2001/2
Copy 3

AGSO

S-type Granites and Related Rocks

Edited by

Bruce Chappell & Peter Fleming

AGSO Record 2001/2

~ *GEOSCIENCE AUSTRALIA* ~

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION
DEPARTMENT OF INDUSTRY, SCIENCE & RESOURCES

AGSO RECORD 2001/02

S-type granites and related rocks

A collection of abstracts for a symposium held to mark the 70th birthday of Professor Allan White, 11-12 January 2001

Edited by BRUCE CHAPPELL[1] & PETER FLEMING[2]

[1]*GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia*
[2]*Department of Earth Sciences, La Trobe University, Vic 3086, Australia*

CANBERRA 2001

Department of Industry, Science & Resources

Minister for Industry, Science & Resources: Senator the Hon. Nick Minchin
Parliamentary Secretary: The Hon. Warren Entsch, MP

Australian Geological Survey Organisation

Chief Executive Officer: Neil Williams

ISSN 1039-0073
ISBN 0 642 39867 4

Recommended bibliographic citation:

Chappell, B.W. & Fleming, P.D. (editors), 2001. S-type granites and related rocks. Australian Geological Survey Organisation Record, 104 pp.

Copies of this *Record* can be purchased from:
Sales Centre
Australian Geological Survey Organisation
GPO Box 378
Canberra, ACT, 2601, Australia
telephone: 02 6249 9519 (domestic) and +61 2 6249 9519 (international)
facsimile: 02 6249 9982 (domestic) and +61 2 6249 9982 (international)
electronic mail: sales@agso.gov.au
internet: www.agso.gov.au/information/bookshop.html

The Convenors, and the Department of Earth Sciences, La Trobe University would like to thank the following sponsors for their kind support:

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

SGGMP
Specialist Group for Geochemistry, Mineralogy, & Petrology

Terra Search Pty Ltd

RIA TerraSystems

BHP

Johnson's Well Mining N.L.
ABN 28 009 174 761

PASMINCO EXPLORATION
A DIVISION OF PASMINCO AUSTRALIA LIMITED

LA TROBE UNIVERSITY
IT'S YOUR FUTURE
SCIENCE TECHNOLOGY ENGINEERING

North Limited

Ashton Mining Ltd

Contents

Allan White 1
Publications of Professor Allan White 2
S-type granites: an introduction 7
Abstracts:
Allen, C.M. 13
Anderson, J.A.C., Fleming, P.D., Price, R.C. 15
Bajwah, Z.U. 17
Blevin, P.L. 19
Bons, P.D., Elburg, M.A. 21
Brown, M, Solar, G.S. 23
Budd, A.R., Bastrakova, I.V., Wyborn, L.A.I. 25
Champion, D.C., Bultitude, R.J. 27
Chappell, B.W., White, A.J.R. 29
Clemens, J.D. 31
Collins, W.J., Richards, S.W. 33
Cook, M 35
Elburg, M.A. 37
Finger, F., Chappell, B.W. 39
Flood, R.H., Shaw, S.E. 41
Foden, J. 43
Geraldes, M.C., Teixeira, W., Babinski, M., van Schmus, W.R., Bettencourt, J.S. 45
Gray, C.M., Kemp, A.I.S. 47
Grew, E.S., Yates, M., Barbier, J., Shearer, C., Sheraton, J., Shiraishi, K, Motoyoshi, Y. 49
Harris, C, Miller, J. 51
Hergt, J.M., Corr, F., Patrick, B., White, A.J.R., Woodhead, J.D., Chappell, B.W. 53
Hogan, J.P., Sinha, A.K. 55
Jiang, S.Y. 57
Johannes, W. 59
Jwa, Y.J. 61
Kemp, A.I.S. 63
Kennan, P. 65
King, P.L., Holloway, J.R. 67
King, P.L., White, A.J.R. 69
Landenberger, B. 71
London, D. 73
Maas, R., Waight, T.E., Nicholls, I.A., Anderson, J.A.C. 75
Maas, R., Kamenetsky, V., Nicholls, I.A., Steele, D. 77
Nagamine, K., Araki, M, Sugisaki, R., Chappell, B.W. 79
Nicholls, I.A., Maas, R., Waight, T.E. 81
Powell, R., White, R., Holland, T.J.B. 83
Putthapiban, P. 85
Scheepers, R. 87
Shimura, T., Kawai, T., Kagashima, S. 89
Silver, L.T. 91
Steele, D.A., Price, R.C. 93
Tulloch, A., Kimbrough, D., Walker, N., Allibone, A. 95
Turner, S., Garland, F., Hawkesworth, C. 97
Williams, I.S. 99
Wyborn, D. 101
Zafar, M., Murata, M., Khan, T., Ozawa, H., Nishimura, H. 103

ALLAN WHITE

Allan White was born near Adelaide on 11 January 1931. He was the last honours student of Sir Douglas Mawson at the University of Adelaide. For his thesis, he carried out mapping north of Broken Hill. He then worked as Mawson's field assistant for 12 months, and commenced a study of granites and associated rocks in the eastern Mt Lofty Ranges, which he continued for his PhD at the University of London. He was then appointed a Lecturer in the Department of Geology at the University of Otago in late 1956.

Allan was an early appointment, in June 1960, to the new Faculty of Science of the Australian National University. He remained in Canberra until his appointment to the foundation Chair of Geology at La Trobe University in 1972, where he was head of department for much of the next 15 years. After a period of retirement, he returned to Melbourne as Director of the Victorian Institute of Earth and Planetary Sciences (VIEPS) in 1996, a position that he left in March 1999. Allan's significant contributions both at La Trobe and VIEPS have been recognised by the establishment of an Allan White Medal that will be awarded each year to outstanding BSc honours graduates in earth science from the three VIEPS universities. The first medal was awarded in December 1999.

Throughout his university career, Allan White was an exceptional teacher who was dedicated to both the intellectual and personal welfare of his students, many of who have gone on to occupy prominent positions in universities, government organisations, and industry. Students who worked closely with Allan White have always regarded that experience as a special privilege. Allan White built up the Earth Sciences Department at La Trobe University from nothing. Both there and later at VIEPS, Allan showed special talents as a leader and administrator.

Allan White has a very distinguished research record and is an author on 98 publications (see pp. 2-6). He has always had wide interests in hard-rock geology, and in his early career he published on a range of topics, including metamorphic rocks and the geochemistry of island arc volcanic rocks. In one sense his research later became more focussed, dealing largely with granites. He has, though, examined those rocks in a remarkably diverse way, studying their field relationships, petrography, mineralogy, and geochemistry, with a detailed knowledge of the relevant experimental results. He has a strong interest in the relationship between granites and mineral deposits and he has a special interest in the role of water in the evolution of granite magmas, leading to the development of volatile phases and, sometimes, mineral deposits.

Publications of Professor Allan White:

Leslie, R.B. & White, A.J.R. 1955. The "Grand" unconformity between the Archaean (Willyama Complex) and Proterozoic (Torrowangee Series) north of Broken Hill, New South Wales. *Transactions of the Royal Society of South Australia* **78**, 121-133.

Chinner, G.A., Sando, M. & White, A.J.R. 1956. On the supposed transformation of tillite to granite at Mount Fitton, South Australia. *Geological Magazine* **93**, 18-24.

Kleeman, A.W. & White, A.J.R. 1956. The structural petrology of portion of the eastern Mt. Lofty Ranges. *Journal of the Geological Society of Australia* **3**, 17-29.

White, A.J.R. & Thatcher, D. 1957. *Geological Atlas of South Australia, Sheet Mannum*. South Australian Geological Survey, Adelaide.

White, A.J.R. 1959. Scapolite-bearing marbles and calc-silicate rocks from Tungkillo and Milendella, South Australia. *Geological Magazine* **96**, 285-306.

Coombs, D.S., White, A.J.R. & Hamilton, D. 1960. Age relations of the Dunedin volcanic complex and some palaeogeographic implications - Part I. *New Zealand Journal of Geology and Geophysics* **3**, 325-336.

Coombs, D.S., White A.J.R. & Hamilton, D. 1960. Age relations of the Dunedin volcanic complex and some paleogeographic implications - Part II. *New Zealand Journal of Geology and Geophysics* **3**, 572-579.

Steiner, A., Brown, D.A. & White, A.J.R. 1960. Occurrence of ignimbrite in the Shag valley, North-east Otago. *New Zealand Journal of Geology and Geophysics* **2**, 380-384.

White, A.J.R. & Whittle, A.W.G. 1961. Occurrence of pentlandite in New Zealand. *New Zealand Journal of Geology and Geophysics* **4**, 446-448.

White, A.J.R. 1962. Aegirine-riebeckite schists from South Westland, New Zealand. *Journal of Petrology* **3**, 38-48.

Lovering, J.F. & White, A.J.R. 1964. The significance of primary scapolite in granulitic inclusions from deep-seated pipes. *Journal of Petrology* **5**, 195-218.

White, A.J.R. 1964. Clinopyroxenes from eclogites and basic granulites. *American Mineralogist* **49**, 883-888.

White, A.J.R. 1964. Stilpnomelane in the Brisbane Metamorphics. *Australian Journal of Science* **26**, 324.

Lambert, I.B. & White, A.J.R. 1965. The Berridale wrench fault: a major structure in the Snowy Mountains of New South Wales. *Journal of the Geological Society of Australia* **12**, 25-33

Taylor, S.R. & White, A.J.R. 1965. Geochemistry of andesites and the growth of continents. *Nature* **208**, 271-273.

Taylor, S.R. & White, A.J.R. 1966. Trace element abundances in andesites. *Bulletin volcanologique* **29**, 177-194.

White, A.J.R. 1966. Genesis of migmatites from the Palmer region of South Australia. *Chemical Geology* **1**, 165-200

White, A.J.R. 1966. Petrology and structure of the Rathjen granitic gneiss of the Palmer region, South Australia. *Journal of the Geological Society of Australia* **13**, 471-489.

White, A.J.R., Compston, W. & Kleeman, A.W. 1967. The Palmer granite – a study of a granite within a regional metamorphic environment. *Journal of Petrology* **8**, 29-50.

Chappell, B.W. & White, A.J.R. 1968. The X-ray spectrographic determination of sulfur coordination in scapolite. *American Mineralogist* **53**, 1735-1738.

Jakeš, P. & White, A.J.R. 1969. Structure of the Melanesian arcs and correlation with distribution of magma types. *Tectonophysics* **8**, 223-236.

Lovering, J.F. & White, A.J.R. 1969. Granulitic and eclogitic inclusions from basic pipes at Delegate, Australia. *Contributions to Mineralogy and Petrology* **21**, 9-52.

Taylor, S.R., Kaye, M., White, A.J.R., Duncan, A.R. & Ewart, A. 1969. Genetic significance of Co, Cr, Ni, Sc and V content of andesites. *Geochimica et Cosmochimica Acta* **33**, 275-286.

Publications of Professor Allan White (continued)

Taylor, S.R., Kaye, M., White, A.J.R., Duncan, A.R. & Ewart, A. 1969. Genetic significance of V and Ni content of andesites - reply to Prof. E.F. Osborne (1969). *Geochimica et Cosmochimica Acta* **33**, 1555-1557.

White, A.J.R. 1969. Some mineral characteristics of high temperature-high pressure 'granulite facies' assemblages. *Geological Society of Australia Special Publication* **2**, 353-359.

Chappell, B.W. & White, A.J.R. 1970. Further data on an 'eclogite' from the Sittampundi Complex, India. *Mineralogical Magazine* **37**, 555-560.

Jakeš, P. & White, A.J.R. 1970. K/Rb ratios of rocks from island arcs. *Geochimica et Cosmochimica Acta* **34**, 849-856.

Mackenzie, D.E. & White, A.J.R. 1970. Phonolite globules in basanite from Kiandra, Australia. *Lithos* **3**, 309-317.

Jakeš, P. & White, A.J.R. 1971. Composition of island arcs and continental growth. *Earth and Planetary Science Letters* **12**, 224-230.

Taylor, S.R., White, A.J.R., Ewart, A. & Duncan, A.R. 1971. Nickel in high-alumina basalts: a reply. *Geochimica et Cosmochimica Acta* **35**, 525-528.

White, A.J.R., Jakeš, P. & Christie, D.M. 1971. Composition of greenstones and the hypothesis of sea-floor spreading in the Archaean. *Geological Society of Australia Special Publication* **3**, 47-56.

Gulson, B.L., Lovering, J.F., Taylor, S.R. & White, A.J.R. 1972. High-K diorites, their place in the calc-alkaline association and relationship to andesites. *Lithos* **5**, 269-279.

Jakeš, P. & White, A.J.R. 1972. Hornblendes from calc-alkaline volcanic rocks of island arcs and continental margins. *American Mineralogist* **57**, 887-902.

Jakeš, P. & White, A.J.R. 1972. Major and trace element abundances in volcanic rocks of orogenic areas. *Geological Society of America Bulletin* **83**, 29-39.

Johnson, R.W., Davies, R.A. & White, A.J.R. 1972. Ulawun Volcano, New Britain. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin* **142**. 42 pp..

White, A.J.R., Chappell, B.W. & Jakeš, P. 1972. Coexisting clinopyroxene, garnet, and amphibole from an 'eclogite', Kakanui, New Zealand. *Contributions to Mineralogy and Petrology* **34**, 185-191.

White, A.J.R., Chappell, B.W. & Cleary, J.R. 1974. Geologic setting and emplacement of some Australian Paleozoic batholiths and implications for intrusive mechanisms. *Pacific Geol*ogy **8**, 159-171.

Chappell, B.W. & White, A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

Chappell, B.W. & White, A.J.R. 1976. Plutonic rocks of the Lachlan Mobile Zone. *Twenty Fifth International Geological Congress, Field Guide Excursion 13C*, 40 pp.

White, A.J.R., Williams, I.S. & Chappell, B.W. 1976. The Jindabyne Thrust and its tectonic, physiographic and petrogenetic significance. *Journal of the Geological Society of Australia* **23**, 105-112.

White, A.J.R., Williams, I.S. & Chappell, B.W. 1976. *Berridale 1:100 000 Geological Sheet*. New South Wales Geological Survey, Sydney.

White, A.J.R., Williams, I.S. & Chappell, B.W. 1977. *Geology of the Berridale 1:100 000 Sheet (8625)*. New South Wales Geological Survey, Sydney.

White, A.J.R. & Chappell, B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

Burns, K.L., Stephansson, O. & White, A.J.R. 1977. The Flinders Ranges breccias of South Australia - diapirs or *décollement*? *Journal of the Geological Society of London* **134**, 363-384.

Beams, S.D., Cramer, J.J., & White A.J.R. 1977. Granitoid types and mineralization with special reference to tin. *In* Yamada, N. (*ed.*) *Plutonism in Relation to Metamorphism*. Toyama, Japan, pp. 89-100.

Publications of Professor Allan White (continued)

Hine, R., Williams, I.S., Chappell, B.W. & White, A.J.R. 1978. Contrasts between I- and S-type granitoids of the Kosciusko Batholith. *Journal of the Geological Society of Australia* **25**, 219-234.

Griffin, T.J., White, A.J.R. & Chappell, B.W. 1978. The Moruya Batholith and geochemical contrasts between the Moruya and Jindabyne suites. *Journal of the Geological Society of Australia* **25**, 235-247.

Collins, W.J., Beams, S.D., White, A.J.R. & Chappell, B.W. 1982. Nature and origin of A-type granites with particular reference to south-eastern Australia. *Contributions to Mineralogy and Petrology* **80**, 189-200.

Kwak, T.A.P. & White, A.J.R. 1982. Contrasting W-Mo-Cu and W-Sn-F skarn types and related granitoids. *Mining Geology* **32**, 339-351.

White, A.J.R. & Chappell, B.W. 1983. Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia. *In* Roddick, J.A. (ed.), *Circum-Pacific Plutonic Terranes*, Geological Society of America Memoir **159**, 21-34.

Chappell, B.W. & White, A.J.R. 1984. I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *In* Xu Keqin & Tu Guangchi (eds), *Geology of Granites and Their Metallogenic Relations*, pp. 87-101. Science Press, Beijing.

White, A.J.R., Collins, W.J. & Chappell, B.W. 1984. Influence of melt structure on the trace element composition of granites. *In* Xu Keqin & Tu Guangchi (eds), *Geology of Granites and Their Metallogenic Relations*, pp. 737-751. Science Press, Beijing.

Fleming, P.D. & White, A.J.R. 1984. Relationships between deformation and partial melting in the Palmer migmatites, South Australia. *Australian Journal of Earth Sciences* **31**, 351-360.

White, A.J.R., Clemens, J.D., Holloway, J.R., Silver, L.T., Chappell, B.W. & Wall, V.J. 1986. S-type granites and their probable absence in southwestern North America. *Geology* **14**, 115-118.

Clemens, J.D., Holloway, J.R. & White, A.J.R. 1986. Origin of an A-type granite: experimental constraints. *American Mineralogist* **71**, 317-324.

White, A.J.R., Clemens, J D., Holloway, J.R., Silver, L.T., Chappell, B.W. & Wall, V.J. 1986. S-type granites and their probable absence in southwestern North America; reply. *Geology* **14**, 805-806.

White, A.J.R., Clemens, J D., Holloway, J.R., Silver, L.T., Chappell, B.W. & Wall, V.J. 1986. S-type granites and their probable absence in southwestern North America; reply. *Geology* **14**, 895.

Stump, E., White, A.J.R. & Borg, S.G. 1986. Reconstruction of Australia and Antarctica: evidence from granites and recent mapping. *Earth and Planetary Science Letters* **79**, 348-360.

Chappell, B.W., White, A.J.R. & Wyborn, D. 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

Smith, I.E.M., White, A.J.R., Chappell, B.W. & Eggleton, R.A. 1988. Fractionation in a zoned monzonite pluton: Mount Dromedary, southeastern Australia. *Geological Magazine* **125**, 273-284.

White, A.J.R. & Chappell, B.W. 1988. Granites. *In* Douglas, J.G. & Ferguson, J.A. (eds), *Geology of Victoria,* pp. 427-439. Victorian Division, Geological Society of Australia.

Tainosho, Y., White, A.J.R., Chen, Y. & Wormald, R. 1988, Regional variation of magnetic susceptibility of the Lachlan fold belt granitoids, southeastern Australia. *Journal of the Geological Society of Japan.* **94**, 657-668.

White, A.J.R. 1988. Intrusive rocks of Victoria. *In* Clark, I., Cook, B. & Cochrane, G.C. (eds). *Victorian Geology Excursion Guide*, pp. 57-66. Australian Academy of Science, Canberra.

White, A.J.R. 1988. Mernda. *In* Clark, I., Cook, B. & Cochrane, G.C. (eds). *Victorian Geology Excursion Guide*, pp. 433-442. Australian Academy of Science, Canberra.

White, A.J.R. & Chappell, B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

Publications of Professor Allan White (continued)

Chappell, B.W., White, A.J.R. & Hine, R. 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

White, A.J.R. & Chappell, B.W. 1989. *Geology of the Numbla 1:100 000 Sheet (8624)*. New South Wales Geological Survey, Sydney.

White, A.J.R., Chappell, B.W., Williams, I.S. & Glen, R.A. 1989. *Numbla 1:100 000 Geological Sheet*. New South Wales Geological Survey, Sydney.

White A.J.R. 1989. Cordierite-muscovite relationships in granites. *Eos* **70**, 110-111.

Chen, Y.D., Price, R.C. & White, A.J.R. 1989. Inclusions in three S-type granites from southeastern Australia. *Journal of Petrology* **30**, 1181-1218.

Chen, Y.D., Price, R.C., White, A.J.R. & Chappell, B.W. 1990. Mafic inclusions from the Blue Gum and Glenbog granite suites, southeastern Australia. *Journal of Geophysical Research* **95**, 17757-17785.

Chen, Y.D., Price, R.C., White, A.J.R. & Chappell, B.W. 1990. Mafic inclusions from the Glenbog and Blue Gum granite suites, southeastern Australia. *Journal of Geophysical Research* **95**, 17757-17785.

Chappell, B.W., Williams, I.S., White, A.J.R. & McCulloch, M.T. 1990. Granites of the Lachlan Fold Belt. ICOG 7 Field Guide Excursion A-2. *Bureau of Mineral Resources Geology and Geophysics Australia, Record* **1990/48**.

Chappell, B.W., White, A.J.R. & Williams, I.S. 1990. Cooma Granodiorite and Berridale Batholith. ICOG 7 Field Guide Excursion B-1. *Bureau of Mineral Resources Geology and Geophysics Australia, Record* **1990/50**.

White, A.J.R. & Chappell, B.W. 1991. Per migma ad magma downunder. *Geological Journal* **25**, 221-225.

