (1991). Samples analysed at Keyworth used a Philips PW1130 diffractometer operated at similar conditions to those above. The width of the ~10 Å peak at half-height was measured using Hiltonbrooks software modified by N J Fortey (BGS) and values were corrected using the standards of Warr & Rice (1994) to concur with measurements carried out at Birkbeck College.

A map showing the sample locations and KI values is shown in Figure 1.

3 Metamorphic map

The metamorphic map shown in Figure 2 is the result of a computer-contoured plot of KI data, manually modified to reflect the influence of localized post–regional metamorphic events. A computer contoured geographical distribution of KI datapoints was initially produced using DeltaGraph 4.0 for Windows software. The pattern was then superimposed on an outline 1:50k geological map of the Lower Palaeozoic strata and contours redrawn where post–metamorphic faulting appeared to modify the overall pattern. In the final version of the map shown in Figure 2, contours of equal crystallinity (isocrysts) are used to delineate four metapelitic zones: late diagenetic zone (KI >0.42); lower anchizone (KI 0.30–0.42); upper anchizone (KI 0.24–0.30) and epizone (KI <0.24). In order to link with published maps for adjacent sheets the intervals used differ slightly from those described in section 2. The errors and precision involved in contouring the crystallinity data (Robinson *et al.*, 1990), were previously determined by multi–sampling at several sites in the Southern Uplands (Merriman & Roberts, 1992), and elsewhere (Roberts *et al.*, 1990). The results from multi–sampled sites indicate that 95% of the samples have indices within the range of values delineated by zonal isocrysts.

The contoured metamorphic map shows a regional pattern that is characterised by the sub-parallelism of isocrysts with the regional strike, and by changes in grade across the strike-parallel, tract-bounding faults. Much of the tectonostratigraphy belongs to just two metapelitic zones. The oldest strata, forming part of the Gala Group, is almost entirely within the late diagenetic zone. On crossing the Lauriston Fault grade generally increases to the lower anchizone across much of the outcrop of the younger Hawick Group. Minor exceptions to this general pattern include a restricted area of high anchizonal and epizonal strata in the north-east of the district, and late diagenetic zone strata along the eastern side of the Dumfries Basin. Both these areas are probably the result of post-metamorphic block tilting associated with the down-east normal faulting which produced the Dumfries, Lochmaben and Moffat basins. Grade appears to decrease to the late diagenetic zone on passing into younger Riccarton Group strata.

4 Metamorphic history

The pattern of regional metamorphism developed in the Lower Palaeozoic rocks of the Lochmaben district can be interpreted in terms of two tectonometamorphic events:

1. Regional very low-grade metamorphism resulting from accretionary burial
2. Uplift and block faulting prior to Permo-Carboniferous basin development

Evidence for accretionary burial is clearly seen in the changes in grade found on either side of the Lauriston Fault, which was initiated as a thrust. The older rocks of the Gala Group are commonly in the late diagenetic zone, whereas the younger rocks of the Hawick Group are mostly at a higher grade in the low anchizone. Similar relationships have been recorded elsewhere along the Lauriston Fault (Akhurst *et al.,* 2001), and in the Ordovician strata forming the Northern Belt (Merriman & Roberts, 1992; Stone, 1995; Hirons *et al*, 1997). Such patterns indicate that younger Hawick Group was buried beneath the older Gala Group and in turn this suggests that the metamorphic pattern was generated by accretionary tectonism (Merriman & Roberts, 2001). The same pattern is not found in the south of the Lochmaben district, where the younger strata of the Riccarton Group are generally at a lower grade than the older Hawick Group. Here burial relationships are normal, i.e. older strata at higher grade than younger strata, indicating that subduction processes had ceased by the early Wenlock.

Post-metamorphic uplift of the district caused reactivation of thrusts as normal faults and also block movement along NNW-trending faults. Movement on both sets of faults is responsible for the present pattern of metamorphism, and also the development of the half-graben basins around Dumfries, Lochmaben and Moffat. Down-east faulting associated with the Lochmaben Basin has preserved the lower grade strata that originally formed the upper level of the Southern Uplands thrust stack (Merriman & Roberts, 2001). East of the southern end of the Moffat Basin, down-west faulting has exhumed an extension of the Moniaive Shear Zone, representing the deeper underplated level of the thrust stack.

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Glossary

Illite crystallinity (IC) Variations in the crystallite size and lattice strain in dioctahedral mica produced in the smectite-I/S-illite-muscovite reaction series, as indicated by the Kubler index.

Kubler index (KI) The width of the X-ray diffraction c.10Å peak at half-height above background, measured as small changes in the Bragg angle $\Delta°2\theta$.

Metapelitic grade The grade of diagenesis and low-grade metamorphism indicated by reaction progress in clay minerals and other phyllosilicates.

