British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Metamorphism of the Palaeozoic rocks of the Torquay district, Devon, 1:50k sheet 350

Integrated Geoscience Surveys Southern Programme

Internal Report IR/01/184

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/01/184

Metamorphism of the Palaeozoic rocks of the Torquay district, Devon, 1:50k sheet 350

R J Merriman and S J Kemp

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Ordnance Survey licence number GD 272191/1999

Key words

Low grade metamorphism, mica (illite) crystallinity.

Front cover

Southdown Cliff, looking westwards. Folds and faults in the inverted limb of the northward verging Man Sands Antiform. Photo. A J J Goode.

Bibliographical reference

MERRIMAN, R J AND KEMP, S J. 2001. Metamorphism of the Palaeozoic rocks of the Torquay district, Devon, 1:50k sheet 350. *British Geological Survey Internal Report*, IR/01/184. 13pp.

Keyworth, Nottingham British Geological Survey 2001

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham and Edinburgh; see contact details below or shop online at www.thebgs.co.uk

The London Information Office maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG
☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.thebgs.co.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU
☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Fax 01491-692345

Parent Body
Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

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 Tony Goode for the samples used in this study which he collected as part of the geological survey of the Torquay district. Brian Leveridge provided a draft geological map and advice on the interpretation of the metamorphic data, for which we are also grateful.

Contents

FIGURES

Summary

The pattern of regional metamorphism indicated by illite crystallinity has been used to interpret the tectonic and thermal history of the Torquay district. The metamorphic pattern is primarily related to the fold-and-thrust geometry but has been modified by later NW-trending faults. Areas of lower grades are associated with limestone and volcanic rock formed on the Torquay and Brixham basin highs that were generated by listric fault block rotation during passive margin rifting. Anchizonal grade associated with these rocks indicates burial under an overburden thickness of at least 5 km. The source of the overburden was the frontal portion of a thrust stack that advanced northwards as the rift system contracted and inverted. The tectonically thickened rear of the stack is represented by epizonal rocks cropping out in the southwest of the district. These rocks formed at temperatures of 300-350ºC under a tectonic overburden of at least 7 km.

1 Introduction

The Palaeozoic rocks of the Torquay district form the most easterly outcrop of the Variscan fold belt of southwest England. Recent mapping to the west of the district, around Plymouth (Leveridge *et al,* in press), has shown that the sedimentary succession developed in a series of E-W parallel extensional half-graben and graben basins and sub-basins that opened and filled sequentially northwards throughout the Devonian and into the Dinantian. Eruptive volcanic centres show a similar migration. Progressive closure and inversion of the rift system followed Late Devonian-Early Dinantian collision to the south (Holder & Leveridge, 1986; Leveridge *et al.,* 1990). Regional low-grade metamorphism was closely associated with the development of a fold-and-thrust belt following closure of the rift system.

During recent remapping of the Torquay district, metapelitic rocks representative of the main stratigraphical units were collected and used to determine illite crystallinity indices. Illite crystallinity provides an indication of metapelitic grade, and the distribution of grades can be used to interpret the tectonic and geothermal history of metamorphic terrains (Merriman & Peacor, 1999). 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; Warr & Rice, 1994). The Kubler index (KI in $\Delta°2\theta$) measures small reductions in the half-height width of the mica ~10 Å XRD (X-ray diffraction) 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; low-anchizone KI 0.30–0.42; high-anchizone KI 0.25–0.30; epizone KI<0.25 (Merriman & Peacor, 1999).

For this study, 98 metapelites were collected from the area mainly within Sheet 350 with some overlap onto Sheet 356 to the south. This represents a sampling density of approximately 1 metapelite sample per 3 km^2. All samples were prepared and analysed by XRD techniques in order to determine the Kubler Index (KI) of illite crystallinity.