Chappell, B.W., English, P.M., King, P.L., White, A.J.R. & Wyborn, D. 1991. *Granites and related rocks of the Lachlan Fold Belt (1:1 250 000 scale map)*. Bureau of Mineral Resources, Geology and Geophysics, Australia.

Chappell, B.W., White, A.J.R. & Williams, I.S. 1991. A transverse section through granites of the Lachlan Fold Belt. Second Hutton Symposium Field Guide. *Bureau of Mineral Resources Geology and Geophysics Australia, Record* **1991/22**.

Wyborn, D., White, A.J.R. & Chappell, B.W. 1991. Enclaves in the S-type Cowra Granodiorite. Second Hutton Symposium Field Guide. *Bureau of Mineral Resources Geology and Geophysics Australia, Record* **1991/24**.

Chen, Y.D., Chappell, B.W. & White, A.J.R. 1991. Mafic enclaves of some I-type granites of the Lachlan Fold Belt, southeastern Australia. *In* Didier, J. & Barbarin, B. (eds), *Enclaves and Granite Petrology*, pp. 113-124. Elsevier, Amsterdam.

Chappell, B.W. & White, A.J.R. 1991. Restite enclaves and the restite model. *In* Didier, J. & Barbarin, B. (eds), *Enclaves and Granite Petrology*, pp. 375-381. Elsevier, Amsterdam.

White, A.J.R., Chappell, B.W. & Wyborn, D. 1991. Enclaves of S-type granites in the Lachlan Fold Belt, southeastern Australia. *In* Didier, J. & Barbarin, B. (eds), *Enclaves and Granite Petrology*, pp. 493-507. Elsevier, Amsterdam.

Bajwah, Z.U., White, A.J.R., Kwak, T.A.P. & Price, R.C. 1991. Hydrothermal alteration associated with the Renison granite western Tasmania: evidence for the evolution of hydrothermal fluids related to tin mineralization. *Bureau of Mineral Resources, Geology and Geophysics, Record* **1990/95**, 3-4.

Creaser, R.A. & White, A.J.R. 1991. Yardea Dacite - large-volume, high-temperature felsic volcanism from the Middle Proterozoic of South Australia. *Geology* **19**, 48-51.

Chappell, B.W. & White, A.J.R. 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1-26.

Publications of Professor Allan White (continued)

Chappell, B.W., White, A.J.R. & Wyborn, D. 1993. The Cowra Granodiorite and its enclaves. IAVCEI Field Guide. *Australian Geological Survey Organisation, Record* **1993/67**.

Bajwah, Z.U., White, A.J.R., Kwak, T.A.P. & Price, R.C. 1995. The Renison Granite, northwestern Tasmania: a petrological, geochemical and fluid inclusion study of hydrothermal alteration. *Economic Geology* **90**, 1663-1675.

King, P.L., White, A.J.R., Chappell, B.W. & Allen, C.M. 1997. Characterization and origin of the aluminous A-type granites of the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* **38**, 371-391.

Chappell, B.W. & White, A.J.R. 1998. Development of P-rich granites by sequential restite fractionation and fractional crystallisation: the Koetong Suite in the Lachlan Fold Belt. *Acta Universitatis Carolinae Geologica* **42**, 23-27.

Chappell, B.W., Bryant, C.J., Wyborn, D., White, A.J.R. & Williams, I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* **48**, 225-236.

White, A.J.R., Chappell, B.W. & Wyborn, D. 1999. Application of the restite model to the Deddick Granodiorite and its enclaves: a re-interpretation of the observations and data of Maas *et al.* (1998). *Journal of Petrology* **40**, 413-421.

Chappell, B.W., White, A.J.R., Williams, I.S., Wyborn, D., Hergt, J.M. & Woodhead, J.D. 1999. Discussion: Evaluation of petrogenetic models for Lachlan fold belt granitoids: implications for crustal architecture and tectonic models. *Australian Journal of Earth Sciences* **46**, 827-831.

Chappell, B.W., White, A.J.R., Williams, I.S., Wyborn, D. & Wyborn, L.A.I. 2000. Lachlan Fold Belt granites revisited: high- and low-temperature granites and their implications. *Australian Journal of Earth Sciences* **47**, 123-138.

Gray, C.M & White, A.J.R. 2001. Reduced granites and volcanics of the Central Victorian Magmatic Province - Field Excursion Guide. Australian Geological Survey Organisation, Record **2001/03**.

Chappell, B.W. & White, A.J.R. 2001. Granites of the Lachlan Fold Belt. *Australian Journal of Earth Sciences (in press)*.

Chappell, B.W. & White, A.J.R. 2001. Two contrasting granite types – 25 years later. *Australian Journal of Earth Sciences (in press)*.

White, A.J.R., Allen, C.M., Beams, S.D., Carr, P.F., Champion, D.C., Chappell, B.W., Wyborn, D. & Wyborn, L.A.I., 2001. Granite suites and supersuites of southeastern Australia. *Australian Journal of Earth Sciences (in press)*.

King, P.L., Chappell, B.W., White, A.J.R. & Allen, C.M. 2001. Are A-type granites the high temperature felsic granites? Evidence from fractionated granites of the A-type Wangrah Suite. *Australian Journal of Earth Sciences (in press)*.

White, A.J.R. 2001. Water, restite, and granite mineralisation. *Australian Journal of Earth Sciences (in press)*.

S-TYPE GRANITES: AN INTRODUCTION

It was Allan White's mapping and careful field observations in the Berridale region (White *et al.* 1977), combined with petrographic and compositional data, that led to recognition that many of the granites of that area comprise a distinct type, derived from sedimentary rocks deep in the crust. The presence of cordierite-bearing granites in parts of southeastern Australia had been known for a long time. Tattam (1925) had suggested that cordierite in the Bulla granite, close to Melbourne, was due to contamination, and Hills (1938) had argued perceptively that the andalusite and cordierite occurring in some granites of the region is of magmatic "pyrogenetic" origin. Baker (1940) reported the widespread occurrence of cordierite granites in the subvolcanic Strathbogie granite. The occurrence of andalusite, sillimanite and cordierite in the regional-aureole Cooma Granodiorite had long been known, as reported by Joplin (1942). The occurrence of two quite distinct types of granites in the Kosciuszko region was apparently first recognised by Dallwitz (in Ball *et al.* 1948). He noted that the majority of granites belonging to a "foliated" group in which the biotite is pleochroic from red-brown to buff, while in the small "massive" bodies the biotite is pleochroic in shades of brown and yellow. Browne (1929) had subdivided the granites of this region into the foliated and massive types, plus gneissic granites represented by Cooma and he correlated these three groups with specific orogenic events. Joplin (1962) showed that there are compositional differences between those three groups, with the gneissic or Cooma type having the highest K_2O/Na_2O ratios and lowest CaO abundances, while the massive granites have the highest Na_2O and CaO contents. In the early 1960's, the general view was that all granites are related and located at different levels in the crust. This was codified in the *granite series* of Read (1948). Granite magmas formed at deep levels in association with high grade metasedimentary rocks and migmatites, and in some cases moved to intrude the upper crust; all granites were derived from metasediments and there were no associated volcanic rocks. Such a view was destined to be short-lived.

This was the situation in 1963 when Allan White and his colleagues began what has developed into a study of granites over the whole of the Lachlan Fold Belt. Mapping was initiated with a BSc Honours project of Ian Lambert (Lambert & White 1965), which was followed by several other BSc theses and other mapping. At about the same time, Pidgeon & Compston (1965) showed that the Sr isotopic compositions of the Cooma granite and its surrounding regional metamorphic rocks were very similar, consistent with derivation of that granite from a sedimentary source. In a PhD study of the Murrumbidgee Batholith, Joyce (1970, 1973) argued that the mafic Clear Range Granodiorite was derived from partial melting of sedimentary rocks. BSc thesis studies of Rick Hine and Ian Williams, later published by Hine *et al.* (1978), provided additional data, in the Jindabyne region, on what would become known as I- and S-type granites. Doubts about a sedimentary source for all granites followed from the study of Hurley *et al.* (1965), who showed that granites of the Sierra Nevada batholith are isotopically primitive. Also, Chappell (1966), in a PhD thesis study of part of the New England Batholith, proposed that the hornblende-bearing granites resulted from partial melting of older igneous rocks, and inferred that the source could not have been sedimentary. That study also made the initial suggestion that the compositional variation within granite suites could result from differing degrees of separation of partial melt from its crystalline residuum. That observation developed into the *restite model* (White & Chappell 1977; Chappell *et al.* 1987), with the implication that the compositions of granites may image those of their source rocks in a rather direct way.

So by the early 1970's, the stage was set for recognition of the I- and S-type granites. It was fortunate that a person of Allan White's wide-ranging talents was working on these rocks. His field and petrographic observations, his appreciation of the relationship between mineral and chemical compositions, both of which must also reflect analogous features of the source rocks, led to the recognition of the two contrasting granite types (Chappell & White 1974, 1992, 2001). A critical observation was that the more mafic S-type granites contain a rich assortment of metasedimentary enclaves, including sillimanite-bearing gneisses. Sillimanite is absent from the exposed country rocks, implying a deeper origin, and these enclaves can be interpreted as fragments of lithic restite (White *et al.* 1999).

The S-type granites comprise a little more than half of the extensive area of granites in the Lachlan Fold Belt and their abundance can be correlated with massive partial melting of the crust at depths ~15-20 km at around 430-420 Ma, with younger ages in the Melbourne Province. Since their original identification in the LFB, other features of these S-type granites have been recognised. Allan White in a conference paper in 1974 pointed out that there is a sharp eastern limit to the occurrence of S-type granites in the Berridale Batholith, later termed the IS-line by White *et al.* (1976). This line marks the eastern limit of large plutons of S-type granites, and those authors stated that "the line probably coincides with the eastern margin of a very thick block of continental crust, possibly crystalline shield". This line has been traced for more than 600 km north from Bass Strait to where it disappears beneath Mesozoic cover rocks. Later studies by Allan White in western Victoria showed the presence of another IS-line of opposite polarity at the western edge of the Melbourne Province. Breaks of this type, where there is a sharp discontinuity in the petrological and geochemical features of granites, including the presence or absence of S-type granites, and also within S- and/or I-type granites, are a distinctive feature of the LFB. Chappell *et al.* (1988) argued that such breaks correspond to analogous differences at depth, and subdivided the LFB into 10 provinces or *basement terranes* on that basis. One such example within an area dominated by S-type granites is provided by the differences between S-type granites in the Kosciuszko and Young batholiths to the east, and the Maragle and Wagga batholiths further west. The more mafic S-type granites in both areas are very similar in composition. However, the more felsic granites of the Wagga Province show the compositional effects of progressive fractional crystallisation, whereas those in the Kosciuszko Province do not.

As felsic S-type granites with composition reflecting the effects of fractional crystallisation are virtually unknown in the Kosciuszko Province, such rocks were not initially recognised in the LFB. They are now known to be important in the Wagga Province (Chappell & White 1998), the Bassian Province of Bass Strait and northeastern Tasmania, and on the Tasmanian West Coast (Chappell 1999). Another important feature that has been identified, initially by Doone Wyborn (Owen & Wyborn 1979), is the extensive occurrence of S-type volcanic rocks, which compositionally can be matched quite closely with plutonic suites (Wyborn *et al.* 1981).

An important feature of the S-type granites of the LFB is the extensive occurrence of old zircon cores. Williams (1995) has shown that zircon cores with age-inheritance are ubiquitous in granites of the extensive S-type Bullenbalong Suite, with the relative amount increasing as the rocks become more mafic. These observations are consistent with the derivation of these rocks from older sedimentary materials, and with the old zircons being a restite component. More importantly, they show that the more mafic S-type granites cannot have been complete melts. Chappell *et al.* (2000) have pointed out that the zircon saturation temperatures (Watson

& Harrison 1983) for the most mafic granites of the Bullenbalong Suite are 810 ± 20 °C. These values represent the maximum temperature at which melts of such compositions could have retained old zircon. Also those estimates must be too high because a large fraction of the Zr in those rocks, that in the older zircons, was not part of a melt. If 50% of the Zr in those mafic S-type granites occurs in older zircon, a reasonable minimum estimate, then the maximum temperature for such melt compositions to have retained that older zircon would have been 750 °C. Temperatures of 750-800 °C are too low for such bulk rock compositions to have been melts, and the presence of a significant restite component, in addition to the old zircon, is inferred in the original magma, along with a more felsic melt.

An alternative possibility is that the more mafic S-type granites containing abundant inherited zircon are cumulative rocks, and for that reason do not represent melt compositions. If this were so then the calculated temperatures would be incorrect. Also, the melts involved in the production of these rocks, being more felsic, would have existed at lower temperatures. However, even if the granites are cumulative, this is not a critical problem for the calculation of zircon saturation temperatures, which are relatively insensitive to changes in bulk composition. For example, 66 analysed granites of the Bullenbalong Suite cover a range from the most mafic S-type granites of the LFB to quite felsic compositions. There is one felsic granite with, for example, much lower abundances of Sr and Zr, that is clearly a melt composition that evolved through fractional crystallisation to lower temperatures, calculated at 751 °C. For all other analysed rocks of this suite the range in zircon saturation temperatures is from 771 to 827 °C. The question is whether some of the more felsic granites towards the lower end of that temperature range might represent melt compositions from which the more mafic rocks formed by the accumulation of certain minerals. However, apart from some granites of the Koetong Supersuite of the Wagga Batholith, which have high Sr contents indicating feldspar accumulation (Chappell & White 1998), and despite intensive sampling, there are no other analysed S-type granites of the LFB that show an enrichment in elements corresponding to possible early-formed minerals. The enrichment of some granites in Sr, indicative of feldspar accumulation, has only been observed in *some* more mafic rocks of the Koetong Supersuite, and also not in other suites. If the mafic S-type granites of the LFB are, in general, cumulative rocks, then such discontinuities in passing from melt compositions to more mafic "cumulative" compositions should be quite widespread. Further, Wyborn *et al.* (1981) pointed out that the compositions of the S-type granites of the LFB correspond broadly with those of the S-type volcanic rocks, and the latter overall are not more felsic than the granites. Certainly the composition of volcanic rocks can be affected by the accumulation of crystals. However, if such a process were generally responsible for the production of more mafic compositions among both the granites and volcanic rocks, it would be reasonable to expect the former to be relatively more mafic in their compositions, with the erupted rocks containing a greater proportion of the more felsic rocks from which crystals had been removed. That is not the case for the S-type granites and volcanic rocks of the LFB.

The S-type granites of the LFB are often fairly closely associated with low-temperature I-type granites (Chappell *et al.* 1998), for which the more mafic magmas also contained a restite component. The production of all of those granites involved the partial melting of quartzofeldspathic rocks in the crust, so that they represent products of crustal recycling, rather than a new component of the crust.

Some S-type granites of the LFB, those of the Cooma Supersuite, have both chemical and isotopic compositions consistent with derivation from sources having compositions represented among the distinctive and widely exposed Ordovician sedimentary rocks. However, the bulk of the S-type granites have Na and Ca contents, which while they are lower than in the I-types, are too high for such a derivation. These much more abundant S-type granites were obtained from source materials more feldspathic than the exposed Ordovician sediments. Precisely what those more feldspathic source rocks were has been a major topic of debate. One view has been that the granites were derived from less mature and more feldspathic sedimentary source rocks than those generally exposed (e.g. Wyborn 1977; White & Chappell 1988; Chappell *et al.* 2000). Another has been that the source materials were mixtures of the Ordovician sedimentary rocks with feldspar-rich igneous rocks, either basaltic (Gray 1984) or tonalitic (Collins 1996).

The S-type granites of the LFB show such a diversity of features (White & Chappell 1988) that it could perhaps be argued that in many respects they provide the definitive occurrence of such rocks. First, they occur in all of the three environments recognised by White *et al.* (1974). However, their occurrences in a *regional aureole* setting are restricted, and the high grade metamorphic rocks associated with the production of the granite magmas are generally not seen, although they undoubtedly occur at depth. In the *contact aureole* environment, S-type granites are extensively development as large plutons in batholiths. Their *subvolcanic* occurrences include both large plutons intruded into related volcanic rocks and also small near-surface bodies. S-type volcanic rocks are widespread. Second, these S-type rocks range compositionally from quite mafic tonalites with colour indices of more than 25, to highly fractionated leucogranites. Granites with wide ranges in compositions can be grouped into suites (White *et al.* 2001). In the Koetong Suite, rocks representative of virtually the complete range of compositions can be brought together within that suite. Third, these granites developed compositionally in more than one way. The more mafic S-type granites are close to their source rocks in composition and when they evolved further, did so by the separation of more felsic melt from mafic restite. In some cases, the felsic melt underwent extensive modification by fractional crystallisation, and those evolved rocks are associated with significant tin mineralisation. That such evolved rocks can be traced continuously in composition to others of quite mafic compositions means that these S-type suites of the LFB are important in understanding the evolution of the evolved peraluminous granites, which more commonly occur elsewhere in the absence of their less fractionated precursors.

There are areas of debate about the S-type granites of the LFB. What precisely were their source rocks? What were the ages of those sources? What do the enclaves tell us about those source materials? Do the enclaves include a component of mafic igneous rocks that would suggest a corresponding component is present in the granite magmas? What was the source of heat that produced such massive partial melting events? What was the tectonic regime in which that heating occurred? How did the magmas leave their source regions and in what manner did they intrude the upper crust, often to erupt at the surface? What is the nature of the relationship with the I-type magmas and are there mixtures of the two types? What was the cause of the variations in isotopic compositions? What are the relative roles of fractional crystallisation and restite fractionation in producing compositional variation? Can hydrothermal alteration still be regarded as playing a role in production of the most felsic rocks? Universal agreement does not exist on any of these questions. Therefore it is appropriate to hold a symposium in January 2001, where points such as these can be discussed. And to highlight a significant aspect of earth science that has developed from the observations of Allan White in the Berridale Batholith more than 30 years ago.

References

BAKER G. 1940. Cordierite granite from Terip Terip, Victoria. *American Mineralogist* **25**, 543-548.

BALL C.W., DALLWITZ W.B. & NOAKES L.C. 1948. Geological reconnaissance of the proposed hydro-electric works in Kosciusko area between Waste Point and Khankoban. *Bulletin of Mineral Resources, Australia, Record* **1948/7**.

BROWNE W.R. 1929. An outline of the history of igneous activity in New South Wales till the close of the Palaeozoic Era. *Proceedings of the Linnaean Society of New South Wales* **54**, 9-34.

CHAPPELL B.W. 1966. Petrogenesis of the granites at Moonbi, New South Wales. PhD thesis, Australian National University, Canberra (*unpubl.*).

CHAPPELL B.W. 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* **46**, 535-551.

CHAPPELL B.W., BRYANT C.J., WYBORN D., WHITE A.J.R. & WILLIAMS I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* **48**, 225-236.

CHAPPELL B.W. & WHITE A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

CHAPPELL B.W. & WHITE A.J.R. 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1-26.

CHAPPELL B.W. & WHITE A.J.R. 1998. Development of P-rich granites by sequential restite fractionation and fractional crystallisation: the Koetong Suite in the Lachlan Fold Belt. *Acta Universitatis Carolinae, Geologica* **42**, 23-27.

CHAPPELL B.W. & WHITE A.J.R. 2001. Two contrasting granite types – 25 years later. *Australian Journal of Earth Sciences* (*in press*).

CHAPPELL B.W., WHITE A.J.R. & HINE R. 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

CHAPPELL B.W., WHITE A.J.R., WILLIAMS I.S., WYBORN D. & WYBORN L.A.I. 2000. Lachlan Fold Belt granites revisited: high- and low-temperature granites and their implications. *Australian Journal of Earth Sciences* **47**, 123-138.

CHAPPELL B.W., WHITE A.J.R. & WYBORN D. 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

COLLINS W.J. 1996. Lachlan Fold Belt granitoids: products of three-component mixing. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 171-179.

GRAY C.M. 1984. An isotopic mixing model for the origin of granitic rocks in southeastern Australia. *Earth and Planetary Science Letters* **70**, 47-60.

HILLS E.S. 1938. Andalusite and sillimanite in uncontaminated igneous rocks. *Geological Magazine* **75**, 296-303.

HINE R., WILLIAMS I.S., CHAPPELL B.W. & WHITE A.J.R. 1978. Contrasts between I- and S-type granitoids of the Kosciusko Batholith. *Journal of the Geological Society of Australia* **25**, 219-234.

HURLEY P.M., BATEMAN P.C., FAIRBAIRN H.W. & PINSON W.H. Jr. 1965. Investigation of initial $^{87}Sr/^{86}Sr$ ratios in the Sierra Nevada Plutonic Province. *Bulletin of the Geological Society of America* **76**, 165-174.