Slaty cleavage microfabric A pervasive planar fabric consisting of submicron-spaced domains of phyllosilicates. Strain-related crystal growth of the phyllosilicates has resulted in their (00l) crystallographic planes being orientated approximately parallel to the fabric. Although the mineral constituents of the microfabric cannot be resolved with the naked eye, their parallel orientation gives rise to a fissility that dominates all other fabric elements of the mudrock and can be exploited to cleave the rock into thin (<10 mm) parallel-sided slates.

Strain-related crystal growth The crystal growth of minerals induced by rock deformation. Strain-related crystal growth is response to several interactive processes, including mechanical grain rotation of existing minerals, pressure-solution (dissolution) recrystallization and grain-boundary migration (dislocation creep) in newly-formed minerals.

Phyllosilicates A group of silicate minerals, including the micas and clay minerals, which consist of SiO_4 tetrahedra linked into flat sheets with an Si:O ratio of 1:5. Cations and water are accommodated between the sheets and such minerals are characterised by a very prominent cleavage parallel to the sheet structure.

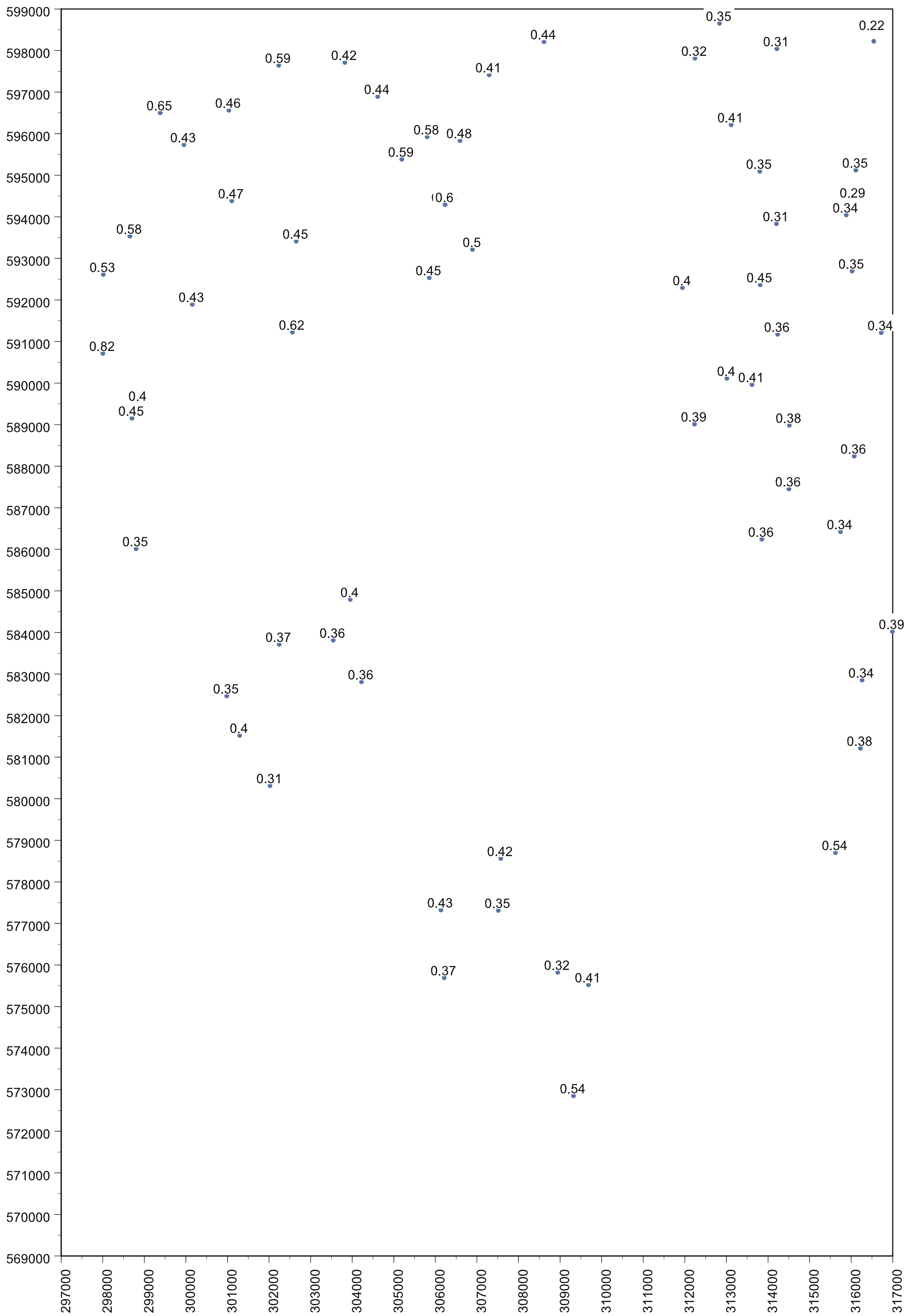

Figure 1. Sample location map and white mica crystallinity (Kubler) indices for the Lochmaben district, Sheet 10W. N.B. Data from neighbouring sheets has been omitted.