2.2 SAMPLE PREPARATION

After removing any surface contaminants with a wire brush, a representative 50 g portion of each sample was stage-ground, using a Cr-steel tema-mill in 5 second bursts, to pass a 1 mm 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 each <1 mm 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

Each glass slip was analysed using a Philips PW1130 series diffractometer equipped with Ni-filtered Cu-Kα radiation and operating at 40kV and 30mA. The KIs of the samples were calculated from the mean of five 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). The width of the ~10 Å peak at half-height was measured using Hiltonbrooks software modified by N J Fortey (BGS) and values were adjusted to concur with previous measurements carried out at Birkbeck College, University of London.

3 Metamorphic map

The metamorphic map shown in Figure 1 is the result of computer contouring of KI data, which was subsequently manually modified to reflect the influence of localized post–metamorphic events. A computer contoured geographical distribution of KI datapoints was initially produced using DeltaGraph Professional 2.0 for Macintosh software. The pattern was then superimposed on an outline 1:50k geological map of the Palaeozoic rocks and contours redrawn where late faulting appeared to modify the overall pattern. In the final version of the map shown in Figure 1, contours of equal crystallinity (isocrysts) are used to delineate five metapelitic zones: late diagenetic zone (KI >0.42); low-anchizone (KI 0.30–0.42); high-anchizone (KI 0.25–0.30), low-epizone (KI <0.20-0.25) and high-epizone (<0.20). The errors and precision involved in contouring the crystallinity data (Robinson *et al.*, 1990), have been 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 map shows a complex pattern of regional low-grade metamorphism that has been substantially modified by NW-trending faults with a dextral strike-slip component of movement. The system of faults that follows the River Dart (i.e. from Scabbacombe Head to Totnes), divides the district into relatively high-grade and low-grade areas. West and southwest of the Dart fault system strata are predominantly in the epizone or high-anchizone, and grade generally increases towards the southeast into older rocks. In the same area, metamafic volcanic rocks containing diagnostic secondary mineral assemblages mainly belonging to the greenschist facies, but one indicates a prehnite-pumpellyite facies assemblage. Lower grade rocks are typical of the area east and northeast of the Dart fault system, where metapelites of the low-anchizone are predominant. East of the Sticklepath Fault, in the vicinity of Torquay, an area of late diagenetic rocks is tentatively contoured and represents the lowest grade rocks found in the district.

4 Metamorphic history

The pattern of low-grade metamorphism largely reflects the basin-and-rise architecture of rifted depositional basins, and their subsequent inversion. Areas of lower grades are associated with limestone and associated volcanic rock formed on the Torquay and Brixham highs that were generated by listric fault block rotation during rifting. However, the anchizonal grades associated with these rocks implies that considerable burial has occurred since deposition. For example, metapelites in the vicinity of the mid-anchizonal isocryst at KI=0.30 probably attained temperatures of around 250ºC (Merriman & Frey, 1999, fig. 3.4). If these temperatures were largely the result of burial, and given estimated palaeogeothermal gradients of up to 50ºC/km (Warr *et al.,* 1991), this would imply an overburden thickness of at least 5km. At lower grades, the rocks close to Torquay are unlikely to have exceeded 200ºC and would require an overburden thickness of at least 4km.

The mostly likely source of the overburden was the family of nappes thrust northwards as the rift system contracted and inverted. During the first phase of the deformation (D_1) and thrusting, associated with fault reversal, a slaty cleavage fabric was generated in the more deeply buried, tectonically thickened mudrock lithologies as basin inversion progressed. This fabric was less well developed in basin rise mudrocks, where initially the overburden was minimal and much of the shortening in associated limestone and volcanic rock sequences was accommodated by early thrusting. The second phase of deformation (D_2) involved further northward movement and stacking of nappes along flat-lying thrusts. This phase introduced a tectonic overburden which was thickest in the south of the Torquay district and thinned northwards. The greatest thickness of overburden is represented by the epizonal rocks cropping out to the southwest of the Dart fault system. These rocks may have formed at temperatures of 300-350ºC under a tectonic overburden of at least 7 km. A northward reduction in the overburden of perhaps 3km is consistent with a wedge-shaped thrust stack rooted to the south. However, at a gradient approaching 1 in 4 the taper of the thrust stack required by the northward reduction in overburden is very steep. Hence the present metamorphic pattern almost certainly reflects juxtaposition of the deeper parts of the thrust stack with basin rise lithologies by fault movements which post-dated the regional metamorphism.