JOPLIN G.A. 1942. Petrological studies in the Ordovician of N.S.W. I. The Cooma Complex. *Proceedings of the Linnaean Society of New South Wales* **67**, 156-196.

JOPLIN G.A. 1962. An apparent magmatic cycle in the Tasman Geosyncline. *Journal of the Geological Society of Australia* **9**, 51-69.

JOYCE A.S. 1970. Geochemistry of the Murrumbidgee Batholith. PhD thesis, Australian National University, Canberra (*unpubl.*).

JOYCE A.S. 1973. Petrogenesis of the Murrumbidgee Batholith, A.C.T. *Journal of the Geological Society of Australia* **20**, 179-197.

LAMBERT I.B. & WHITE A.J.R. 1965. The Berridale Wrench Fault: a major structure in the Snowy Mountains of New South Wales. *Journal of the Geological Society of Australia* **12**, 25-33.

OWEN M. & WYBORN D. 1979. Geology and geochemistry of the Tantangara and Brindabella 1:100 000 sheet areas. *Bulletin of Mineral Resources, Australia, Bulletin* **204**, 52 pp.

PIDGEON R.T. & COMPSTON W. 1965. The age and origin of the Cooma granite and its associated metamorphic zones. *Journal of Petrology* **6**, 193-222.

READ H.H. 1948. Granites and granites. *In* Gilluly, J. (ed.) *Origin of granite*. The Geological Society of America Memoir **28**, 1-19.

TATTAM C.M. 1925. Contact metamorphism in the Bulla area. *Proceedings of the Royal Society of Victoria* **37**, 230-247.

WATSON E.B. & HARRISON T.M. 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* **64**, 295-304.

WHITE A.J.R., ALLEN C.M., BEAMS S.D., CARR P.F., CHAMPION D.C., CHAPPELL B.W., WYBORN D. & WYBORN L.A.I. 2001. Granite suites and supersuites of southeastern Australia. *Australian Journal of Earth Sciences* (*in press*).

WHITE A.J.R. & CHAPPELL B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

WHITE A.J.R. & CHAPPELL B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

WHITE A.J.R., CHAPPELL B.W. & WILLIAMS I.S. 1977. *Geology of the Berridale 1:100 000 Sheet (8625)*. Geological Survey of New South Wales, Sydney.

WHITE A.J.R., CHAPPELL B.W. & WYBORN D. 1999. Application of the restite model to the Deddick Granodiorite and its enclaves: a re-interpretation of the observations and data of Maas *et al.* (1998). *Journal of Petrology* **40**, 413-421.

WHITE A.J.R., CHAPPELL B.W. & CLEARY J.R. 1974. Geologic setting and emplacement of some Australian Paleozoic batholiths and implications for intrusive mechanisms. *Pacific Geology* **8**, 159-171.

WHITE A.J.R., WILLIAMS I.S. & CHAPPELL B.W. 1976. The Jindabyne Thrust and its tectonic, physiographic and petrogenetic significance. *Journal of the Geological Society of Australia* **23**, 105-112.

WILLIAMS I.S. 1995. Zircon analysis by ion microprobe: the case of the eastern Australian granites. *Leon T. Silver 70th Birthday Symposium and Celebration*, The California Institute of Technology, 27-31.

WYBORN D., CHAPPELL B.W. & JOHNSTON R.M. 1981. Three S-type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research* **86**, 10335-10348.

WYBORN L.A.I. 1977. Aspects of the geology of the Snowy Mountains region and their implications for the tectonic evolution of the Lachlan Fold Belt. PhD thesis, Australian National University, Canberra (*unpubl.*).

WHAT PLAGIOCLASE CAN TELL US ABOUT THE PETROGENESIS OF THE JINDABYNE SUITE

Charlotte M. Allen

Ore Genesis Group, Research School of Earth Sciences, Australian National University, Canberra ACT 0200

The Jindabyne Suite was one of the I-type suites used by Chappell & White (1974) to propose the subdivision of I- and S-type granites. It was described by Hine *et al.* (1978). Nine plutons have been grouped in the Jindabyne Suite (Bugtown, Fentonville, Biggam, Round Flat, Gaden, Jindabyne, Pendergast, Moonbah, and Grosses Plain). This grouping is relatively uncontroversial; on the other hand, the petrogenesis of the suite is.

The Jindabyne Suite is an excellent example of the suite classification concept because it has mineralogical features that make it distinct from other rocks in the vicinity. The suite comprises rocks of quartz diorite and more abundant tonalite compositions. Gabbros were initially considered a part of the suite (Hine *et al.* 1978) but later removed on geochemical grounds (White & Chappell 1989). The diagnostic features of the suite are high anorthite cores (>An_{70}) in plagioclase and the absence of titanite in the hb+bt+mt±cpx intermediate rocks that might otherwise be expected to contain it.

To date, three main rival models have been put forth for the petrogenesis of this suite. Chappell, White and coworkers have advocated a restite unmixing origin to explain the diversity of rock types. Moreover, Chappell *et al.* (1998) classified the Jindabyne Suite as a 'low-temperature I-type'. Wall *et al.* (1987) advocated an origin of variation within the Jindabyne Suite by fractional crystallisation. Cousins *et al.* (1998) have proposed that three end-member magmas mixed then fractionated to form the Jindabyne Suite. Importantly they use the most mafic rock in the area, the Blind Gabbro, as one end-member.

In hand specimen, the Jindabyne Suite is unusual as compared to Cordilleran tonalites in that it is compositionally restricted; modal K-feldspar is very sparse. Biotite (and hornblende) crystallised early in the Jindabyne Suite, sequestering potassium, and indicating a water-rich magma early in the crystallisation process. Likewise, very high anorthite contents of plagioclase in intermediate to mafic rock compositions can be achieved in water-rich igneous environments; such anorthitic plagioclases are not necessarily the product of melting reactions (restite).

Preliminary, detailed trace element data from plagioclase using the LA-ICP-MS limits the models mentioned above. Plagioclase from three rocks provided by W. Collins and S. Cousins were analysed: Blind Gabbro, and two Jindabyne tonalites, one relatively felsic. In the tonalites, plagioclases are tripartite: $An_{>70}$, An_{60-40} and $An_{<30}$. Whereas many of the high An cores have discrete boundaries, some euhedral and some anhedral, the boundaries between the other zones are less well-defined. Gabbros contain plagioclase more calcic than An_{70}. Spot analysis of plagioclase in the Blind Gabbro yielded trace element patterns distinct from all plagioclase analyses from the tonalites. In all results, there is a pronounced positive Eu anomaly, but relative to the tonalites, Blind Gabbro plagioclases have much flatter LREE patterns, lower REE concentrations, and very low Pb contents (1-5 ppm). Several elements vary systematically with An content in the gabbro. For instance Pb, Sr, La, and Eu increase with decreasing anorthite content ($An_{93\ \mathrm{to}\ 82}$) but Eu/Eu* becomes smaller. Sr ranges from 545 to 865 ppm, and La from 0.5 to 6.0 ppm. Tonalite plagioclases contain five to ten times the Pb content (11-30 ppm) of those from the gabbro and even the most An-rich plagioclases from the tonalites (An_{91-70}) have greater REE concentrations (La = 6.7 to 15.8 ppm). The patterns of *all* anorthite zones from the tonalites are similar with only an increase of the size of Eu anomaly and somewhat reduced Sr contents being conspicuous in the Ca-poorest plagioclase. Sr in the three anorthite zones, high, medium and low, respectively, have Sr contents of 880-550, 540-380, and 430-360ppm. Eu/Eu* increases in the most albitic plagioclase by virtue of both decreased LREE and increased Eu.

These findings rule out a direct contribution of An-rich plagioclase from gabbros into the tonalites by some mixing process. It is unlikely that this plagioclase crystallised from a magma related to the Jindabyne Suite; the Blind Gabbro should be relegated to its own suite, as advocated by White & Chappell (1989). Furthermore, the trace element pattern similarity of cores, mantles and rims of plagioclase from Jindabyne tonalites points to some continuous process - fractional crystallisation with variation of a_{H_2O} could be considered the most likely.

References

CHAPPELL B.W., BRYANT C.J., WYBORN D., WHITE A.J.R. & WILLIAMS I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* **48**, 225-235.

CHAPPELL B.W & WHITE A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

COUSINS S., COLLINS W.J., MCCULLOCH M.T. & ANDREW A. 1998. Crust-mantle mixing in the I-type Jindabyne Suite: a Nd-Sr-O isotope study. *Geological Society of Australia, Abstracts* **49**, 95.

HINE R., WILLIAMS I.S., CHAPPELL B.W. & WHITE A.J.R. 1978. Contrasts between I- and S-type granitoids of the Kosciusko Batholith. *Journal of the Geological Society of Australia* **25**, 219-234.

WALL V.J., CLEMENS J.D. & CLARKE D.B. 1987. Models for granitoid evolution and source compositions. *Journal of Geology* **95**, 731-749.

WHITE A.J.R. & CHAPPELL B.W. 1989. Geology of the Numbla 1:100,000 sheet 8624. New South Wales Geological Survey, 160 pp.

GEOLOGICAL ASPECTS OF METASEDIMENTARY ENCLAVES FROM THE PYALONG "S-TYPE" GRANITE, CENTRAL VICTORIA, AUSTRALIA

J.A.C. Anderson[1,2], P.D. Fleming[1] & R.C. Price[1,3]

[1]Department of Earth Sciences, La Trobe University, Vic 3086, Australia
[2]Johnsons Well Mining N.L., Leonora, WA 6438, Australia
[3]School of Science and Technology, University of Waikato, Hamilton, New Zealand

Introduction

Enclaves have long been recognised as distinctive features of Lachlan Fold Belt (LFB) granites (e.g. White & Chappell 1977; Vernon 1983), although their significance in granite petrogenesis has been interpreted in contrasting ways (e.g. Maas *et al.* 1997, compared with White *et al.* 1999). It has been argued that biotite-rich, tectonised enclaves were derived from sedimentary precursors (e.g. Price 1983) and are commonly termed "metasedimentary enclaves" (MSE). Enclaves of this type occur in both I- and S-type granites of the LFB but are much more abundant in the latter. Fleming (1996) proposed that many MSE preserve the structural history of the crust from which they are derived; either that of the granitic source region or that of the wall-rocks through which the granite host passed on the way to the level of emplacement. In this study, MSE from a single LFB granite body have been examined to determine the relationship between this type of enclave and the granitic host.

The granite unit chosen for study is the S-type Pyalong Adamellite (White & Chappell 1988), one of two principal units of the central Victorian Cobaw Complex; the other main unit is the Baynton Granodiorite. The Pyalong Adamellite forms a 1-6 km wide rim covering an area ~ 225 km^2, surrounding the central units of the Complex. The intrusion has been dated at 359 ± 7 Ma (biotite K-Ar; Stewart 1971) and is considered typical of central Victorian Devonian S-type granites. Mineralogically, the adamellite comprises orthoclase, quartz, plagioclase and red-brown biotite, with minor cordierite, apatite, monazite, zircon, and ilmenite. Enclaves are common in this intrusion, which was emplaced across the boundary between two major tectonostratigraphic zones. The country rocks of the complex include Ordovician sediments to the west, a central strip of Cambrian rocks (marking the eastern boundary of the Bendigo-Ballarat Zone), and Silurian sediments to the east (Melbourne Zone).

Enclaves

Enclaves overall constitute < 1% of total outcrop within the Pyalong Adamellite but are locally abundant (> 10% of outcrop). The abundance of MSE (up to 10% of outcrop) increases with proximity to the inner contact with the Baynton Granodiorite, especially in a zone located ~ 250 m from the inner contact. Hornfels fragments (hornblende-hornfels facies) are common within 250 m of the outer contact of the intrusion but are rare elsewhere. MSE include quartz-rich and felsic schistose metasedimentary varieties, quartz- and biotite-deficient cordierite-orthoclase types, quartz fragments, biotite-rich mafic clots, and types reminiscent of regional metamorphic rocks such as migmatites, quartzofeldspathic gneisses, and calc-silicates. We suggest that the different varieties represent an intrinsic separation into enclaves that have undergone partial melting and those that have not. The mineralogy of the MSE is type-dependent, but the assemblage extant in the predominant schistose variety typically includes quartz, alkali feldspar, plagioclase and biotite, with lesser fibrolitic sillimanite, zircon, monazite, apatite and ilmenite. Cordierite is an important mineral in many MSE, and relics of garnet, spinel and corundum also occur. This assemblage is consistent with derivation from the middle crust under upper amphibolite facies conditions.

Rb/Sr isotopic characteristics of the adamellite and the MSE are distinctly different from those of the exposed Silurian and Ordovician country rocks, precluding the possibility that the adamellite and its enclaves have been locally derived. Sm/Nd isotopic data also indicate that the MSE are not representative of the source rocks of the host adamellite. MSE that have not been depleted by partial melting have CaO and Na_2O contents in excess of routine LFB flysch, which precludes local derivation.

Discussion

Anderson *et al.* (1998) have shown that the deformation histories preserved in MSE from granites across the southern LFB are similar to each other, but the MSE show more complex deformation than the Ordovician or Silurian country rocks surrounding the host intrusions. The Pyalong Adamellite intruded after the second of three deformations recognised in the country rocks, yet some MSE preserve four deformations. Superficially this implies that the granites and their MSE were derived from a complexly deformed, pre-Ordovician basement. However, SHRIMP U/Pb data (J.A.C. Anderson *et al.* unpub. data) indicate that the zircon populations of the Pyalong Adamellite and its MSE include a post-Proterozoic component; inheritance patterns in the MSE are identical to those established for the Ordovician LFB flysch. Although the exact age of the sedimentary component in the adamellite is equivocal, the MSE are almost certainly derived from unexposed and geochemically distinctive Ordovician material that has experienced a different deformation history from that preserved in the country rocks surrounding the pluton. This also suggests a structurally heterogeneous crust in the region. The MSE could represent samples of a metasedimentary basement underlying the presently exposed country rocks, but Sm/Nd isotopic data may preclude the possibility that the adamellite was directly derived from an MSE-like source. The MSE appear to be accidental xenoliths of an unexposed Ordovician terrane and were not a significant component contributing to the generation of the magma represented by their host granite. They do, however, provide information about the composition and structural history of unexposed segments of the deeper crust.

References

ANDERSON J.A.C., PRICE R.C. & FLEMING P.D. 1998. Structural analysis of metasedimentary enclaves: implications for tectonic evolution and granite petrogenesis in the southern Lachlan Fold Belt, Australia. *Geology* **26**, 119-122.

FLEMING P.D. 1996. Inherited deformation structures in metasedimentary enclaves in granites as "windows' into deeper levels of the crust. *Tectonophysics* **267**, 177-185.

MAAS R., NICHOLLS I.A. & LEGG C. 1997. Igneous and metamorphic enclaves in the S-type Deddick Granodiorite, Lachlan Fold Belt, SE Australia. *Journal of Petrology* **38**, 815-841.

PRICE R.C. 1983. Geochemistry of a peraluminous granitoid suite from NE Victoria, Australia. *Geochimica et Cosmochimica Acta* **47**, 31-42.

STEWART A.J. 1971. K-Ar dates from the Cobaw Granite, Central Victoria. *Proceedings of the Royal Society of Victoria* **84**, 213-215.

VERNON R.H. 1983. Restite, xenoliths and microgranitoid enclaves in granites. *Journal and Proceedings of the Royal Society of New South Wales* **116**, 77-103.

WHITE A.J.R. & CHAPPELL B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

WHITE A.J.R. & CHAPPELL B.W. 1988. Petrology of igneous rocks. *In:* Douglas J.G. & Ferguson J.A. eds. *Geology of Victoria*, pp. 427-439. Geological Society of Australia, Melbourne.

WHITE A.J.R., CHAPPELL B.W. & WYBORN D. 1999. Application of the restite model to the Deddick Granodiorite and its enclaves – a reinterpretation of the observations and data of Maas *et al.* (1997). *Journal of Petrology* **40**, 413-421.

METALLOGENIC SIGNIFICANCE OF PALAEOPROTEROZOIC GRANITES (S- AND I-TYPE) IN THE PINE CREEK OROGEN, NORTHERN TERRITORY, AUSTRALIA

Zia U Bajwah

Northern Territory Geological Survey, Department of Mines and Energy, Darwin NT 0801, Australia

During the Palaeoproterozoic, the Pine Creek Orogen was the site of massive intrusive activity, which led to the emplacement of large numbers of plutons in the western (Litchfield Province) and central part of the region. These granites intrude the orogenic sequence, which was deformed and metamorphosed during the 1880–1850 Ma Barramundi Orogeny (Page 1997). The sequence is underlain by late Archaean granite-gneiss complexes (2700–2500 Ma, zircon U-Pb data), and is in turn overlain by relatively undeformed rocks of the McArthur and Victoria-Birrindudu Basins.

In the Litchfield Province, syn- to post-orogenic granites were emplaced during 1860–1835 Ma, based on Rb-Sr isotopic data (Page *et al.* 1984), and are mainly confined to the west of the Giants Reef Fault. They are commonly foliated but massive porphyritic and pegmatitic phases exist. Among these, the Two Sisters, Soldiers Creek, Jammine and Allia Creek Granites are associated with Sn-Ta mineralisation. The constituent minerals in these granites are quartz, K-feldspar, plagioclase, biotite, muscovite ± garnet ± sillimanite (De Ross 1987). Chlorite and sericite as a result of alteration are present in many rocks. Accessory minerals are tourmaline, apatite, zircon ± ilmenite ± monazite. Mafic inclusions contain quartz, biotite, muscovite and feldspars. Geochemically, they are low in Na_2O, CaO and high in Al_2O_3, whereas K_2O is moderate. Mol. $Al_2O_3/(Na_2O + CaO + K_2O)$ indicates that they are peraluminous. Sr is low whereas Rb is moderately high. These features resemble those of S-type granites (Chappell & White 1974). Petrological and geochemical data indicate further that they are reduced fractionated granites.

In the Central Region, intrusive activity (1835–1800 Ma) is represented by the emplacement of the Cullen Batholith and several other satellite plutons. Some of these (e.g. Allamber Springs, Tabletop, Tennyson and Mount Bundey) are related to gold, base metal and uranium mineralisation (Bajwah 1994). These granites are mainly I-type and contain quartz, K-feldspar, plagioclase, biotite and hornblende. Accessory minerals are apatite, magnetite, sphene, zircon, allanite, epidote, fluorite ± monazite. An important feature is the development of weak diffuse hydrothermal alteration throughout, represented by chloritisation and sericitisation. These granites are generally high in K_2O, CaO, Na_2O and low in Al_2O_3 (metaluminous to weakly peraluminous) compared to their counterpart S-type granites in the region. Magnetic susceptibility measurements indicate that they belong to the magnetite-series granites. Geochemically, these granites are distinct and are characterised by elevated levels of Ba, Rb, Sr U and particularly LREE.

Geological, petrological and geochemical data suggest that the S-type granites were derived from hydrous silicate melt, produced during partial melting of sedimentary rocks at temperatures of 680-750 °C. It appears that fractionation and differentiation were responsible for further saturation of the magma in water and a vapour phase, which ultimately led to the formation of pegmatite and greisens. In the final stages of magma consolidation, evolution of a supercritical fluid phase rich in K, B, Cl, Sn and Ta took place; this was responsible for mineralisation. In contrast, the I-type granites of the Central Region were derived from partial melting of igneous rocks. The melt produced was probably anhydrous (> 900 °C). Fractional crystallisation played a major role during magma ascent and crystallisation, enriching the late residual melt in H_2O and other volatiles, and in metals. Initially, fO_2 was high, and progressively increased as magma went through the final stages of differentiation. Close to the solidus, separation of melt-rich fluids (gold, base metals and uranium) responsible for mineralisation in the adjacent metasediment, took place.

The metallogenic significance of these granites is attributed to the first order suite classification (S- and I-types). These characteristic features are inherited from the processes of magma generation from contrasting source rocks and subsequent crystallisation histories under variable physico-chemical conditions. These contrasting styles of mineralisation have also been reported from various areas, and an understanding of these is important in area selection for mineral exploration.

References

BAJWAH Z.U. 1994. A contribution of geology, petrology and geochemistry to the Cullen Batholith and related hydrothermal activity responsible for mineralisation, Pine Creek Geosyncline, Northern Territory. *Northern Territory Geological Survey, Report* **8**.

CHAPPELL B.W. & WHITE A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

DE ROSS G. 1987. The geochemistry and petrology of the granites of the Litchfield Province. *Northern Territory Geological Survey, Technical Report* **GS1987/15** (unpubl.)