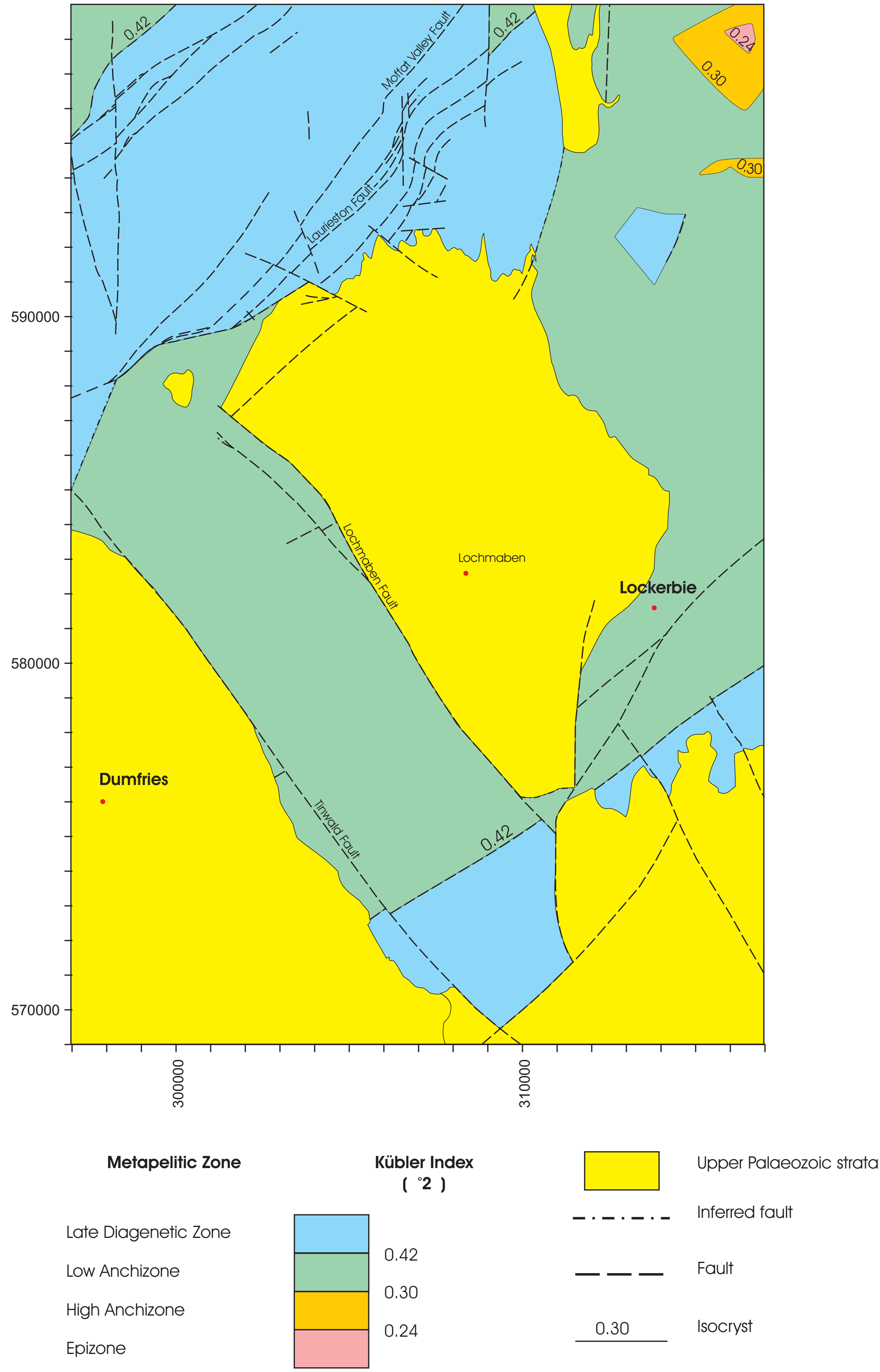

Figure 2. Contoured metamorphic map of white mica crystallinity (Kubler) indices for the Lochmaben district, Sheet 10W.