5 References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

HOLDER, M T, and LEVERIDGE, B E. 1986. Correlation of the Rhenohercynian Variscides. *Journal of the Geological Society of London* **143**, 141-147.

KISCH, H J. 1991. Illite crystallinity: recommendations on sample preparation, X-ray diffraction settings and interlaboratory standards. *Journal of Metamorphic Geology*, **9**, 665-670.

LEVERIDGE, B E, HOLDER, M T, and GOODE, A J J. 1990. Geology of the country around Falmouth. *Memoir of the British Geological Survey*, Sheet 352 (England and Wales).

LEVERIDGE, B E, HOLDER, M T, GOODE, A J J, SCRIVENER, R C, JONES, N, and MERRIMAN, R J. (*in press*). Geology of the Plymouth and south-east Cornwall district. *Memoir of the British Geological Survey*, Sheet 348 (England & Wales).

MERRIMAN, R J, and ROBERTS, B. 1992. The low grade metamorphism of Lower Palaeozoic strata on the Rhins of Galloway, SW Scotland. *British Geological Survey Technical Report* **WG/92/40**.

MERRIMAN, R J, and FREY, M. 1999. Patterns of very low–grade metamorphism in metapelitic rocks. 61-107 in *Low–grade Metamorphism.* FREY, M. and ROBINSON, D. (editors). Blackwell Science.

MERRIMAN, R J, and PEACOR, D R. 1999. Very low–grade metapelites: mineralogy, microfabrics and measuring reaction progress. 10-60 in *Low–grade Metamorphism.* FREY, M. and ROBINSON, D. (editors). Blackwell Science.

MERRIMAN, R J, ROBERTS, B, and PEACOR, D R. 1990. A transmission electron microscope study of white mica crystallite size distribution in a mudstone to slate transitional sequence, North Wales, U K. *Contributions to Mineralogy and Petrology*, **10,** 27-40.

ROBERTS, B, MORRISON, C, and HIRONS, S. 1990. Low grade metamorphism of the Manx Group, Isle of Man: a comparative study of white mica ‘crystallinity’ techniques. *Journal of the Geological Society of London*, **147**, 271-277.

ROBINSON, D, WARR, L, and BEVINS, R E. 1990. The illite ‘crystallinity’ technique: a critical appraisal of its precision. *Journal of Metamorphic Geology*, **8**, 333-344.

WARR, L, PRIMMER, T J, and ROBINSON, D. 1991. Variscan very low-grade metamorphism in southwest England: a diastathermal and thrust-related model. *Journal of Metamorphic Geology*, **9**, 751-764.

WARR, L, and RICE, A H N. 1994. Interlaboratory standardization and calibration of clay mineral crystallinity and crystallite size data. *Journal of Metamorphic Geology*, **12**, 141–152.