PAGE R.W. 1997. Some key geochronological constraints for Palaeoproterozoic crustal evolution of northern Australia. *Australian Geological Survey Organisation, Record* **1997/44**.

PAGE R.W., BOWER M.J. & GUY D.B. 1984. Isotopic study of Early Proterozoic granitoids in the Litchfield Block, Northern Territory. *BMR Journal of Geology and Geophysics* **9**, 219-223.

METALLOGENY OF S-TYPE GRANITES

Phillip L Blevin

PetroChem Consultants Pty Ltd, PO Box 1270 Tuggeranong ACT 2900

S-type granites are the principal source of Sn and W, and are historically important sources of U. There are two important features of these granites that set their metallogeny apart from other granite types. First, only the most felsic and most fractionated S-types are strongly mineralised. Second, the ore element assemblages that characterise the high temperature, proximal centres of S-type mineralising systems (the core element assemblage), are relatively restricted in diversity, being dominated by Sn and/or W. Halogens (F, Li, B, Be) and Nb-Ta may also comprise core element assemblages in less common examples and in related pegmatites. This contrasts with Sn, W, Mo, Au, Cu, REE, halogens, etc that may represent core element associations in mineralising systems that are related to I-type granites.

Factors determining the metallogeny of S-type granites

The relatively restricted core element assemblages that characterise S-type metallogeny is a function of several interrelated factors linked to source, intensive-variable and source-based considerations.

S-type granites, being derived from mature metasedimentary materials, are endowed with typical crustal abundances of ore-forming elements. These elements are either concentrated or depleted in the melt during fractional crystallisation depending on the magma compositional parameters (ASI) and intensive variables (fO_2, fS_2) etc. The high (and low) concentrations of elements such as Sn, W, Th, F, B, etc, versus Cu, Mo, Au, are a result of these processes rather than "specialised" processes or inheritance. While Nd and Sr isotopic compositions of S-types vary according to the age of their source materials, the fundamental metallogenic character of both isotopically evolved (Lachlan type) and relatively unevolved (eg. New England Orogen) S-type granite suites remains the same.

The role of fractional crystallisation processes is also critical in determining the metallogenic potential of S-type granites. S-type granite suites that do not show chemical and petrographic evidence for pronounced fractional crystallisation are invariably unmineralised. Although the "restite model" remains controversial, there is a simple elegance in the way in which the observed behaviour of ore-forming elements, and the occurrence of mineralisation in S-types, can be accounted for using this hypothesis.

S-type granites are also typically reduced. Relative oxygen fugacities range from FMQ (fayalite-quartz-magnetite) to strongly reduced (ΔFMQ = -3, e.g. the S-type granites of central Victoria). The relatively poor correlation between the ASI (Aluminium Saturation Index) and fO_2 for eastern Australian S-type granites is good evidence for source-related factors on the relative oxidation of S-type magmas as the primary control, rather than melt composition and structure. Early sulfide precipitation would be expected in these reduced magmas, presumably removing chalcophile elements from the melt phase. In addition to the effect on S behaviour, fO_2 determines the absence of primary magnetite and titanite in S-type magmas. This robs Sn of a crystalline phase to partition into during crystallisation, thus encouraging its retention within the melt. Mo however finds ready sites in ilmenite and perhaps biotite. Ore-forming elements contained within the unmelted restite portion of magmas would also be unavailable for incorporation into the melt fraction and any subsequent exsolving hydrothermal phase.

Metal associations and mineralisation

S-type granites are only strongly mineralised when highly fractionated and then in a relatively restricted range of core ore element assemblages dominated by Sn and/or W-centred systems. High temperature core signatures to these systems are usually Sn ± B, W-Sn ± B, F, Sn-B-Be, etc. Sn-centred systems can be subdivided into F or B-dominant, with the latter typically characterised by deposits hosted in tourmaline-cemented breccia, indicating explosive degassing. Pegmatites may or may not be present. Zonation with falling temperature is typically Sn → Cu → Zn-Pb-Ag (± Au) to distal As and F. Alternatively ore zoning may be around high temperature W with proximal Sn followed by Cu → Zn-Pb-Ag, etc. Ba ± F-Pb associations are also common. Cu may comprise a distinct zone in some systems. Bi may be well represented in places, as can even be Mo. Pegmatite mineralisation can include Nb and Ta in addition to halogens. U mineralisation is also associated with S-type granites following its accumulation within the melt during extended fractional crystallisation.

Secondary deposits of Sn, monazite, ilmenite, zircon and U can be derived from S-type granites. Such granites can also act as chemical traps for mineralised fluids. The reduced nature of these granites may act as a reductant on externally sourced hydrothermal fluids. This is often the case for Au-bearing fluids of either igneous or meta-hydrothermal origin. The efficiency of this reductant capacity of S-type granites is hampered, however, by their usually relatively low total Fe contents.

Mineralisation associated with fractionated S-type granites also retains and amplifies characteristics of strongly fractionated peraluminous melts. These include elevated U/Th ratios, depleted Th, Y (HREE), and elevated P contents. Apatite and monazite are common as accessory minerals in S-type greisens and as a hydrothermal vein accessory in some S-type W and Sn deposits, whereas allanite, xenotime (± monazite) are more typical REE-bearing assemblages of I-type granite greisens. These contrasts are well "seen" in airborne radiometric images where highly fractionated S-type granites have elevated U and K channels, but low Th channels, while all three are elevated in I-type granites.

Exploration

Exploration for mineralisation in S-type granites should be focussed on the most evolved members of suites that show evidence for extended fractional crystallisation. These granites would be felsic, "near minimum melt' in character and have compositional characteristics diagnostic of extended fractional crystallisation (e.g. high Rb contents). Of course, a useful tool in Sn exploration is the recognition of historical Sn mining as a criterion for area selection. As an alternative, "green fields" exploration using granite composition should also be encouraged. Mineralising magmatic hydrothermal systems are also shallowly emplaced within the crust, but in order to be prospective should not be too deeply eroded. Mineralising S-type plutons are magnetically quiet, and may be associated with zones of hydrothermally induced low magnetism (except where marked precipitation of pyrrhotite has occurred). High K and U, but relatively low Th signatures on radiometric images would also be characteristic. Hydrothermal aureoles over buried granites should have the same radiometric character. Stream sediment dispersion haloes of F, B and Sn are characteristic.

A contrast with many Sn systems produced from I-type granites of intermediate oxidation states, is the tendency of the latter to produce dispersed primary mineralisation, characterised by ore districts where most tin is mined from placers shed from low grade deposits. Such granites, however, have similar hard rock deposit styles as their reduced S-type counterparts.

FRACTAL SIZE DISTRIBUTION OF PLUTONS: AN EXAMPLE FROM THE LACHLAN FOLD BELT, AUSTRALIA

Paul D. Bons[1] & Marlina A. Elburg[2]

[1]Tektonophysik - Institut für Geowissenschaften. Universität Mainz, D-55099 Mainz, Germany.
[2] Department of Geology and Geophysics, University of Adelaide, SA 5005, Australia.

Introduction

Many recurrent phenomena or events that can be assigned a certain magnitude or size obey a frequency distribution law that states that the number ($N_{>S}$) of "events" that are larger than size or magnitude S is related to S by:

$$N_{>S} = K \cdot S^{-m} \tag{1}$$

Here K is a constant related to the absolute number of events and m the distribution exponent. Such a distribution is termed fractal (Turcotte 1992). If S is expressed as a linear length scale, then m is the fractal dimension. This fractal distribution has been found to apply to a large range of phenomena, such as commodity prices, sizes of cities, frequency of word usage (Bak 1997, and references therein) and, in geology, earthquake frequencies, ore tonnage and hydrocarbon reservoirs (Turcotte 1992, and references therein), turbidite bed thicknesses (Rothman *et al.* 1994), and vein widths (Manning 1994; Clark *et al.* 1995).

Fractal pluton size distribution in the Lachlan Fold Belt

We measured the exposed areas of a population of 500 granitic plutons in a 150,000 km^2 area in the southeast of the Lachlan Fold Belt, Australia (Chappell *et al.* 1991; Chappell *et al.* 2000). This pluton population also follows a fractal distribution, with two distinct ranges where equation (1) holds. Small plutons (up to about 10 km^2) have a fractal dimension of $m = 0.7$, while larger plutons, up to 4000 km^2, have a fractal dimension of $m = 1.4$.

We explain the difference in exposed size distribution between the two ranges with the limited chance of small plutons to be exposed at the current surface. The larger plutons are all exposed, and we can therefore use their size distribution to get an insight into the whole population. This gives a total of about 1070 plutons larger than 1 km^2 that were intruded. About half of these are now exposed, while the other half is either buried beneath the current surface or completely eroded away.

Estimated total volume of all plutons

McCaffrey & Petford (1997) proposed a power-law relationship between height and horizontal length of plutons, based on collected data from plutons all over the world. Using this relationship, it is possible to estimate the total volume of all plutons in the study area, including those that are now not exposed. The estimated total volume is about $1 \cdot 10^5$ to $1.75 \cdot 10^5$ km^3. This corresponds to an estimated 0.7 to 1.2 km^3 per square kilometre when evenly spread out over the whole study area.

Size distribution of S- and I-type plutons

The 500 exposed plutons can be divided into different sub-populations, although not all plutons are classified by Chappell *et al.* (1991). I-types are the most numerous (234 plutons) and closely follow the pattern for all plutons, with $m = 1.6$. The 83 defined S-type granites have a distinctly shallower trend for the large plutons, with $m = 1.2$. The total number of

S-type plutons that once intruded is estimated at about 270. The shallower slope means that S-type granites come in relatively more large plutons than the rest of the granites. The plutons west and east of the "I-S line" (Chappell *et al.* 1988) show no difference in their size distribution.

References

BAK P. 1997. *How nature works - The Science of Self-Organized Criticality*. Oxford University Press, Oxford.

CHAPPELL B.W., WHITE A.J.R. & HINE R. 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

CHAPPELL B.W., ENGLISH P.M., KING P.L., WHITE A.J.R. & WYBORN D. 1991. Granites and related rocks of the Lachlan Fold Belt. Bureau of Mineral Resources, Geology and Geophysics, Canberra, Australia, scale 1: 1 250 000 map.

CHAPPELL B.W., WHITE A.J.R., WILLIAMS I.S., WYBORN D., & WYBORN L.A.I. 2000. Lachlan Fold Belt granites revisited: high- and low-temperature granites and their implications. *Australian Journal of Earth Sciences* **47**, 123-138.

CLARK M.B., BRANTLEY S.L. & FISHER D.M. 1995. Power-law vein-thickness distributions and positive feedback in vein growth. *Geology* **23**, 875-978.

MANNING C.E. 1994. Fractal clustering of metamorphic veins. *Geology* **22**, 335-338.

MCCAFFREY K.J.W. & PETFORD N. 1997. Are granite intrusions scale invariant? *Journal of the Geological Society, London* **144**, 1-4.

ROTHMAN D.H., GROTZINGER J.P. & FLEMINGS P. 1994. Scaling in turbidite deposition. *Journal of Sedimentary Research* **A64**, 59-67.

TURCOTTE D.L. 1992. *Fractals and Chaos in Geology and Geophysics*. Cambridge University Press, Cambridge.

EVIDENCE FOR MULTISTAGE PROCESSES LINKING RESIDUAL MIGMATITES DERIVED FROM METAPELITE TO S-TYPE LEUCOGRANITES

Michael Brown & Gary S. Solar

Laboratory for Crustal Petrology, Department of Geology, University of Maryland, MD 20742-4211, USA

We propose multistage processes of melting, fractional crystallisation and separation of residual and cumulate material from evolved liquid, to relate leucosomes and smaller-volume granites in lower crustal migmatites and granulites (largely composed of cumulate and residual phases) to S-type leucogranites in plutons emplaced in the middle and upper crust (largely crystallised from evolved liquid) (cf. White & Chappell 1977). The upper crust lies above the brittle-viscous transition; the crust below is separated by the transition to viscous anatectic flow into middle and lower crust. Thus, migmatites are typical of the upper amphibolite to granulite facies lower crust. Melt loss is demonstrated by the residual bulk composition of many regional migmatite and granulite terranes. The form of leucosomes in regional migmatites in orogens commonly is structurally controlled, and although leucosomes mostly have cumulate rather than melt compositions, they are inferred to demonstrate melt flow pathways in partially molten rocks (e.g. Brown *et al.* 1999). Thus, in metasedimentary protoliths, melt flows from grain boundaries to bedding-parallel leucosomes, to dilatant sites that link to form melt transfer networks, unless bulk flow disrupts primary structure. Similar features are observed from the onset of muscovite dehydration melting (lower melt loss, mildly residual rocks) to UHT conditions (higher melt loss, strongly residual rocks), although there are differences in detail in leucosome volume and distribution. In the middle and upper crust, leucogranites appear to have crystallised from the accumulated evolved melt extracted from the lower crust.

The processes that operate are illustrated by reference to migmatites and S-type leucogranites of the Acadian Metamorphic Belt of the Northern Appalachians, USA. We use structural, petrological and geochemical variations among migmatites and granites to test whether leucogranite in plutons is related to leucosomes and m-scale bodies of leucogranite in migmatites (Solar & Brown 2001b). In New Hampshire (NH) and Maine (ME), Siluro-Devonian turbidites of the Central Maine Belt were metamorphosed under high-T – low-P facies series conditions during deformation within a Devonian crustal-scale shear zone system defined by km-scale zones of apparent flattening (AFZs) that anastomose around lozenges of apparent constriction (ACZs) (Solar & Brown 1999, 2000, 2001a). At upper amphibolite facies, metapelitic rocks partly melted, the onset of which is recorded by a migmatite front that separates non-anatectic rocks, which deform by solid-state viscous flow, from anatectic rocks. Melting was initiated due to orogenic thickening and enhanced thermal energy from the decay of anomalous concentrations of heat-producing elements in parts of the metasedimentary protolith. The resulting migmatites are divided into stromatic and heterogeneous types that correspond to structural zones, which suggests that migmatisation was syntectonic (Solar & Brown 2001b). Further, m-scale granite bodies within the migmatites vary with type of migmatite – sheets in stromatic migmatite (in AFZs) and cylinders in heterogeneous migmatite (in ACZs) – to record evidence of syntectonic melt flow through deforming crust (Brown & Solar 1999). Work in NH (Lathrop *et al.* 1994) and ME (Brown & Pressley 1999; Pressley & Brown 1999) suggests that leucogranite in coeval syntectonic plutons (e.g. the Kinsman (NH) and Phillips (ME) plutons) was sourced from protoliths with geochemical characteristics similar to Central Maine Belt metasedimentary rocks, which raises the issue of genetic relations among migmatite and granite.

Migmatites have melt-depleted compositions relative to the metapelitic rocks, trending on Harker plots between residual phases (biotite, sillimanite and garnet), and quartz and the feldspars. Among the heterogeneous migmatites are schlieric granites which have cumulate compositions, most likely formed by fractional crystallisation of melt accumulated at the site, and loss from the site of the evolved liquid. Migmatite leucosomes are peraluminous, but they do not have compositions that could represent frozen primary liquids derived by muscovite dehydration partial melting of metapelite. We interpret leucosomes to represent the cumulate products of fractional crystallisation after variable loss of an evolved liquid. Smaller-volume granites are peraluminous with a wide range of compositions, but none of the analysed sample represents a primary melt composition. We interpret smaller-volume granites to be composed of variable amounts of entrained residual and cumulate quartz, plagioclase and biotite, together with some intercumulus melt that remained after loss of most of the evolved liquid. Common leucogranites of the Phillips pluton have a similar range of silica to the smaller-volume granites, but chemical compositions that suggest crystallisation of evolved liquids derived by fractional crystallisation of primary muscovite-dehydration melts. These data suggest that common leucogranites of the Phillips pluton could represent liquids extracted after approximately 20% fractional crystallisation from a migmatite source similar to that exposed nearby. Only granite from the largest of the smaller-volume bodies in the migmatites has a composition similar to common leucogranites of the Phillips pluton; it is interpreted to have a similar origin from an evolved liquid composition that was arrested during extraction from the partially molten source.

The growth of late retrograde muscovite in the migmatites is interpreted to be a response to migration of the volatile phase evolved on crystallisation of leucosomes and smaller-volume granites (Solar & Brown 2001b; cf. Kohn *et al.* 1997).

References

BROWN M. & PRESSLEY R.A. 1999. Crustal melting in nature: prosecuting source processes. *Physics and Chemistry of the Earth* (A) **24**, 3, 305-316.

BROWN M.A., BROWN M., CARLSON W.D. & DENISON C. 1999. Topology of syntectonic melt flow networks in the deep crust: inferences from three-dimensional images of leucosome geometry in migmatites. *American Mineralogist* **84**, 1793-1818.

BROWN M & SOLAR G.S. 1999. The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm. *Tectonophysics* **312**, 1-33.

KOHN M.J., SPEAR F.S. & VALLEY J.W. 1997. Dehydration-melting and fluid recycling during metamorphism: Rangeley Formation, New Hampshire, USA. *Journal of Petrology* **38**, 1255-1277.

LATHROP A.S., BLUM J.D. & CHAMBERLAIN C.P. 1994. Isotopic evidence for closed-system anatexis at midcrustal levels; an example from the Acadian Appalachians of New England. *Journal of Geophysical Research* **99**, 9453-9468.

PRESSLEY R.A. & BROWN M. 1999. The Phillips Pluton, Maine, USA: Evidence of heterogeneous crustal sources, and implications for granite ascent and emplacement mechanisms in convergent orogens. *Lithos* **46**, 335-366.

SOLAR G.S. & BROWN M. 1999. The classic high-*T* — low-*P* metamorphism of west-central Maine, USA: is it post-tectonic or syn-tectonic? Evidence from porphyroblast-matrix relations. *Canadian Mineralogist* **37**, 289-311.

SOLAR G.S. & BROWN M. 2000. The classic high-*T* — low-*P* metamorphism of west-central Maine, USA: is it post-tectonic or syn-tectonic? Evidence from porphyroblast-matrix relations. Reply. *Canadian Mineralogist* **38**, 1007-1026.

SOLAR G.S. & Brown M. 2001a. Deformation partitioning during transpression in response to Early Devonian oblique convergence, Northern Appalachian orogen, USA. *Journal of Structural Geology* **22** (in press).

SOLAR G.S. & BROWN M. 2001b. Petrogenesis of Migmatites in Maine, USA: Possible Source of Peraluminous Leucogranite in Plutons. *Journal of Petrology* **42** (in press).

WHITE A.J.R. & CHAPPELL B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

PROTEROZOIC S-TYPE GRANITES OF AUSTRALIA

Anthony R. Budd, Irina V. Bastrakova & Lesley A.I. Wyborn

Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601, Australia

S-type granites are rare in the Proterozoic of Australia, representing only 2.9% of mapped outcrop area of granites of that age. The Australian Geological Survey Organisation, in collaboration with state and territory geoscience organisations and universities, has completed a project on the "Metallogeny of Australian Proterozoic Granites (APG)". Geological, geochemical and geochronological data obtained from the public-domain (maps and commentaries, reports, theses, and journals), and from AGSO and state and territory geological survey databases, were gathered for some 650 units throughout Australia. More than 7000 geochemical analyses were used to assign the APG into ~ 90 suites and supersuites, using the criteria of White (1995). About 60 attributes, including field criteria (size, shape, mineralogy, alteration, *etc.*) and chemical criteria (31 geochemical variation diagrams) were assessed for each suite. These criteria were included in a report, and were coded (along with host rock and mineral occurrence data) into a GIS (Wyborn *et al.* 1998a). Although the principal aim of the project was to provide a metallogenic assessment of all APG as summarised in Wyborn *et al.* (1998b), numerous other conclusions were drawn from the dataset (e.g. Wyborn *et al.* 1998c and Wyborn *et al.* 1997), relating to the genesis of granites in the Australian Proterozoic and to the development of the Australian continent.

Obervations

The APG can be divided into I-type (88.8%), S-type (2.9%) and unclassified (8.3%). A key finding was the division of the APG into nine broad types (modified from Wyborn *et al.* 1992), of which two are S-type (Table 1) and occurring in 8 of the 19 Proterozoic provinces. Many APG that had previously been regarded as S-type on the basis of mineralogy (e.g. muscovite- or garnet-bearing) have now been shown not to be, using geochemical criteria (as per White *et al.* 1986). The vast majority of granites are I-granodiorite in composition; there are no I-tonalites (55-65% SiO_2, using the scheme of Chappell & Stephens 1988), and only 1.3% are I-trondhjemites (Na/K>4 – Maramungee type). The majority of granites (85.1% of total) are Sr-depleted and Y-undepleted (Kalkadoon, Nicholson, Cullen, Sybella and Hiltaba types); Wyborn *et al.* (1992) suggested that this indicates an elevated geotherm. Only 2.1% of I-types are Sr-undepleted and Y-depleted, represented by the Sally Downs type. Each of these granite types has a distinct metallogenic potential. The majority (~ 80%) of S-types show, at most, limited fractionation, and are represented by the Forsayth type, while the remainder, represented by the Allia type, are fractionated and associated with Sn mineralisation.