Appendix 1 Summary of sample numbers, sample locations and KIs

1. Sheet 10W samples

Sample No.	Square	Easting	Northing	IC
BRS890	NX	298000	592600	0.53
BRS891	NX	297900	590700	0.82
BRS1001	NX	298790	586000	0.35
BRS1041	NY	300140	591880	0.43
BRS1042	NX	298640	593520	0.58
BRS1043	NX	299940	595720	0.43
BRS1044	NX	299370	596490	0.67
BRS1045	NX	299370	596490	0.65
BRS1046	NY	301020	596550	0.46
BRS1047	NY	302640	593400	0.45
BRS1048	NY	302550	591210	0.62
BRS1049	NY	313840	586230	0.36
BRS1050	NY	314490	587440	0.36
BRS1051	NY	314500	588970	0.38
BRS1052	NY	313600	589950	0.41
BRS1053	NY	314220	591160	0.36
BRS1054	NY	313800	592350	0.45
BRS1055	NY	316710	591200	0.34
BRS1058	NY	316010	592680	0.35
BRS1059	NY	315870	594030	0.34
BRS1060	NY	314190	593820	0.31
BRS1061	NY	313100	596200	0.41
BRS1062	NY	314200	598030	0.31
BRS1063	NY	306880	593200	0.50
BRS1064	NY	306580	595820	0.48
BRS1065	NY	305790	595910	0.58
BRS1066	NY	306220	594280	0.53
BRS1067	NY	306220	594280	0.60
BRS1068	NY	304600	596880	0.44
BRS1069	NY	305180	595370	0.59
BRS1070	NY	305840	592520	0.45
BRS1071	NY	307280	597400	0.41
BRS1072	NY	308600	598200	0.44
BRS1073	NY	302010	580300	0.31

Sample No.	Square	Easting	Northing	IC
BRS1074	NY	301280	581510	0.40
BRS1075	NY	303530	583800	0.36
BRS1076	NY	304210	582800	0.36
BRS1077	NY	303940	584780	0.40
BRS1078	NY	302230	583700	0.37
BRS1079	NY	300970	582460	0.35
BRS1080	NX	298690	589140	0.45
BRS1081	NX	298840	589500	0.40
BRS1082	NY	301090	595370	0.47
BRS1084	NY	317180	598890	0.30
BRS1088	NY	316530	598210	0.22
BRS1091	NY	316060	588230	0.36
BRS1092	NY	315730	586410	0.34
BRS1095	NY	316980	584010	0.39
BRS1096	NY	316250	582840	0.34
BRS1097	NY	316210	581200	0.38
BRS1099	NY	315610	578690	0.54
BRS1100	NY	309670	575510	0.41
BRS1101	NY	308930	575810	0.32
BRS1102	NY	307500	577300	0.35
BRS1103	NY	306120	577310	0.43
BRS1104	NY	307560	578550	0.42
BRS1105	NY	306200	575680	0.37
BRS1106	NY	309310	572840	0.54
BRS1107	NY	302220	597630	0.59
BRS1108	NY	303810	597700	0.42
BRS1116	NY	311930	592280	0.40
BRS1117	NY	312230	597800	0.32
RJM682	NY	313000	590100	0.40
RJM683	NY	313790	595080	0.35
RJM684	NY	316040	594390	0.29
RJM685	NY	316100	595110	0.35
RJM686	NY	312820	598640	0.35
RJM687	NY	312220	589000	0.39

2. Sheet 10E

Sample No.	Square	Easting	Northing	IC
BRS1056	NY	317280	592100	0.38
BRS1057	NY	317780	592970	0.33
BRS1083	NY	317350	596990	0.31
BRS1089	NY	318500	595400	0.35

Sample No.	Square	Easting	Northing	IC
BRS1090	NY	318900	594490	0.29
BRS1093	NY	317390	585600	0.36
BRS1094	NY	318510	589250	0.40
BRS1098	NY	317270	580300	0.38

3. Sheet 16W

Sample No.	Square	Easting	Northing	IC
BRS1085	NY	316520	501170	0.40
BRS1086	NY	316680	599200	0.36
BRS1087	NY	315900	599120	0.34

Sample No.	Square	Easting	Northing	IC
GY1001	NT	312040	601550	0.42
GY1005	NT	312060	601530	0.33
GY1042	NT	304180	601610	0.89
GY1006	NT	313540	602460	0.25

4. Sheet 9E

Sample No.	Square	Easting	Northing	IC
BRS888	NX	295500	593600	0.35
BRS889	NX	296500	592600	0.48
BRS1000	NX	295270	598380	0.30
BRS1002	NX	296600	585370	0.64
BRS1003	NX	294080	585230	0.58
BRS1109	NX	296180	594720	0.36

Sample No.	Square	Easting	Northing	IC
BRS1110	NX	294550	593680	0.51
BRS1111	NX	296500	591890	0.55
BRS1112	NX	296220	591500	0.73
BRS1113	NX	295020	590220	0.56
BRS1114	NX	296710	590000	0.39
BRS1115	NX	292040	591100	0.69