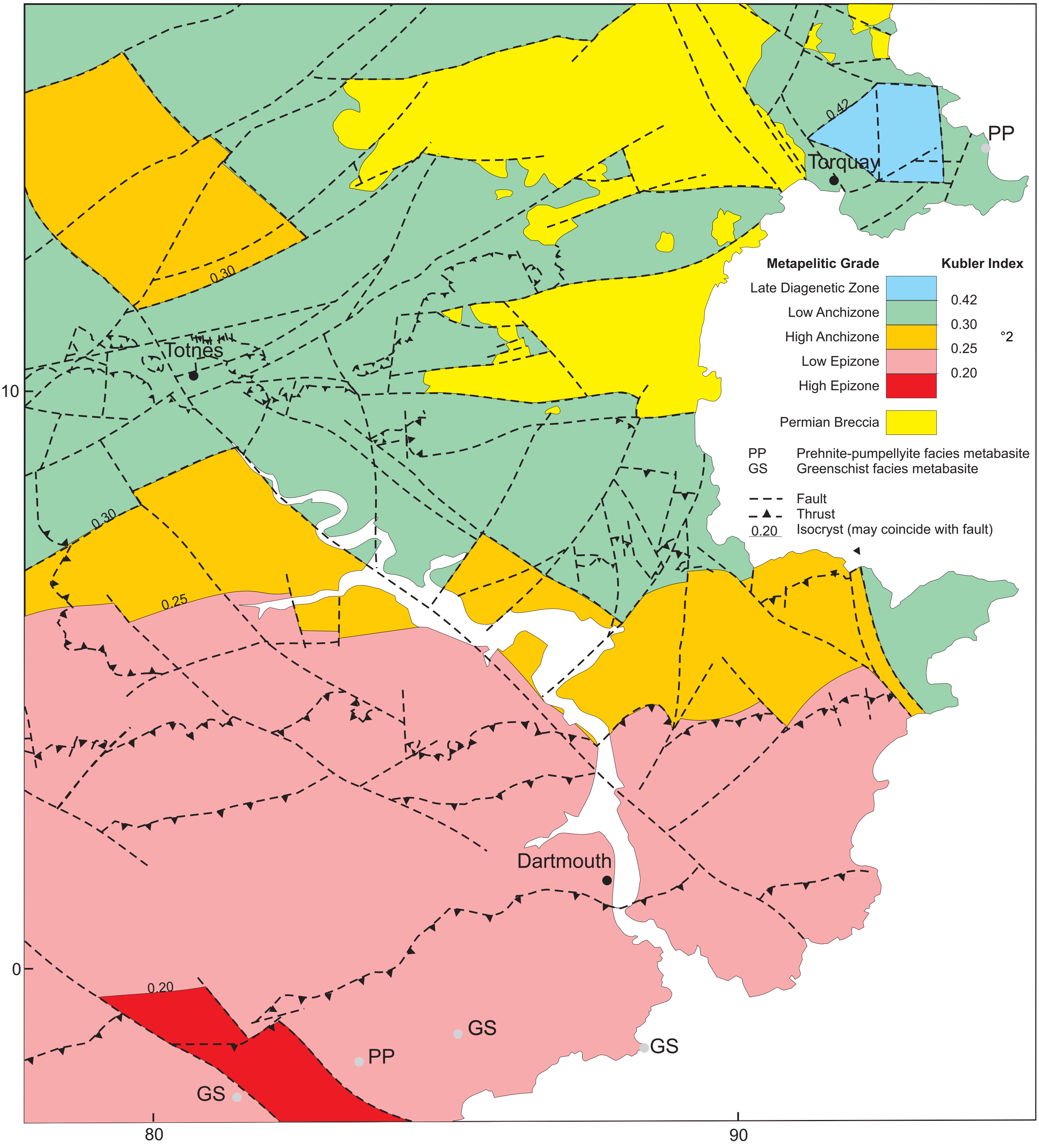

Figure 1. Contoured metamorphic map of white mica crystallinity (Kubler) indices for the Torquay district.