In general, the S-type APG are two-mica granites with coarse muscovite. Garnet is rare, and sillimanite and cordierite are even more so. Most of the Forsayth type are gneissic or migmatitic and/or exist in moderately to highly metamorphosed terranes, and contain metasedimentary xenoliths. The Allia type occur in greenschist facies terranes, are (deuterically) altered, and have common pegmatites

Table 1: Australian Proterozoic S-type suites

Suite	*Type*	*Province*	*Age (Ma)*	*Area km²*	*Character**	*Mineralisation*
Miltalie	Forsayth	Gawler	2015	200 km²	contact, restite	none
Bradshaw	Forsayth	Arnhem	1850	565 km²	contact, restite	none
Allia Creek	Allia	Pine Creek	1845	415 km²	contact, fractionated	Sn
Monaghans	Forsayth	Mount Isa	1804	<10 km²	contact, restite	none
Chararoo	Forsayth?	Gascoyne	1800	<2245 km²	contact, restite	none
Gin Creek	Forsayth	Mount Isa	1740	82 km²	regional, restite	none
Barrow Creek	Allia	Arunta	1713	245 km²	contact, fractionated	Sn
Potosi	Forsayth	Broken Hill	1690	459 km²	contact, restite	none
Forsayth	Forsayth	Georgetown	1550	1100 km²	regional, restite	none

* contact aureole *vs* regional aureole granites as used by White *et al.* 1986.

Why are there so few S-type granites?

Despite an evelated geotherm, significant metamorphic and thermal events and formation of deep basins, only 2.9% of APG are S-type. This contrasts strongly with the Palaeozoic Lachlan Fold Belt of eastern Australia where a little more than 50% of outcropping granites are S-type (Chappell & White 1992). Some deep sedimentary basins containing feldspathic greywacke were formed at times during the Proterozoic, but the majority of basins are terrestrial or shallow marine, containing carbonates, sandstones and shales. The most probable causes for there being so few S-type granites are either that source rocks were of infertile compositions, or that flysch sediments in the deep basins were too wet, causing any melt generated to solidify on ascent and to be not yet exposed.

Acknowledgements

David Champion, Phil Blevin and Roger Skirrow reviewed and constructively improved this abstract.

References

CHAPPELL B.W. & STEPHENS W.E. 1988. Origin of infracrustal (I-type) granite magmas, *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 71-86.

CHAPPELL B.W. & WHITE A.J.R. 1992. I- and S-type granites in the Lachlan Fold Belt, *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1-26.

WHITE A.J.R. 1995. Suite concept in igneous geology. Leon T. Silver 70th Birthday Symposium and Celebration, *Abstracts, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California.*

WHITE A.J.R., CLEMENS, J.D., HOLLOWAY, J.R., SILVER, L.T., CHAPPELL, B.W. & WALL, V.J. 1986. S-type granites and their probable absence in southwestern North America, *Geology* **14**, 115-118.

WYBORN L.A.I, WYBORN D., WARREN R.G. & DRUMMOND B.J. 1992. Proterozoic granite types in Australia: implications for lower crust composition, structure and evolution, *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 201-209.

WYBORN L.A.I., ORD A., HOBBS B. & IDNURM M. 1997. Episodic crustal magmatism in the Proterozoic of Northern Australia – a continuum crustal heating model for magma generation, *Australian Geological Survey Organisation, Record* **1997/44**, 131-134.

WYBORN L.A.I., BASTRAKOVA I.V. & BUDD A.R. 1998a. Using GIS in a data-driven, mineral systems approach to assess the mineral potential of Australian Proterozoic granites, *Geological Society of Australia, Abstracts* **49**, 480.

WYBORN L.A.I., BUDD A.R. & BASTRAKOVA I.V. 1998b. Australian Proterozoic granite-related ore systems, *Geological Society of Australia, Abstracts* **49**, 481.

WYBORN L.A.I., IDNURM M., BUDD A.R., BASTRAKOVA I.V., HAZELL M.S. & EDGECOMBE S.M. 1998c. What do ~ 10,000 whole rock geochemical analyses tell us about Australian Proterozoic intraplate igneous activity? *Geological Society of Australia, Abstracts* **49**, 484.

PALAEOZOIC S-TYPE GRANITES OF THE HODGKINSON PROVINCE, FAR NORTH QUEENSLAND

David C. Champion[1] & Robert J. Bultitude[2]

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601, Australia
[2]Geological Survey of Queensland, Dept of Mines and Energy, GPO Box 194, Brisbane, Qld 4001, Australia

Palaeozoic S- and I-type granites crop out extensively (~ 3400 km^2) in the eastern and central parts of the Ordovician–Devonian Hodgkinson Province of far north Queensland. S-types dominate and form two NW to NNW trending belts, sub-parallel to major structural elements in the province. They have been subdivided into two major (Cooktown, Whypalla) and five minor (Mount Alto, Wangetti, Tinaroo, Mount Formartine, Emerald Creek) supersuites (Bultitude & Champion, 1992; Champion & Bultitude, 1994). Most are Permian (~ 280–255 Ma); only the Emerald Creek and Mount Formartine Supersuites are older.

The high-level Cooktown Supersuite (CSS ~ 250 km^2) crops out in the easternmost part of the province. It consists of muscovite–biotite syenogranite and monzogranite, with widespread miarolitic cavities and granophyric intergrowths. Significant characteristics include the presence of minor cordierite (extensively altered) and tourmaline in most units, as well as rare garnet, sillimanite, and andalusite locally. Enclaves are generally scarce, although they make up to ~ 30% of a few units. The most common/significant enclaves are of quartz, metasedimentary gneiss, Hodgkinson Province rocks (mainly in contact zones) and rare biotite-rich 'microdiorite'.

Granites of the Whypalla Supersuite (WSS ~ 1800 km^2) are exposed W and SW of the CSS. They consist of muscovite–biotite monzogranite, minor syenogranite, and rare granodiorite. Accessory minerals include tourmaline and garnet (both early and late); rare sillimanite has also been reported. The widespread presence of minor garnet is characteristic. Early-formed orthopyroxene, partly replaced by biotite, is preserved in a relatively mafic, pressure-quenched unit. Enclaves are similar to those found in the CSS.

The minor S-type supersuites consist mainly of two-mica monzogranites with features similar to the WSS. Most notable are the garnet–tourmaline–muscovite-bearing granites of the Mount Alto and Wangetti Supersuites (MASS & WaSS). Tourmaline (up to 7%) was an early magmatic phase in these granites, biotite being scarce or absent. Another characteristic is the presence of large, irregular and interstitial, apatite grains. Such apatites are also found in the CSS, in some units of the WSS, and in the Mount Formartine Supersuite (MFSS).

The CSS granites are very felsic ($SiO_2 > 72\%$) and potassic, with major- and trace-element contents - e.g. low Ba, Sr, and moderate to high Rb, Sn - indicative of high degrees of fractionation. Al_2O_3, Na_2O, P_2O_5 ASI, and U increase with increasing SiO_2, whereas Th decreases. Marked depletions in LREE, Zr, HREE, and Y indicate significant fractionation of accessory phases such as zircon and monazite. The WSS granites ($SiO_2 > 71\%$) have many geochemical similarities with the CSS granites, and show similar trends. Noteworthy differences between the two supersuites include significantly higher CaO, Sr, Ba, Pb, and lower Rb, Sn, V, Cr in the WSS.

Granites of the Tinaroo Supersuite (TSS) and the older Emerald Creek Supersuite (ECSS), are very similar to the WSS. The late Devonian MFSS (Zucchetto *et al.* 1999) closely resembles the CSS, although it is more mafic (68-69% SiO_2). In contrast, the felsic granites (SiO_2 > 73%) of the WaSS and MASS are extremely fractionated. They show marked depletion in TiO_2, CaO, MgO, FeO*, strong enrichment in Al_2O_3 and P_2O_5 (especially the WaSS), and distinctive trends of decreasing K_2O and increasing Na_2O. Rb, Cs, U, Nb, Zn and Ga increase significantly whereas Ba, Sr, Th, Zr, Y, LREE, HREE, Eu, Cr and Ni decrease to very low levels with fractionation.

ε_{Nd} values (Champion & Bultitude 1994) for the Permian S-type granites range from -2.0 to -6.4 (14 analyses). Significantly, they overlap with those for Permian I-type granites of the Hodgkinson Province (-2.5 to -6.0), and are more primitive than the values for nearby Carboniferous I-type granites and older rocks to the west (-7 to -15 at 280 Ma). However, they do overlap with ε_{Nd} for an Ordovician granite (-6.0 at 280 Ma) exposed on the southeastern margin of the province.

Possible petrogenetic models for the generation of S-type granites, in general, range from crustal melting to multi-component mixing. The most obvious potential source for the north Queensland S-type granites is the voluminous quartzofeldspathic flysch of the Hodgkinson Province. However, most of these rocks are too mature, and with isotopic signatures (ε_{Nd} values of -11 to -15 at 280 Ma), reflecting their derivation from felsic rocks similar to those exposed in the Proterozoic inliers to the west. Volcanolithic arenites, with the appropriate ε_{Nd} value (-4.7 at 280 Ma), although not common, have been found in the far eastern part of the province. Consequently, Champion & Bultitude (1994) proposed a source protolith comprising both supracrustal and infracrustal arc-derived rocks, of late Proterozoic and/or early-middle Palaeozoic age. These rocks either form part of, or underlie the Hodgkinson Province assemblage. The presence of Devonian and Ordovician granites in the region, with similar chemical and isotopic signatures to the S-type granites, strongly indicates the existence of older protoliths capable of producing such granites.

Multi-component models are more difficult to evaluate. The scarcity of 'microdioritic' enclaves and other possible indicators of mixing/mingling in the Permian S-type granites, combined with the overlapping Nd isotopic signatures for the Permian S- and I-type granites, imply that magma mixing was not a significant factor. This does not rule out multiple-source components as implied by the range in ε_{Nd} values shown by the S-type granites. One possibility is a multi-component protolith comprising either a heterogeneous source (such as a mixture of supracrustal and infracrustal rocks) or, alternatively, a mixed source produced during a pre-Permian magmatic event that involved significant crustal (sedimentary) contamination. Both scenarios are compatible with the preferred model protolith described above.

References

BULTITUDE R.J. & CHAMPION D.C. 1992. Granites of the eastern Hodgkinson Province - their field and petrographic characteristics. *Queensland Department of Resource Industries Record* **1992/6**.

CHAMPION D.C. & BULTITUDE R.J. 1994. Granites of the eastern Hodgkinson Province. II. Their geochemical and Nd-Sr isotopic characteristics and implications for petrogenesis and crustal structure in north Queensland. *Queensland Department of Resource Industries Record* **1994/1**.

ZUCCHETTO R.G., HENDERSON R.A., DAVIS B.K. & WYSOCZANSKI R. 1999. Age constraints on deformation of the eastern Hodgkinson Province, north Queensland: new perspectives on the evolution of the northern Tasman Orogenic Zone. *Australian Journal of Earth Sciences* **46**, 105-114.

KOETONG SUITE OF THE LACHLAN FOLD BELT: SEQUENTIAL RESTITE CRYSTAL FRACTIONATION AND FRACTIONAL CRYSTALLISATION OF AN S-TYPE MAGMA

Bruce W. Chappell[1] and Allan J.R. White[2]

[1]GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia
[2]Department of Earth Sciences, La Trobe University, Vic 3086, Australia

S-type granites are the dominant igneous rocks in the Wagga Province of the Lachlan Fold Belt (LFB) and the majority of the granites of that region are assigned to the Koetong Suite, with a total exposed area of 6740 km^2. This is a little more than 10% of the area of all granites in the LFB. A unique feature of the granites of that suite, compared with other S-type suites of the LFB, is that they range continuously in composition from comparatively mafic rocks through to very felsic strongly fractionated granites. The most mafic granites contain abundant biotite and cordierite, and their composition is thought to be close to that of the sedimentary source rocks. It is the continuous gradation through a wide range in composition that gives these granites their special interest, since the products of the complete process of fractionation that ultimately produced the felsic granites can be examined. This is particularly useful in understanding the genesis of other very felsic granites that are not associated with more mafic rocks, such as those elsewhere in the LFB and in the Cornubian Batholith of south-western England. Price (1983) gave a detailed account of felsic granites of the Koetong Suite in Northeast Victoria. A preliminary account of the suite over a larger area has been given by Chappell & White (1998).

The chemical compositions of the more mafic granites of the Koetong Suite resemble those of other mafic S-type suites of the LFB. They contain low abundances of Na, Ca and Sr, and the Fe_2O_3/FeO ratios are low. The SiO_2 contents are high for such mafic (Fe- and Mg-rich) granites. Relative to many I-type granites of comparable SiO_2 contents they contain higher abundances of the trace transition metals. The mafic granites of the Koetong Suite are strongly, but somewhat variably, corundum normative; for example, the nine samples from the relatively mafic Wantabadgery unit of the Koetong Suite which are thought to have compositions determined by the presence of both melt and restite, have an average SiO_2 content of 68.1% and range from 2.63% to 4.13% (average normative *C* is 3.17%).

The most felsic granites of the Koetong Suite have compositions that project close to those of experimentally determined "minimum-temperature" melts. For the five analysed samples that contain more than 90% of normative $Q + ab + or$ in the system Q-Ab-Or-H_2O, the average proportions of those three components are $Q_{39}ab_{28}or_{33}$. This compares with the experimentally determined H_2O-saturated value at 50 MPa of $Q_{40}ab_{29}or_{31}$ (Tuttle & Bowen 1958). It is noteworthy that those five samples from the Koetong Suite are also strongly corundum-normative with an average value of 3.57% *C*. That those rocks represent melt compositions, with at most very little modification by hydrothermal alteration, is firmly established.

Unlike many relatively felsic granites of other S-type suites of the LFB, those of the Koetong Suite show clear compositional evidence of fractional crystallisation, with abundances of elements such as Rb, Nb and Cs rising, and Sr and Ba falling, by factors of three or more, as the rocks become more felsic. Thus, as the rocks trend towards "minimum-temperature" major element compositions they develop distinctive "fractionated" trace element properties.

Sr is the key element for understanding the relationship between the various granites of the Koetong Suite. For most of those granites the abundance of Sr increases in a regular way with decreasing SiO_2, from the low concentrations of the most felsic rocks up to values around 140 to 150 ppm in the most mafic rocks. However, there is an additional group of rocks in which the Sr contents are significantly higher, that are interpreted as rocks in which feldspars accumulated in the magma. These cumulative rocks contain elevated Sr levels because of the high crystal/melt partition coefficients of that element for feldspars, and consequently a bulk-rock distribution coefficient much greater than one. The formation of such rocks is a necessary corollary to the development of granite compositions by fractional crystallisation, but they are not generally seen together as they are in the granites of the Koetong Suite.

The recognition that the cumulative rocks in the Koetong Suite plot well above the main compositional trend for Sr on a variation diagram against SiO_2, supports the contention that none of the rocks on the main trend are cumulative. Our interpretation of the data is that the granites with SiO_2 contents between 73.5% and 69.6% SiO_2 were melts and comprise a liquid line of descent. The rocks with SiO_2 contents close to 69.6% correspond to the primary melts of the Koetong Suite. The granites containing less than 69.2% SiO_2 formed as mixtures of such melts with varying amounts of restite, so that the most mafic compositions are close to the source rock compositions. Thus the Koetong Suite provides the unusual opportunity to study both source rock and primary melt compositions, and a continuous series of more evolved fractionated melt compositions with their complementary cumulative rocks.

The higher P_2O_5 abundances in the fractionated S-type granites and the increase in abundance with fractional crystallisation are consistent with their peraluminous compositions. Wolf & London (1994) have shown experimentally that the solubilities of apatite in a haplogranite melt, and equivalent P_2O_5 abundances, increase linearly with increasing Al_2O_3 saturation. The data of Wolf & London (1994) show that the fractionated S-type granites of the LFB were never saturated in P, so that the element behaved incompatibly and increased in abundance with fractional crystallisation.

A study of the Koetong Suite has shown that apart from a fertile character, specialised or unusual source rocks are not needed to produce highly fractionated granites containing relatively high amounts of P, Rb, Cs, Nb, Sn, W, and other elements. All of the features of such granites can be explained on the basis of partial melting of rocks such as feldspathic greywackes in the crust, followed by complete restite removal and extended fractional crystallisation.

References

CHAPPELL B.W. & WHITE A.J.R. 1998. Development of P-rich granites by sequential restite fractionation and fractional crystallisation: the Koetong Suite in the Lachlan Fold Belt. *Acta Universitatis Carolinae Geologica* **42**, 23-27.

PRICE R.C. 1983. Geochemisty of a peraluminous granitoid suite from north-eastern Victoria, south-eastern Australia. *Geochimica et Cosmochimica Acta* **47**, 31-42.

TUTTLE O.F. & BOWEN N.L. 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. Geological Society of America Memoir 74.

WOLF M.B. & LONDON D. 1994. Apatite dissolution into peraluminous haplogranitic melts: an experimental study of solubilities and mechanisms. *Geochimica et Cosmochimica Acta* **56**, 4127-4145.

S-TYPE GRANITES – MODELS AND EVIDENCE

John D. Clemens

Centre for Earth and Environmental Science Research, Kingston University, Penrhyn Rd, Kingston-upon-Thames, Surrey KT1 2EE, UK

Preamble

Despite a common perception that it represents a perverse divergence, it is perfectly possible to believe in the existence of S- and I-type granites (and the implications for the nature of their protoliths), yet disbelieve in the applicability of the restite-unmixing model for chemical variation in granitic magmas. The view that this position is contradictory seems to arise from a peculiar confusion between objective reality (the existence of mineralogical/chemical varieties of granites) and a human construct (a cherished but subjective model for the origin of observed chemical variations). The truth or falsity of the restite model has little bearing on the reality of S-type granites and what they may mean for the composition and geological/ tectonic development of the crust in which they occur.

Allan White's mapping and careful field observations in the Berridale region, combined with petrographic and compositional data led to recognition of S-type granites, and White and Chappell in 1974 erected the S-I classification with impeccable validity; the isotopic evidence demands contrasting source reservoirs for S- and I-type magmas. In the 1960s, Chappell made the initial suggestion that the compositional variation within granites could result from differing degrees of separation of partial melt from its crystalline residue. This idea developed into the restite-unmixing model, with the implication that the compositions of granites may 'image' those of their source rocks in a simple way. The existence of S- and I-type granites shows that granites *do* image their sources, but there is no requirement that such imaging be simple. There are other, equally mathematically valid models, and none of them represents a unique solution.

Metasedimentary enclaves

The more mafic S-type granites contain metasedimentary enclaves, including sillimanite-bearing gneisses. Sillimanite is usually absent from the exposed country rocks, so this implies a generally deeper, higher-T origin for the magmas. Using this logic, such enclaves were interpreted as restitic. However, in most cases, such enclaves do not have the expected melt-depleted compositions, and biotite remains a stable phase, its crystals defining prograde metamorphic fabrics. Since biotite breaks down during partial melting, this strongly suggests that these metasedimentary enclaves are actually mid-crustal xenoliths, rather than restites. In any case, the geochemical and experimental data suggest sources dominated by aluminous metagreywackes. Restites produced from these would be dominated by Qtz, minor Bt, Grt, Opx and Pl. Metamorphic-textured enclaves with these compositions are rare to absent in S-type granites, so this suggests that crystalline restites, of any kind, cannot have been major volumetric components of S-type magmas.

Zircons

An important feature of S-type granites (and indeed most granites) is the occurrence of old, inherited zircon cores. This is consistent with the derivation of these rocks from older crustal materials, and with the zircons having a restitic component. The zircons and Zr concentrations are now considered to hold definitive proof of the presence of abundant restite in granites, and of the operation of restite unmixing. Hence, it seems worth discussing the evidence more closely.

A large proportion of the Zr in a given granitic rock may be restitic, but this does not mean that a similarly large proportion of the CaO or MgO, for example, is hosted in restite. We cannot take the occurrence of a substantial restitic population among the zircons to imply an equally substantial restitic component in the rest of the rock. There are two reasons why restitic zircons would be preferentially incorporated into granitic magmas while other restitic components may be minor. The first is that zircon is highly refractory during partial melting – witness its common preservation in high-T granulite terranes, in rocks that have been extensively partially melted. The second is that very many zircons in metamorphic rocks are enclosed within crystals of mafic silicates (mainly biotite in metasediments). During partial melting, the biotite decomposes (either to garnet and/or cordierite, or to orthopyroxene), liberating zircons that, because of their small size, are carried away as the melt rapidly segregates and ascends, leaving the coarser-grained restitic phases behind.

It has been argued that zircon saturation temperatures for some relatively mafic granites are too low for such bulk rock compositions to have been melts, thus implying a significant restite component in the magmas. This reasoning is erroneous. First, it is likely that the more mafic granites are cumulates, rather than former liquids, so the saturation T in such a composition is meaningless anyway. Second, this reasoning assumes equilibrium processes, with respect to trace-element concentrations in partial melts. There is much evidence that equilibrium is unlikely to be attained with respect to zircons, monazites, etc., even though the major minerals probably do reach equilibrium with melt. The rates of melting and melt segregation/extraction simply outpace the attainment of equilibrium for refractory phases such as zircon. The disequilibrium zircons cannot be used to infer low melting T for the origin of the magmas or high restite contents. Indeed, a low-T interpretation is inconsistent with the results of the application of well-calibrated geothermometers in S-type rocks, which indicate $T > 800$ and most probably > 850 °C.

Unfettered mixing and other crimes

Multi-component mixing models have been proposed for the Lachlan Fold Belt (LFB) granites, but they are mathematically non-unique, and can be seen to be deficient when the Pb isotopes of zircons are studied in detail. The ages of LFB granite zircons do not match those of detrital zircons in the Palæozoic metasediments. Since the dominant ages are Early Palæozoic and Proterozoic, it seems likely that crust of this age, and geochemically different from the exposed rocks, not only underlies much of the LFB, but forms a component in the granite magma source. The dominant protolith is supposed to be Cambrian or younger, but this only means that some Cambrian or younger thermal event resulted in zircon growth.

S-type rocks range in composition from quite mafic tonalites to leucogranites. The more mafic S-types are said to be close to their source rocks in composition because they evolved by the separation of more felsic melt from mafic restite. The problem here is that no objective evidence has ever been presented to show that the mafic minerals concentrated in such rocks are restitic instead of magmatic cumulates. In short, there is no necessity to believe in the restite (or any other particular) model in order to make sense of the chemistry of the LFB granites. Indeed, too much faith in models of various kinds may be holding back progress in understanding the LFB and its geological and tectonic evolution.

TO MIGMA ADD MAGMA: RELATION OF THE COOMA COMPLEX TO THE S-TYPE MURRUMBIDGEE BATHOLITH

W. J. Collins & S.W. Richards

School of Geosciences, University of Newcastle, Callaghan, NSW 2305, Australia

White et al. (1974) described granite plutons as *regional-aureole*, *contact-aureole* and *subvolcanic*, depending on the nature of the surrounding rocks. The type regional-aureole pluton was the Cooma "granite", which is a small (~ 14 km^2) body within a high-grade migmatitic aureole of maximum 10 km width. The aureole consists of metamorphic zones grading outward from migmatite, through gneisses to knotted schists to low grade slates, and can be traced northward some 50 km through and adjacent to the eastern lobe of the S-type Murrumbidgee Batholith. Migmatites terminate some 30 km north of Cooma, but the gneisses and schists persist as a gradually narrowing contact aureole some 20 km farther north. These features demonstrate physical continuity between the Cooma Complex and the batholith. At its northern termination near Canberra, the batholith has intruded its own volcanic cover, the Paddys River Volcanics. Therefore, the batholith varies continuously from regional-aureole in the south, through contact-aureole, to subvolcanic in the north and is part of a tilted crustal section, dipping shallowly to the north. Thus, the Cooma Metamorphic Complex might be considered the "root zone" of the Murrumbidgee Batholith.

Structural analysis of the Cooma Complex indicates five deformation events within the low-grade zone. D_1 and D_2 are preserved as inclusion trails within porphyroblasts, and D_3, D_4, D_5 represent subsequent folding events. The regional structures are N-trending, inclined, tight, D_3 folds with strong S_3 axial planar slaty to schistose cleavage. D_3 produced sporadic flat-lying folds and D_3 folds are N-trending, steeply E-dipping, associated with sporadic reverse faults. In the high-grade zone, the regional D_3 folds are intrafolial, isoclinal structures transposed into the migmatitic fabric. This indicates that lit-par-lit injection occurred during D_3 and implies a parallelism of metamorphic isograds with the regional S_3 foliation. The Cooma "granite" post-dates peak metamorphism as it intruded early D_5, which produced the common N-trending upright migmatitic folds and the gneissic foliation in the high-grade aureole. Thus, the Cooma "granite" was not the cause, but rather the effect, of the metamorphism.

The high-grade aureole around the Murrumbidgee Batholith is also a D_3 phenomenon. Exactly the same microstructural relations that exist in the Cooma Complex can be observed in the Murrumbidgee aureole. The N-trending, metre- to kilometre-scale sheet-like lenses of the batholith are concordant with the D_3 structures, and have the same peak-metamorphic and regional S_3 foliation as the aureole. The lack of thermal overprinting of the metamorphic assemblages is consistent with granite intrusion during peak metamorphism. These features confirm that emplacement of the Murrumbidgee Batholith was the cause of the high-grade metamorphism at Cooma. Indeed, mapping of F_5 fold structures and granite contacts shows that the aureole dips under the batholith as an inverted metamorphic sequence. This implies that the Murrumbidgee Batholith once overlay the Cooma Complex, but has been removed by subsequent erosion.

White & Chappell (1988) distinguished the S-type Cooma "granite" from the batholithic S-type granites, based on textural, chemical and isotopic differences, and suggested that it was derived from the surrounding high-grade metasediments. We concur with this interpretation, but add that the subtly higher contents of Ca, Na and Sr in the granite, compared to the sediments, results from the presence of distinctive, complexly zoned, plagioclase phenocrysts in the pluton. The slight offset in Sr and O isotopic data to more primitive values in the granites (Munksgaard 1988) is consistent with this interpretation. In the southern parts of the batholith, several km north of Cooma, all gradations between Cooma "granite" and Murrumbucka tonalite exist as metre-scale intersheeted lenses. Present in all magmatic phases are the distinctive plagioclase crystals, which also suggests that a small component of Murrumbidgee granite magma is present in the Cooma "granite".

Detailed field mapping of selected exposures shows that some of the Cooma "granite" was derived by local segregation of a more mobile component from the migmatites, preferentially along the regional S_3 gneissosity. It has accumulated in the axial planes of F_5 folds and thus is locally discordant to the adjacent migmatites. Preservation in the granite of tight, metre-scale F_5 folds, defined by migmatitic enclaves, confirms the very local segregation in some places. Much of the residual or restitic phases have been entrained in the mobilisate and as such, the granite is best viewed as a nebulitic migmatite or diatexite. To this "migma" has been added Murrumbidgee granite magma containing the distinctive plagioclase crystals, to produce the Cooma "granite".

The Murrumbidgee Batholith has the hallmark features of batholithic S-type granites of the Lachlan Fold Belt, including contact aureole and comagmatic cordierite-bearing S-type volcanics. The granites have a much greater silica range than Cooma, extending from ~60-78% SiO_2 (Joyce 1973). At similar silica contents to the Cooma "granite", the Murrumbidgee granites have significantly higher Ca, Na, Sr, but lower TiO_2, total FeO, P_2O_5, Ni, V and Cr. Do these granites geochemically relate to the Cooma diatexite? Interestingly, a number of small gabbroic bodies have been identified within the Murrumbidgee Batholith, some of which show extensive hybridisation with the granitic phases, and it will be necessary to evaluate whether or not these have influenced the nature and composition of the S-type granites.

References

JOYCE A.S. 1973. Petrogenesis of the Murrumbidgee Batholith, A.C.T. *Journal of the Geological Society of Australia* **20**, 179-197.

MUNKSGAARD N.C. 1988. Source of the Cooma Granodiorite, New South Wales – a possible role of fluid-rock interactions. *Australian Journal of Earth Sciences* **35**, 263-378.

WHITE A.J.R. & CHAPPELL B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

WHITE A.J.R., CHAPPELL B.W. & CLEARY J. 1974. Geologic setting and emplacement of some Australian Paleozoic batholiths and implications for intrusive mechanisms. *Pacific Geology* **8**, 159-171.

ARSENIC GEOCHEMISTRY IN GRANITES OF THE NEW ENGLAND BATHOLITH

Michael Cook

GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia

Granites of the New England Batholith (NEB) have significantly enriched average As concentrations (7.35 ppm average from 502 analyses) than previously reported averages for granitic rocks worldwide (average = 1.5 ppm), and a large number of what may be considered extreme values (> 10 ppm). Within the NEB, 16% (81/502) of analyses contain more than 10 ppm As. In contrast, in granites of the Lachlan Fold Belt, only 1% (22/2200 analyses) contain As levels in excess of 10 ppm, with a much lower overall average of 2.24 ppm. Elevated As levels occur in both S-type, and in two of the three I-type supersuites of the NEB, with only the I-type Clarence River Supersuite having "normal" levels. The geochemical behaviour of As is cryptic and shows poor correlation (calculated correlation coefficients < 0.1) with any other measured elements. As values may range by up to two orders of magnitude in otherwise geochemically homogeneous samples from the same pluton.

The highest As values are largely confined to plutons, regardless of supersuite or granite composition, located in two narrow (< 30 km wide) corridors that intersect near the location of the Hillgrove Au-Sb mineral field. One is oriented NW-SE while the other runs NNE-SSW and both correspond to previously described zones of hydrothermal fluid movement and mineralisation. This suggests that the high As values are not magmatic characteristics of the granites, but have been overprinted by subsequent hydrothermal enrichment, along these identified zones of fluid movement. Similar, Late Permian post-magmatic hydrothermal activity related to a Late Permian extensional regime has been identified as the source of Au-Sb mineralisation in the Hillgrove and Rockvale mining districts within the corridors and is thought to be related to the high As contents of the granites.

Removal of all analyses within the two corridors (182 analyses, average = 14.58 ppm As) results in a significant reduction in the overall average As value in the NEB. The overall average is reduced to 3.24 ppm (320 analyses), with a systematic difference between the I- and S-type suites apparent, with S-types significantly enriched (average = 6.81 ppm As) relative to I-types (average = 2.61 ppm). In the Lachlan Fold Belt, a similar, although less pronounced division is observed with S-types (2.83 ppm) enriched relative to I-types (1.96 ppm). Individual NEB supersuite averages, after removing analyses in the corridors, are: Bundarra (9.03 ppm), Hillgrove (5.48 ppm), Uralla (3.75 ppm), Clarence River (2.58 ppm) and Moonbi (2.06 ppm). A systematic correlation is observed between these average As levels and reported $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ values for the various supersuites (O'Neil *et al.* 1977), with As concentrations increasing as the granites become more obviously S-type. This variation is consistent with the significantly higher As contents that are reported in likely sedimentary source rocks compared with any igneous source (e.g. Baur & Onishi 1978).

References

BAUR W.H. & ONISHI H. 1978. Arsenic 33. In Handbook of Geochemistry II-3 (ed. K.H. Wedepohl). Springer Verlag. Berlin

O'NEIL J.R., SHAW S.E. & FLOOD R.H. 1977. Oxygen and hydrogen isotope compositions as indicators of granite genesis in the New England Batholith, Australia. Contributions to Mineralogy and Petrology **62**, 313-328.

GENERATION OF MICROGRANITOID ENCLAVES IN S-TYPE GRANITES BY MAGMA MINGLING AND CHEMICAL EQUILIBRATION

Marlina A. Elburg

Department of Geology and Geophysics, University of Adelaide, SA 5005 Australia.

Introduction

It has been argued that S-type granites are characterised by the presence of metasedimentary enclaves, while microgranitoid (or microgranular) enclaves are only found in I-type granites (Chappell 1978). This idea has been used to support the restite theory, in which granites are thought to consist of a minimum temperature melt and entrained restitic material from the source region of the magma (White & Chappell 1977). Within this theory, granites are thought to 'image their sources' and give us direct information on the chemical composition of their source region. The enclaves found in granites are thereby interpreted as larger pieces of unmelted, refractory material entrained as a solid during ascent of the magma.

Alternative ideas on microgranitoid enclaves say that they are either cumulates, chilled margins, or globules of a more mafic magma that mingled with the host magma while it was still partially liquid (Vernon 1984). Although all theories can be valid in certain instances, a study of two enclave-bearing S-type granites in the central Lachlan Fold Belt shows that their petrogenesis can best be explained by magma mingling and subsequent equilibration with the host granite.

Data

The majority of enclaves found in the studied granites, the Wilsons Promontory Batholith (WPB) and the Warburton Granodiorite (WG), are not obviously metasedimentary, since they do not display any sedimentary or gneissic layering, and do not contain an overabundance of highly aluminous minerals such as cordierite, garnet or spinel. Some enclaves contain high-level metasedimentary xenoliths, which can easily be distinguished from the host enclave by their layering and the presence of porphyroblastic cordierite. The enclaves are finer-grained than the host rock, although megacrysts that are the same size as the minerals in the host rock, are present in many enclaves. K-feldspar megacrysts are typically overgrown by a plagioclase rim, and plagioclase megacrysts often show discontinuous reverse zoning.

Nearly all WPB enclaves are mineralogically similar to their host rock: they contain plagioclase and quartz, and biotite is the only ferromagnesian mineral (Elburg & Nicholls 1995). K-feldspar is rare, although it does occur as megacrysts. Both zircon and apatite can occur in a needle-like habit. The age of the needle-like zircon is the same as that of the magmatic zircon in the host rock. FeO* and K_2O contents of the enclaves are correlated, reflecting the importance of biotite as a host for both these oxides. The enclaves have very similar initial Sr and Nd isotopic values to the host, although enclaves with higher REE contents tend to have somewhat higher ε_{Nd} values.

Although most WG enclaves are also similar to their host, there are rare enclaves that contain mineralogical zoning, from a core with orthopyroxene, to a mantle with amphibole, and a rim with biotite as the main ferromagnesian mineral (Elburg 1996). Three out of four enclaves analysed have lower initial Sr and higher Nd isotopic ratios than the host. One enclave with biotite as the only ferromagnesian mineral has isotopic ratios that are virtually indistinguishable from those of the host.

Interpretation

The fact that the microgranitoid enclaves contain low-grade xenoliths from the contact aureole of the granite, shows that they cannot have been pieces of solid material entrained from the (mid crustal) source region of the magma. It is therefore not possible that they represent pieces of restite. The similarity in age between the magmatic zircons in the enclaves and in the host rocks also argues against this interpretation. The field, mineralogical, geochemical and geochronological data are most easily interpreted as reflecting enclave petrogenesis by mixing, mingling and chemical equilibration. The megacrysts within the enclaves are likely to have been derived from the partially solidified host rock, of which small mounts mixed with a more mafic magma that contained a larger component of mantle-derived melt than the granitic magma. Since both the temperature and chemical environment of the mafic magma were different from that of the host, the megacrysts were partially resorbed and overgrown by minerals of a different composition. After this event, the hybridised mafic magma came into contact with the main body of host magma and mingled with it. The volumetrically minor amount of hybrid magma cooled quickly, resulting in the growth of needle-like zircon and apatite, and an average small grainsize. When the temperature of the hybrid magma had reached that of the host rock, a certain amount of residual liquid was still left within the enclaves. Diffusion between the residual liquid in the enclave and the liquid in the host resulted in a movement of water and K_2O into the enclaves. Since this changed the composition of the residual melt within the enclave, the original ferromagnesian minerals, such as pyroxene, became unstable and changed into amphibole, and later biotite. Since this reaction diminished the amount of K_2O in the residual liquid within the enclave, more potassium diffused into the enclave with the result that more pyroxene changed into biotite. This process has gone to completion in the WPB enclaves, but can be seen arrested in the WG enclaves.

The presence of mafic magmas, with a large component of mantle-derived melt, at the time of granite petrogenesis can be taken as an indication that they were the heat source for crustal melting. The fact that the isotopic composition of S-type granites does not directly reflect that of exposed metasediments can indicate that the mafic magma also contributed chemical components to the granitic magma.

References

CHAPPELL B. W. 1978. Granitoids from the Moonbi District, New England Batholith, Eastern Australia. *Journal of the Geological Society of Australia* **25**, 267-283.

ELBURG M. A. & NICHOLLS I. A. 1995. The origin of microgranitoid enclaves in the S-type Wilson's Promontory Batholith, Victoria: evidence for magma mingling. *Australian Journal of Earth Sciences* **42**, 423-435.

ELBURG M. A. 1996. Evidence of isotopic equilibration between microgranitoid enclaves and host granodiorite, Warburton Granodiorite, Lachlan Fold Belt, Australia. *Lithos* **38**, 1-22.

VERNON R. H. 1984. Microgranitoid enclaves in granites - globules of hybrid magma quenched in a plutonic environment. *Nature* **309**, 438-439.

WHITE A. J. R. & CHAPPELL B. W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

S-TYPE GRANITES OF THE VARISCAN FOLD BELT

F. Finger[1] & B.W. Chappell[2]

[1]Institut für Mineralogie, Universität Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria
[2]GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia

S-type granites are very widely developed in the Variscan Fold Belt of Europe. That belt extends from Iberia, Brittany and Cornwall in the west to Central Europe in the east, a distance of more than 2000 km. The major exposures of Variscan granites occur in the Massif Central and the Bohemian Massif. Parts of the belt were re-worked during the Alpine Orogeny. These Variscan S-type granites (VSG), and those of the Lachlan Fold Belt, comprise two of the most extensive developments of S-type granites. Ages of the VSG range approximately from 350 Ma to 275 Ma. I-type granites are often associated with the VSG, but the latter are dominant throughout the region north of the Alpine Front.

The Variscan Fold Belt resulted from continental collision, with most granites forming during the post-collisional stage. Particularly along the central axis of that belt, the exposed granites were emplaced at depths of 10-15 km, and some may have formed *in situ*. Away from that axis, the granites were emplaced at shallower levels. In constructing his granite series as a sequence corresponding to the depth of formation of granites, Read (1949) took as his example the granites extending from the Massif Central to Cornwall, a sequence of decreasing depth of granite development, from migmatites and anatectic granites to intrusive granites.

Variscan S-type granites of central Europe

Within the Variscan granites of central Europe (Finger *et al.* 1997) there are a few early-stage (340 Ma) deformed S-type granites and associated migmatites. These may represent a phase of water-present syn-collisional crustal melting related to nappe-stacking. Such a process has been invoked by some workers as the main S-type granite-forming process. However, the most typical VSG plutons are post-collisional, with ages ca. 330-310 Ma. Very abundant among those are coarse-grained, moderately peraluminous two-mica granites with K-feldspar megacrysts. Locally these evolved to produce strongly fractionated end-members with high P and Rb contents. Large bodies of such highly-fractionated "specialised" S-type granites are only known from the Erzgebirge (Förster *et al.* 1999). That area, near the border between Germany and the Czech Republic is one of the classic metal provinces (Agricola 1556) with high abundances of Sn, W and U.

Another group of the VSG comprise moderately mafic diatexites, mainly biotite granodiorites to monzogranites, with high restite contents, often containing cordierite. These rocks are associated with high-T metamorphic rocks (~ 500 Mpa). Hence, the Variscan belt also provides the opportunity to study the processes of formation of S-type granites *in situ*.

The Cornubian Batholith

The Cornubian Batholith (Stone & Exley 1985) comprises six major bodies of S-type granite in southwestern England. The granites are late-Variscan in age (294 to 275 Ma) and comprise two-mica granites and much less abundant Li-mica granites. These intrusive rocks are associated with major Sn mineralisation and this small portion of the crust has yielded 2 500 000 tonnes of Sn, plus significant amounts of Cu and W. The two-mica granites are felsic and strongly peraluminous and a comparison with experimental data shows that the rocks attained their major element composition under conditions of crystal-liquid equilibrium at magmatic temperatures. Minor elements that are relatively very abundant are Li, B, Cs and U, while Rb, Ga and Sn are quite abundant and P is high in amount for felsic rocks. Sr, Ba, and the trace transition metals are low in amount. These trace element abundances are ascribed to a process of fractional crystallisation of a melt derived from the partial melting of feldspathic greywackes in the crust. The average composition of these granites is remarkably similar to some fractionated S-type granites from the Lachlan Fold Belt. The Cornubian Batholith is an area of extremely high heat flow. Wheildon *et al.* (1981) reported an average value of 124 ± 8 mWm^{-2} from 26 heat flow measurements in these granites, approximately twice that found for normal continental crust.