Appendix 1 Summary of sample numbers, sample locations and KIs

Sample No.	Square	Easting	Northing	IC
TG703	SX	7960	6090	0.42
TG704	SX	7840	5600	0.24
TG705	SX	7960	5500	0.24
TG706	SX	8000	5440	0.22
TG707	SX	7980	4980	0.2
TG708	SX	8060	4940	0.19
TG709	SX	8180	4800	0.19
TG710	SX	8600	4980	0.19
TG711	SX	8630	5200	0.18
TG712	SX	8480	5270	0.20
TG713	SX	8240	5550	0.23
TG714	SX	8960	5840	0.38
TG715	SX	8950	5880	0.27
TG716	SX	7970	5690	0.26
TG717	SX	8250	5530	0.23
TG718	SX	8280	5320	0.20
TG719	SX	8390	5150	0.22
TG720	SX	8470	5440	0.22
TG721	SX	8590	5430	0.21
TG722	SX	8640	5320	0.29
TG723	SX	8170	5090	0.22
TG724	SX	8590	4790	0.22
TG725	SX	8570	4800	0.28
TG726	SX	8520	4780	0.21
TG727	SX	7800	4960	0.17
TG728	SX	7780	5380	0.27
TG729	SX	7890	6210	0.32
TG730	SX	9030	5700	0.22
TG731	SX	9020	5710	0.34
TG733	SX	9400	6390	0.31
TG744	SX	9320	6345	0.36
TG745	SX	9264	6361	0.43
TG746	SX	9194	6383	0.31
TG747	SX	9168	6438	0.55
TG748	SX	9112	6455	0.40
TG749	SX	9034	6345	0.43
TG750	SX	9002	6288	0.42
TG753	SX	8887	5937	0.27
TG762	SX	8490	4720	0.19
TG767	SX	8613	5150	0.23
TG768	SX	8310	5145	0.21
TG769	SX	8608	5128	0.21
TG775	SX	8370	6560	0.33
TG776	SX	8190	6340	0.30
TG777	SX	8150	6250	0.29
TG778	SX	7840	6400	0.26
TG779	SX	7990	6460	0.26
TG780	SX	8200	6430	0.35
TG781	SX	8420	6240	0.31
TG782	SX	8590	6600	0.35
TG783	SX	8190	6620	0.38
TG784	SX	7930	6770	0.35
TG785	SX	7920	6640	0.30
TG786	SX	7910	6630	0.34
TG787	SX	7820	6330	0.30
TG788	SX	8850	5550	0.29
TG789	SX	8960	5280	0.26
TG790	SX	8890	5190	0.21
TG791	SX	8860	5110	0.20
TG792	SX	8980	5060	0.21
TG793	SX	9150	5330	0.21
TG794	SX	9170	5530	0.26
TG795	SX	8860	5320	0.23
TG796	SX	8420	5070	0.22
TG808	SX	8010	4760	0.22
TG809	SX	8870	5030	0.21
TG810	SX	8760	5110	0.24
TG811	SX	8710	5090	0.22
TG812	SX	9140	5210	0.26
TG813	SX	9120	5230	0.21
TG814	SX	7780	5210	0.22
TG815	SX	7920	5040	0.27
TG816	SX	7970	5030	0.23
TG817	SX	8120	5380	0.19
TG818	SX	9100	5430	0.23
TG819	SX	8970	5440	0.25
TG820	SX	8880	5380	0.22
TG821	SX	8900	5440	0.20
TG822	SX	8890	5460	0.19
TG823	SX	8870	5490	0.23
TG824	SX	9330	5490	0.36
TG825	SX	8590	5560	0.23
TG826	SX	8570	5760	0.31
TG827	SX	8160	5990	0.30
TG828	SX	8120	6200	0.30
TG829	SX	8600	6100	0.33
TG830	SX	8570	6160	0.30
TG831	SX	9050	5460	0.21
TG832	SX	8520	6370	0.38
TG833	SX	8640	6280	0.31
TG834	SX	8680	6230	0.30
TG835	SX	8720	6190	0.32
TG836	SX	8930	6250	0.31
TG837	SX	8750	6280	0.36
TG838	SX	8750	5850	0.22
TG839	SX	9100	5550	0.30
TG840	SX	9280	5440	0.18
TG841	SX	8780	5420	0.22