References

AGRICOLA G. 1556. *De Re Metallica libri XII.* Hieronymus Froben & Nicolaus Bischof, Basle.

FINGER F., ROBERTS M.P., HAUNSCHMID A., SCHERMAIER A. & STEYRER H.P. 1997. Variscan granitoids of central Europe: their typology, potential sources and tectonothermal relations. *Mineralogy and Petrology* **61**, 67-96.

FÖRSTER H.-J., TISCHENDORF G., TRUMBULL R.B. & GOTTESMANN B. 1999. Late-collisional granites in the Variscan Erzgebirge, Germany. *Journal of Petrology* **40**, 1613-1645.

READ H.H. 1949. A contemplation of time in plutonism. *Quarterly Journal of the Geological Society of London* **105**, 101-156.

STONE M. & EXLEY C.S. 1985. High heat production granites of southwest England and their associated mineralization: a review. *High Heat Production (HHP) Granites, Hydrothermal Circulation and Ore Genesis.* London: The Institution of Mining and Metallurgy, pp. 571-593.

WHEILDON J., FRANCIS M.F., ELLIS J.R.L. & THOMAS-BETTS A. 1981. *Investigation of the S.W. England Thermal Anomaly Zone.* Luxembourg: Commission of European Communities Report EUR 7276 EN, 410 pp.

THE S-TYPE GRANITE SOURCE-ROCK DEBATE: POSSIBLE ADDITIONAL FELSIC COMPONENT FORMED BY FRACTIONATION OF MANTLE-DERIVED MAFIC HEAT-SOURCE MAGMAS

R. H. Flood & S. E. Shaw

GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia.

The recognition and clear enunciation of the mineralogical, chemical and isotopic differences between S- and I-type granites by Chappell & White (1974) has been a lasting contribution to the understanding of granites. Although the initial global acceptance led to some misuse of the term S-type as fully synonymous with peraluminous (in spite of that original paper clearly stating that I-types can be peraluminous), the continued use of the term, and the further refinements of the distinctions between I and S-type granites (Chappell & White 1992; Chappell *et al.* 1998) have given S-type granites a well deserved place in the petrology textbooks.

One aspect of S-type granite genesis presently debated is the exact source of the S-type magmas. Chappell & White (1992) pointed out that the composition of most of the Lachlan Fold Belt (LFB) S-type granites does not accord with partial melting of deeper equivalents of the Ordovician metasedimentary rocks into which most are emplaced. They, and Phillips *et al.* (1981), argued that the source rocks were more feldspar-rich metasedimentary rocks that occur at depth. Experimental studies have also shown that melting of such strongly peraluminous metasedimentary protoliths would produce melts more peraluminous than most of the S-type granites (Green 1976; Clemens & Wall 1981).

In the New England Batholith (NEB), both the S-type granites and their surrounding sedimentary rocks are enriched in Na_2O relative to their counterparts in the LFB. Hensel *et al.* (1985) have also argued that the S-type granites of the NEB cannot be derived by partial melting of the dominant metasedimentary rocks they intrude and also suggest a more feldspar-rich metasedimentary protolith occurs at depth. As an alternative to the solely meta-sedimentary protolith, Gray (1984) suggested that the spectrum of LFB S- and I-type granites could be formed as mixtures of a granitic partial melt of Ordovician metasedimentary rocks and a mantle-derived mafic magma. Keay *et al.* (1997) expanded the mixing model to include a third component derived from partial melting of lower crustal greenstones.

In situ Lu and Hf isotopic ratios of zircons indicate that there could be yet another process that might influence the composition of both S- and I-type granites. Griffin *et al.* (2001) have developed an elegant technique that allows the $^{176}Hf/^{177}Hf$ isotopic composition of zircon grains to be determined using LAM-MC-ICPMS microanalysis. Combined with LAM-ICPMS U/Pb ages as a test for zircon inheritance in individual grains, ε_{Hf} values allow an estimate of the relative contributions from crustal (low ε_{Hf}, i.e. old) and mantle sources (high ε_{Hf}, i.e. young) based on model age calculations. Griffin *et al.* (2001) have documented ranges of up to15 ε_{Hf} units in different I-type granites from eastern China that record differences in melt compositions from several crustal sources and a more primitive mantle-derived component.

A similar story is emerging from a study of a Moonbi Supersuite pluton (Walcha Road) in the NEB. LAM-ICPMS U/Pb microanalyses indicate that almost all zircons have a crystallisation age of 249 ± 1 Ma. There is a range of ε_{Hf} of 19 units, the older T_{DM} ages consistent with a late Proterozoic or Early Palaeozoic crustal source magma. The most felsic part of this pluton, although a mix of ε_{Hf} values, has some with ε_{Hf} values giving model T_{DM} ages approximating the age of the pluton. This suggests a second felsic magma but one with a mantle Hf signature. Such mixing of two felsic magmas might otherwise be hard to detect. We suggest that the high ε_{Hf} felsic magma is a fractionation product of a gabbroic heat source magma emplaced below the crustal protolith.

Mixing of a felsic mantle component in S-type granites would change the isotopic composition of the S-type magma in the same direction as basalt but not necessarily shift the magma towards more mafic compositions. Such mixing could be a factor in producing the lower $^{87}Sr/^{86}Sr$ initial ratios in the more felsic members of the Bullenbalong Supersuite reported by Chappell *et al.* (1999). It may also be a factor in producing the lower $\delta^{18}O$ values of the leocogranite plutons of the NEB relative to the more mafic plutons of that batholith (O'Neil *et al.* 1977).

While our preliminary observations do not exclude the other suggested models used to explain the relationship of the S-type granites to their source materials, it may be possible to determine whether primary magmatic zircons derived from different source rocks occur in felsic S-type granites. If mixing of two felsic magmas one with crustal and one with mantle isotopic signatures occurs, it may also be possible to use the abundance of the different types of zircons to evaluate the degree to which this process controls the composition of S-type granites.

References

CHAPPELL B.W. & WHITE A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

CHAPPELL B.W. & WHITE A.J.R. 1992 I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1-26

CHAPPELL B.W., BRYANT C.J., WYBORN D., WHITE A.J.R. & WILLIAMS I.S. 1998. High- and low-temperature granites. *Resource Geology* **48**, 225-236.

CHAPPELL B.W., WHITE A.J.R., WILLIAMS I.S., WYBORN D., HERGT J.M. & WOODHEAD J.D. 1999 Discussion and reply: evaluation of petrogenetic models for Lachlan Fold Belt granitoids: implications for crustal architecture and tectonic models. *Australian Journal of Earth Sciences* **46**, 827-836.

CLEMENS J.D. & WALL V.J. 1981 Origin and crystallization of some peraluminous (S-type) granitic magmas. *Canadian Mineralogist* **19**, 111-131.

KEAY S., COLLINS W.J. & MCCULLOCH M.T. 1997. A three-component Sr-Nd isotopic mixing model for granitoid genesis, Lachlan fold belt, eastern Australia. *Geology* **25**, 307-310.

GRAY C.M. 1984 An isotopic mixing model for the origin of granitic rocks in southeastern Australia. *Earth and Planetary Science Letters* **70**, 47-60.

GREEN T.H. 1976 Experimental generation of cordierite- or garnet-bearing granitic liquids from a pelitic composition. *Geology* **4**, 85-88.

GRIFFIN W.L., XIAG WANG, JACKSON S.E., PEARSON N.J., O'REILLY S.Y., XISHENG XU & XINMIN ZHOU 2001. Zircon chemistry and magma genesis, SE China: *In situ* analysis of Hf isotopes, Tonglu and Pingtan Igneous Complexes. *Lithos*, submitted manuscript.

HENSEL H.D., MCCULLOCH M.T. & CHAPPELL B.W. 1985. The New England Batholith: constraints on its derivation from Nd and Sr isotopic studies of granitoids and country rocks. *Geochimica et Cosmochimica Acta* **49**, 369-384.

O'NEIL J.R., SHAW S.E. & FLOOD R.H. 1977 Oxygen and hydrogen isotope compositions as indicators of granite genesis in the New England Batholith, Australia. *Contributions to Mineralogy and Petrology* **62**, 313-328.

PHILLIPS G.N., WALL V.J. & CLEMENS J.D. 1981 Petrology of the Strathbogie Batholith: a cordierite bearing granite. *Canadian Mineralogist* **19**, 47-63.

S- AND I-TYPE GRANITE FORMATION IN THE ROSS-DELAMERIAN FOLD BELT

J Foden

Department of Geology and Geophysics, University of Adelaide, SA 5005 Australia.

The dispute over the origin of granite, particularly in the Lachlan Fold Belt, has been considerable and encapsulates debate repeated in many other global granitic terranes (White & Chappell 1988; Chappell & White 1974, 1992; Collins 1998; Chappell 1996). Are granites essentially an infracrustal phenomenon? Or do they involve a mixture of crustal and mantle sources? A second issue in the Tasman Orogen questions the extent to which granites are directly related to subduction processes.

The first Palaeozoic orogen to form in the eastern Gondwanan margin was the Cambro-Ordovician "Ross-Delamerian" Belt (RDB). This orogen hosts granitic rocks and felsic volcanics with ages in the range ~ 520 Ma to 480 Ma and underwent deformation (Foden *et al.* 1999) from the early Middle Cambrian (514 Ma) through to the Early Ordovician (~ 490 Ma). This Cambrian activity was concurrent with subduction-related arc volcanism ~ 1000 km to the east in the Takaka Terrane in New Zealand (Munker & Cooper 1995). In the Delamerian, felsic magmatism occurred during convergence and continued during the post-tectonic stages. Mafic magmatism occurred in the pre-convergent extensional phase, and continued weakly during the convergent stage. In the RDB, the cessation of deformation was accompanied by abrupt uplift and by the onset of bimodal magmatism. That terminal uplift suggests a sudden change in crustal buoyancy (Turner et al. 1996) and was accompanied by molassic sedimentation eastwards into the LFB. The convergent stage of orogenic evolution localised initial deformation at the thermally weakened axes of prior rifts. This first stage of crustal thickening took place by recumbent folding and west vergent thrusting. Later deformation and crustal shortening proceeded by localised upright folding.

The application of Nd-, Sr-, Pb- and O-isotope data and inherited zircon population age frequencies provide very firm evidence that both I- and S-type granites in both the Delamerian and Lachlan Fold Belts (LFB) are continuum mixtures of contemporary mantle and crustal sources. The Nd model age data indicate that LFB and RDB granites are displaced towards values which are significantly younger than any of the known Precambrian crust. These data also indicate a strong bimodal distribution of model ages with the I-types having younger mean model ages than the S-types. Intriguingly, in the RDB and in some LFB granite suites, the crustal end member of the mantle-crust source continuum appears to be the sedimentary fill of the directly pre-orogenic basin, with little or no older crust. In the Delamerian this crustal source was the Early Cambrian Kanmantoo Group which is easily distinguished from all Precambrian crustal sources by its very distinctive inherited zircon age frequency signature.

Magmatic sources and magma chambers.

Whilst the isotopic compositions of granite suites from the LFB and the RDB fall between the crust and the mantle, there is a strong tendency for the I-types to cluster towards the mantle end-member and the S-types towards the crustal end-member. This dichotomy reflects two magma production situations:

1. "Mafic" magma chambers (Type 1) contaminated by and mingled with melts of the local metasediments (I-types) in AFC-type processes (Sandiford *et al.* 1992).
2. Crustal melts (Type 2) formed in the heated *zones* around the upwelling mantle or close to mafic or I-type granite intrusions.

On binary isotope mixing diagrams, notional evolutionary directions start at either end member, I-types from the mantle end, and S-types from the crust. As illustrated by the classical exposures of the Vivonne Bay complex in southwestern Kangaroo Island, S-type magma chambers originate above mafic or I-type granite intrusions, as migmatite complexes physically contaminated by veining and dyking from the underlying magmatic heat sources. The Vivonne Bay site provides a very clear view of the *in situ* production of melts from the Kanmantoo Group. There the metasedimentary rocks show a progressive increase in melting along a traverse across the contact aureole of an intrusive I-type granite. Elsewhere, in eastern Kangaroo Island, Late Delamerian S-type rhyodacite dykes show composite mingling with contemporary mafic magmas, suggesting that crustal melting was also produced by direct mafic intrusion.

In the South Australian Delamerian Orogen not only can we assign the main source of the S-type granites to the Kanmantoo Group, but it is also clear that the most psammitic-feldspathic lithologies within this formation are the preferential source of the S-type melts. Field evidence on Kangaroo Island clearly shows that wholesale melt development from these lithologies yields a restite-rich, biotite granodiorite magma. These *in situ* S-type magmas are identical to other S-type intrusions elsewhere in the belt, including those at Victor Harbor, Taratap, and Harrow in western Victoria.

Recent high resolution TMI imagery allows confident remote discrimination between I- and S-type intrusions. I types are more magnetic, with complex internal magnetic structures. These features are very consistent with observations by Wiebe (1996) and Collins *et al.* (1999) suggesting that I-type magma chambers (Type 1) are commonly the sites of repeated injection of mafic parental melt into cooling and fractionating melt bodies, yielding dynamic composite magma bodies. By contrast, the less magnetic S-types show little internal detail.

References

CHAPPELL B.W. 1996. *Journal of Petrology* **37**, 449-470.

CHAPPELL B.W. & WHITE A.J.R. 1992. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 71-86.

CHAPPELL B.W. & WHITE A.J.R. 1974. *Pacific Geology* **8**, 173-174.

COLLINS W.J., RODRIGUEZ L.G. & WEIBE R.A. 1999. Fourth Hutton Symposium Abstracts, 20

COLLINS W.J. 1998. *Australian Journal of Earth Sciences* **45**, 483-500.

FODEN J., SANDIFORD M., DOUGHERTY-PAGE J. & WILLIAMS I. 1999. *Australian Journal of Earth Sciences* **46**, 377-389.

MUNKER C. & COOPER R.A. 1995. *Journal of Geology* **103**, 687-700.

SANDIFORD M., FODEN J., ZHOU S. & TURNER S. 1992. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 83-93.

TURNER S.P, KELLEY S., VANDENBERG A.H.M., FODEN J., SANDIFORD M & FLOTTMAN T. 1996. *Geology* **24**, 941-944.

WHITE A.J.R. & CHAPPELL B.W. 1988. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

WEIBE R.A. 1996. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 233-242.

POST-COLLISIONAL NEOPROTEROZOIC S-TYPE GRANITES IN SW AMAZON CRATON: CRUSTAL MAGMATISM RECORDING CRATONIC (RODINIA ?) STABILISATION

M.C. Geraldes[1], W. Teixeira[1], M. Babinski[1], W.R. van Schmus[2] & J.S. Bettencourt[1]

[1]Geochronological Research Center (CPGeo) Instituto de Geociências, Universidade de São Paulo, Brazil.
[2]Department of Geology, University of Kansas, KS, 66045 USA

Introduction and Geological Setting

The Amazonian Craton can be divided into two major crustal domains (i) the Archaean nucleus which is included in the Central Amazonian Province, and (ii) Proterozoic Geochronological Provinces, represented by the Maroni-Itacaiúnas (ca 2.2 Ga), the Ventuari-Tapajós (1.95 Ga to 1.55 Ga) and the Rio Negro-Juruena (1.55 Ga to 1.4 Ga). The Rondonian-San Ignacio Province was developed later and marked by important events involving magmatic arc setting and continental collision processes between 1.57 Ga and 1.42 Ga. Finally, the youngest Sunsás-Aguapeí Province comprises mainly metavolcano-sedimentary sequences and granites, including older terranes that were reworked between 1.3 Ga and 1.0 Ga. Its evolution has been associated with the inversion of the marginal belt succeeding the continent-continent collision event (Aguapeí Thrusting) responsible for the origin of the S-type magmatism (São Domingos Suite) reported here.

São Domingos Suite

The São Domingos Suite (SDS) comprises a roughly circular body and the main lithology is a white, isotropic and fine-grained granite. Pegmatitic facies also may be observed near to the borders, presenting higher contents of biotite and muscovite. Magmatic layering may be observed locally, due to higher amounts of biotite or garnets. K-feldspar, quartz, plagioclase, biotite, muscovite and garnet are the major minerals; zircon, apatite and oxides occur as accessories.

Two U-Pb (single grain) zircon ages were obtained for this unit. The first one comprises four points and yielded an age (upper intercept) of 930 ± 12 Ma (two-mica-pegmatite). The second, also with four points, yielded an age (upper intercept) of 936 ± 26 Ma (garnet-bearing granite).

A Pb/Pb isochron age (5 points) obtained on leaches of garnets yielded an imprecise age of 891 ± 110 Ma (MSDW = 0.59). A two point Sm/Nd mineral isochron (K-feldspar and garnet) yielded an age of 927 ± 5 Ma. Both isochron ages are in agreement, within analytical errors, with U/Pb ages in zircons. The above radiochronologic data strongly indicate that SDS crystalized at *ca* 920 Ma, younger than the Aguapeí Thrust Belt cooling age which achieved a greenschist metamorphic-peak and produced micaceous minerals (sericite) that yield K/Ar ages ranging from 970 to 870 Ma. This age difference may suggest that the origin of the SDS at an extensional regime post-dates the collisional process of the Aguapeí Thrust Belt.

The Nd isotopic evidence (ε_{Nd} values in the range from −14 to −2) indicates an origin from crustal protoliths. In addition, two SDS samples yielded δ^{18}Ovalues of + 8.6‰ and + 9.0‰, and whole rock chemical analyses indicate a slightly peraluminous character for the SDS rocks, suggesting a mixture probably from a pelitic metasediment and mantle-derived sources for the granite genesis.

SDS is hosted by Mesoproterozoic basement rocks comprising the Santa Helena Suite and by the Pontes e Lacerda Metavolcano Sedimentary Sequence. The Santa Helena Suite is represented by tonalites, orthogneisses and granites and comprises a calc-alkaline suite of 1480 to 1420 Ma related to an extensive arc-related magmatism of the Rondonian/San Ignacio Province and may represent the probable magmatic source for the SDS rocks. Pontes e Lacerda Metavolcano Sedimentary Sequence is represented by ocean floor basalts (*ca* 1.51 Ga), banded iron formations, cherts, and clastic metasediments. Chemical and clastic metasediments of this unit may represent the second source rock for the SDS origin.

SW Amazonian Craton at the Meso-Neoproterozoic boundary and global correlations
The western part of the Amazonian Craton, like the Grenville Province, is a multi-orogenic region formed between 1.8 and 1.0 Ga where successive magmatism, metamorphism and deformation occurred, and variably reworked older provinces. Proterozoic evolution of this sector of the Amazonian Craton allows temporal correlations between the tectonic events in the southwestern Amazonian Craton, Laurentia and Baltica and thereby provides constraints for global reconstructions.

At the Meso-Neoproterozoic boundary, the SW Amazonian Craton was affected by an important continental distension (rifting), represented by basaltic magmatism and deposition of the sediments (Sunsás Group in Bolivia and the Aguapeí Group in Brazil) in a continental margin environment. These episodes were followed by deformation (ca 1000 Ga) and alkali-plutonism (ca 920 Ma) associated with the final stage of regional uplift, cooling and extension, when cratonization was gradually achieved.

Correlatable post-collisional igneous episodes in the Grenville Province are represented by several granite plutons and aplite dykes intruded between ca 966-956 Ma, following the crustal thickening. In the Sveconorwegian orogen (1.1-0.9 Ga) (Baltic Shield) synchronous post-collisional bimodal rift-related AMCG intrusions and dolerites are recorded at a *ca* 966 to 956 Ma interval. Also marking the end of the tectonic activities the Rogaland AMCG complex and other norite-anorthosite complex and related hybrid rocks, which appear to lack Grenvillian correlatives, are recorded in SW Sweden.

TWO-COMPONENT MODEL FOR SOUTHEASTERN AUSTRALIAN GRANITIC ROCKS – REITERATION AND DEVELOPMENT

C.M. Gray[1] & A.I.S Kemp[2]

[1]Department of Earth Sciences, La Trobe University, Vic 3086, Australia
[2]Department of Geology, Australian National University, Canberra, ACT 0200, Australia

The two-component model for the genesis of southeastern Australian granitic rocks (Gray 1984) interplaying crustal- and mantle-derived components, attempted to accommodate the following issues: (a) crustal melting of quartzofeldspathic rocks in high grade metamorphic settings in the region; (b) some granitic rocks have compositions consistent with direct melting of local metasedimentary rocks; (c) the majority of granitic compositions are incompatible with direct melting; and (d) these latter rocks exhibit linear compositional variation and isotopic systems consistent with the involvement of basaltic material in their genesis.

The specifics of the model were as follows. A crustal magma was produced by melting the local quartzofeldspathic metasedimentary substrate, part of the earliest Palaeozoic turbidite succession (the more feldspathic component of high-grade metamorphic areas, rather than the widespread low-grade turbidites). Thus the crustal end-member was a magma akin to the Cooma Granodiorite with a silica content ~ 72%. Increasing degrees of interaction of this crustal magma with batches of basaltic magma drove compositions to lower silica and generated linear compositional variation. Different batches of basaltic magma produced different suites of granites. The model has the ancillary strengths of simple explanations for mafic igneous enclaves and provision of a mechanism for crustal heating.

Post-1984, evidence for basaltic interaction with granitic magmas has been supported by progressively more field evidence, strengthening this aspect of the model. While it is contended that the two-component model remains the simplest and most comprehensive genetic theory, nonetheless, modification is required for it to become more realistic. This expansion involves the nature of the crustal component and comes from consideration of four settings in southeastern Australia where granitic rocks are associated with migmatites. The genetic conclusions are focussed on granitic rocks in the Berridale and Kosciuszko Batholiths.

Crustal component

The issue of whether there is a widespread metasedimentary component in the granitic rocks of southeastern Australia is examined via the geochemistry of quartzofeldspathic metasedimentary rocks from four regional sedimentary packages; sedimentation of these rocks occurred during the tectonic cycle that gave rise to the granitic rocks. Chemical variation diagrams demonstrate that compositions in the 70-75% SiO_2 range have sufficient Ca-Na-K to be fertile compositions for granitic magma generation. Specifically, distinctive geochemical signatures in individual settings link local metasedimentary rocks and granitic rocks of both peraluminous and metaluminous chemistry. The widespread development of zircon with a distinctive inherited age pattern which can be matched in regional turbidites is also consistent with significant metasedimentary involvement. Conclusion: all the granitic rocks considered have a major metasedimentary component; the component was the local, fertile metasedimentary material of the orogenic cycle that gave rise to the granitic rocks.

Regression of geochemical variation diagrams to 72% SiO_2 for granitic rocks of the Berridale and Kosciuszko Batholiths indicates variation in the crustal end-member compositions. The compositions are quartzofeldspathic and unexceptional, though only the most peraluminous match their CaO, Na_2O and K_2O with local metasedimentary rocks; detailed examination of the geochemistry proves that the majority of end-members cannot be bulk samples of metasedimentary material. However, chemical relationships are satisfied if the crustal component ranges from a bulk sedimentary composition to leucosome derived by partial melting of the metasedimentary material. From these considerations it is possible to gain a measure of the extent of leucosome and residuum separation in the magma source.

Mantle-derived component

Physical evidence of interaction between mafic magmas and granitic magmas is seen in numerous features such as synplutonic basaltic dykes, mafic igneous enclaves and calcic cores to plagioclase in some granitic rocks. Gabbros in association with granitic rocks while generally in low abundance are widespread. Primarily two-component interaction is evidenced by linear geochemical variation from granitic to gabbroic compositions as in the Jindabyne Suite. However, limited compositional variation in most granite systems lacking gabbroic members renders projection to hypothetical basalt compositions at ~ 50% SiO_2 imprecise. Nonetheless, the regressions do project to putative basalts with the common feature of a high-Al composition. It is proposed that high-Al basalt is a fundamental ingredient in granite magma genesis.

Reference

GRAY C.M. 1984. An isotopic mixing model for the origin of granitic rocks in southeastern Australia. *Earth and Planetary Science Letters* 70, 47-60.

GRANULITE-FACIES BERYLLIUM PEGMATITES IN THE ULTRAHIGH-TEMPERATURE NAPIER COMPLEX, ENDERBY LAND, EAST ANTARCTICA: RELEVANCE TO FORMATION OF S-TYPE GRANITES FROM PARTIAL MELTING IN THE LOWER CRUST

Edward S. Grew[1], Martin G. Yates[1], Jacques Barbier[2], Charles K. Shearer[3], John W. Sheraton[4], Kazuyuki Shiraishi[5] & Yoichi Motoyoshi[5]

[1]Department of Geological Sciences, University of Maine, 5790 Bryand Center, Orono, Maine 04469, USA
[2]Department of Chemistry, McMaster University, Hamilton, Ontario L8S 4M1, Canada
[3]Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131, USA
[4]Stoneacre, Bream Road, St Briavels, Lydney, Glos GL15 6TL, UK
[5]National Institute of Polar Research, 1-9-10 Kaga, Itabashi-ku, Tokyo 173-8515, Japan

Granulite-facies complexes contain lower crustal rocks in which the beginning of the anatectic process leading to granite formation as envisaged by Allan White (e.g. White & Chappell 1977) can be studied. One possible example of S-type granite formation is exhibited by the ultrahigh-temperature (UHT) Napier Complex (T = 1000-1100 °C, P = 0.7-1.1 GPa, e.g. Harley 1998), where metapelitic rocks are cut by peraluminous pegmatites ca 2500 Ma in age that may represent the initiation of S-type granitic melts. Four of these pegmatites contain Be minerals (Grew 1981; Grew *et al.* 2000). That the pegmatites were emplaced at high temperatures and low water activities is evidenced by the presence of sillimanite + K-feldspar and sapphirine-khmaralite (a Be mineral closely related to sapphirine, Barbier *et al.* 1999) + quartz, in contrast to the muscovite and beryllian cordierite or beryl characteristic of "wetter", lower-temperature pegmatites usually associated with S-type granitic melts. Host rocks to the Be pegmatites are quartz-rich granulites in which sapphirine coexisted with quartz at the peak of the UHT metamorphism.

Three Be pegmatite bodies are *en echelon* pods up to 2 m in length at two localities in Khmara Bay, whereas the fourth is a vein 5 cm thick near Mt. Pardoe. Characteristic of two pods are sillimanite prisms 5-10 cm long, masses 1-5 cm across of wagnerite, $(Mg,Fe)_2PO_4F$, coarse biotite flakes, and aggregates 5-10 cm across rich in surinamite, $(Mg,Fe)_3Al_3O[AlBeSi_3O_{15}]$. The surinamite aggregates are more abundant in the quartz cores of the pods than in the outer microcline-rich zones. Coarse-grained sapphirine-khmaralite is separated from quartz by successive coronas of sillimanite and garnet with surinamite grains concentrated along the boundary between the sillimanite and garnet coronas or inside the latter. Aggregates of hematite-ilmenite intergrowths, sillimanite, musgravite, $(Mg,Fe,Zn)_2Al_6BeO_{12}$, surinamite and/or corundum penetrate sapphirine-khmaralite. The third pegmatite pod is characterized by foliated aggregates of khmaralite, biotite, garnet, surinamite, sillimanite, musgravite and/or chrysoberyl. The Mt. Pardoe pegmatite contains orthopyroxene, wagnerite and rare surinamite.

The Be pegmatites evolved in three major stages. During the first stage, melt from anatexis of sapphirine-bearing metapelites crystallized as pegmatites in inter-boudin spaces soon after temperatures peaked during the UHT event and during the waning stages of associated deformation. The primary carrier of Be in the pegmatites at the time of their intrusion was a sapphirine that after subsequent annealing recrystallized either to khmaralite (when Be > 0.5 atoms per 20 O) or to beryllian sapphirine. The second stage was a discrete event at ~ 800-900 °C, ~ 0.8-0.9 GPa, which resulted in reaction of sapphirine with quartz to form corona assemblages of sillimanite + orthopyroxene (or garnet) in the host rocks and sillimanite + garnet + surinamite in the Be pegmatites. Other investigators have attributed this second stage to isobaric cooling following UHT metamorphism. The third stage includes two metamorphic events at temperatures not exceeding ~ 700 °C. During this stage, surimanite broke down to beryllian cordierite ± Al-poor orthopyroxene. The presence of late-formed andalusite as well as kyanite in the pegmatites indicates that pressures decreased to 0.3 GPA, which is consistent with decompression inferred by other investigators for these two events.

Beryllium is one of the trace elements characteristically enriched in pegmatites associated with S-type granites. Granulite-facies complexes are potentially a source of Be because there is no evidence for loss of Be during granulite-facies metamorphism. For example, Be contents of the Napier Complex quartz-rich granulites hosting the Be pegmatites range from 0.8 to 7.1 ppm and average 3.7 ± 2.1 ppm. This overlaps the range reported for most pelitic and semi-pelitic rocks, both unmetamorphosed and metamorphosed (1-4 ppm Be, Grew *et al.* 2000; cf. calculated Be content of 3 ppm for the upper crust, Taylor & McLennan, 1995). Given geochemical evidence for derivation of the Be pegmatites by anatexis of the host rocks, Grew *et al.* (2000) suggested that Be in the pegmatites originated from the host rocks. The mechanism for mobilizing and concentrating Be in the pegmatites probably involved sapphirine. The Be content of sapphirine in the host-rock is 60 to 600 times the whole-rock Be content. Fluorine is critical to mobilizing Be and the presence of the relatively F-rich minerals, wagnerite, and biotite (1.8-2.2 wt% F), suggests that significant amounts of fluorine may have been present in the pegmatitic melt.

In summary, melting of sapphirine-bearing pelitic rocks under UHT conditions can extract sufficient Be for its concentration in the resulting anatectic melt. S-type granites derived from melting in the lower crust could thus still have Be contents comparable to granites derived from cordierite- or mica-bearing rocks melted at higher levels in the crust as discussed by White & Chappell (1977).

Acknowledgements
Fieldwork was supported by the Australian National Antarctic Research Expedition (1979) and the Japanese Antarctic Research Expedition (1999). ESG's research was supported by U.S. National Science Foundation grant OPP-9813569 to the University of Maine.

References

BARBIER J., GREW E.S., MOORE P.B. & SU S.-C. 1999. Khmaralite, a new beryllium-bearing mineral related to sapphirine: a superstructure resulting from partial ordering of Be, Al and Si on tetrahedral sites. *American Mineralogist* **84**, 1650-1660

GREW E.S. 1981. Surinamite, taaffeite, and beryllian sapphirine from pegmatites in granulite-facies rocks of Casey Bay, Enderby Land, Antarctica. *American Mineralogist* **66**, 1022-1033.

GREW E.S., YATES M.G., BARBIER J., SHEARER C.K., SHERATON J.W., SHIRAISHI K. & MOTOYOSHI Y. 2000. Granulite-facies beryllium pegmatites in the Napier Complex in Khmara and Amundsen Bays, western Enderby Land, East Antarctica. *Polar Geoscience* **13** (in press).

HARLEY S.L. 1998. On the occurrence and characterization of ultrahigh-temperature crustal metamorphism. *In:* Treloar, P.J. & O.Brien, P.J. eds. *What Drives Metamorphism and Metamorphic Reactions?*, pp. 81-107. Geological Society Special Publication **138**.

TAYLOR S.R. & MCLENNAN S.M. 1995. The geochemical evolution of the continental crust. *Reviews in Geophysics* **33**, 241-265.

WHITE A.J.R. & CHAPPELL B.W. 1977. Ultrametamorphism and granitoid genesis. Tectonophysics **43**, 7-22.

OXYGEN ISOTOPE GEOCHEMISTRY OF FELSIC VOLCANIC ROCKS FROM THE LARGE IGNEOUS PROVINCES OF GONDWANA

Chris Harris & Jodie Miller

Department of Geological Sciences, University of Cape Town, Rondebosch, 7700, Republic of South Africa

It was demonstrated by O'Neil & Chappell (1977) and O'Neil *et al.* (1977) that oxygen isotopes provide an excellent means to distinguish S- and I-type granites. Chappell & White (1992) concluded that "oxygen isotopic studies could be the single best discriminant between the two granite types in that area [Lachlan Fold Belt, Australia] but data are unfortunately limited in distribution. As is often the case this parameter might not appear to be such a good discriminator between the two granite types if comprehensive data were available". Oxygen isotopes are well suited to discriminating between S- and I-type sources because the former has distinctly higher (generally $\delta^{18}O$ 10-14‰) than the latter ($\delta^{18}O$ 7-10‰). The fact that oxygen is a major element lends a robustness to any interpretation. The major drawback with oxygen isotopes is that low-temperature alteration tends to increase $\delta^{18}O$ values significantly. This can be overcome by analysing fresh mineral separates.

Large volcanic provinces that developed near present-day continental margins potentially provide an important magmatic record of crustal and mantle geodynamics during the break-up and dispersal of supercontinents. Gondwana has four such large volcanic provinces: the Ferrar (~ 180 Ma: Encarnacion *et al.* 1996), Karoo (~ 180 Ma: Allsopp *et al.* 1984; Duncan *et al.* 1997), the Chon Aike (175-190 Ma: Pankhurst & Rapela 1995) and the Parana/Etendeka (~ 135 Ma: Hawkesworth *et al.* 1992) provinces.

The Chon Aike province is almost entirely felsic, and the Ferrar is almost entirely composed of basaltic rocks. The Karoo and the Parana/Etendeka are dominated by voluminous basaltic volcanism but contain a substantial felsic magmatic component. The felsic volcanic rocks have been relatively neglected by comparison with the associated basaltic rocks in each province, but provide an important record of the input of crust into these large magmatic systems during the initial stages of continental breakup.

The petrogenesis (and the mode of emplacement) of the felsic volcanic rocks of the Karoo and the Parana/Etendeka provinces remain highly controversial. Petrogenetic models vary from prolonged fractional crystallisation accompanied by crustal contamination (Garland *et al.* 1995) to crustal melting (Harris & Milner 1995).

Rhyolites (*sensu lato*) may potentially form from direct fractional crystallisation from basalt, or by high-temperature, anhydrous partial melting of crustal materials (in which case large-volume rhyolites may be thought of as the surface expression of granulite facies metamorphism), or by crustal contamination of basalt. The Lebombo rhyolites of the Karoo province have anomalously low $\delta^{18}O$ values (4.4 to 6.8‰). Harris & Erlank (1992) suggested that these low $\delta^{18}O$ values resulted from high-temperature interaction between circulating meteoric water and the source material which was underplated Karoo-age basaltic magma. At present there are few systematic data available within the rhyolite stratigraphy. In Swaziland a near continuous section is available through 5 km of rhyolite flows. Recent work has attempted to constrain the temporal history of fluid circulation during rifting of the African-Antarctic margin.

Most Etendeka/Paraná rhyolites have generally high $\delta^{18}O$ values (10.1-11.6‰), which indicates a much larger component of continental crust. Any petrogenetic model involving prolonged assimilation-fractional crystallisation of a basaltic parent must invoke improbably large amounts of assimilation and/or an improbably high $\delta^{18}O$ of the contaminant. Thus it is much more likely that these rhyolites were produced by melting of metasedimentary rocks. A minority of Etendeka/ Paraná rhyolites have $\delta^{18}O$ values between 6.5 and 7.7 ‰. It is possible that they were produced by fractional crystallisation accompanied by moderate amounts of assimilation. Alternatively, they represent partial melts of underplated basaltic material of Etendeka/ Paraná basalt as in the case of the Lebombo rhyolites.

References

ALLSOPP H.L., MANTON W.I., BRISTOW J.W. & ERLANK A.J. 1984. Rb-Sr geochronology of Karoo felsic volcanics. *Special Publication of the Geological Society of South Africa* **13**, 273-280.

CHAPPELL B.W. & WHITE A.J.R. 1992. I- and S-type granites in the Lachlan Fold Belt *Geological Society of America Special Paper* **272**, 1-26.

DUNCAN R.A., HOOPER P.R., REHACEK J., MARSH J.S. & DUNCAN A.R. 1997. The timing and duration of the Karoo igneous event, southern Gondwana. *Journal of Geophysical Research* **102**, 18127-18138.

ENCARNACIÓN J., FLEMING T.H., ELLIOT D.H. & EALES H.V. 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana. *Geology* **24**, 535-538.

GARLAND F., HAWKESWORTH C.J. & MANTOVANI M.S.M. 1995. Description and petrogenesis of the Paraná Rhyolites, southern Brazil. *Journal of Petrology* **36**, 1193-1227.

HARRIS C. & ERLANK A.J. 1992. The production of large volume, low-$\delta^{18}O$ rhyolites during the rifting of Africa and Antarctica: the Lebombo Monocline, southern Africa. *Geochimica et Cosmochimica Acta* **56**, 3561-3570.

HARRIS C. & MILNER S. 1995. Crustal origin for the Paraná rhyolites: discussion of 'Description and petrogenesis of the Paraná Rhyolites, southern Brazil' by Garland *et al.* (1995). *Journal of Petrology* **38**, 299-302.

HAWKESWORTH C.J., GALLAGHER K., KELLEY S., MANTOVANI M., PEATE D.W., REGELOUS M. & ROGERS N.W. 1992. Paraná magmatism and the opening of the South Atlantic. *Geological Society Special Publication* **68**, 221-240.

O'NEIL J.R. & CHAPPELL B.W. 1977. Oxygen and hydrogen isotope relations in the Berridale batholith. *Journal of the Geological Society of London* **133**, 559-571.

O'NEIL J.R., SHAW S.E. & FLOOD R.H. 1977. Oxygen and hydrogen isotope compositions as indicators of granite genesis in the New England Batholith, Australia. *Contributions to Mineralogy and Petrology* **62**, 313-328.

PANKHURST R.J. & RAPELA C.R. 1995. Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia. *Earth and Planetary Science Letters* **134**, 23-36.

S-TYPES *VS* S-TYPES: TWO CASE STUDIES FROM SOUTHERN NSW

Janet Hergt[1], Frank Corr[1], Benjamin Patrick[1], Allan White[1], Jon Woodhead[1] & Bruce Chappell[2]

[1]School of Earth Sciences, The University of Melbourne, Vic 3010, Australia
[2]GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia

The Cooma Granodiorite is a most unrepresentative example of S-type magmatism in the Lachlan Fold Belt. It is a regional-aureole granite, with close compositional (including isotopic) similarities to its host metasedimentary rocks (e.g. Pidgeon & Compston 1965; Chappell 1984; Munksgaard 1988; White & Chappell 1988). Even when combined with the Bethanga and Geehi suites into the Cooma Supersuite, the total area is small compared with other S-type granites. Despite the small areal extent, it might be argued that this unusual compositional end-member provides unparalleled opportunities to investigate S-type granite genesis. In short, if we can unravel the processes involved in generating these extreme S-types, this may also constrain the petrogenesis of the volumetrically more significant suites.

Our studies

The observations presented here are based on two detailed studies, conducted in 1998 and 1999 at the University of Melbourne, of an area around Tumbarumba in southern NSW. The first aimed to distinguish the Geehi and Tom Groggin suites in the Maragle Batholith both in the field, and using thin-section observations and bulk-rock compositional data. The second examined a single Geehi Suite pluton in the same area, particularly with respect to intra-pluton whole-rock, mineral and enclave compositional variations. The results of these studies have revealed subtle features which might now be usefully considered within a wider context.

Evidence for two suites of S-type granites in the Maragle Batholith was first revealed from geochemical analysis of samples collected from the region around Geehi (Wyborn 1977), where the compositions were identified as belonging to either the Geehi or Tom Groggin S-type suites. Both types are extensively developed around Tumbarumba which provides a rare opportunity to examine the characteristics of both the Cooma Supersuite (Geehi) and more typical S-type (Tom Groggin) granites together in a single locality.

The two suites often appear very similar in hand specimen but the deeply weathered nature of key outcrops means that mapping individual phases in the main granite body, where they appear to coexist, has not been possible. One single pluton was identified in the Ournie Creek area however, that appears to be entirely Geehi in character.

While distinguishing between Geehi and Tom Groggin samples is difficult in the field, thin-section observations serve to identify the members of each suite. Plagioclase is far less abundant than K-feldspar in the Geehi rocks and, more specifically, there are no Ca-rich cores in the Geehi plagioclase crystals. In general, plagioclase cores vary between An_{40-45}, rather than more calcic than An_{55} in Tom Groggin samples, and oscillatory zoning of the former is absent or very rare. In addition, cordierite grains in Geehi granites invariably contain sillimanite needles throughout, and commonly have inclusions of quartz and biotite (unlike cordierites in Tom Groggin samples).

As with all Cooma Supersuite granites, the Geehi Suite is characterised chemically by low CaO (< 1.5 wt.%), Na_2O (< 1.5 wt.%) and high normative corundum (> 5%). In contrast, Tom

Groggin samples have higher CaO and Na_2O, making them compositionally similar to more typical S-types of the Lachlan Fold Belt. These chemical features are consistent with the observations above where plagioclase would appear to be in excess during partial melting to form the Tom Groggin Suite (i.e. restitic cores), but not so for the Geehi Suite. Thus, small variations in the plagioclase content of the source rocks of these two suites might go some way to explaining both the petrographic and geochemical features observed in our study.

A key finding in the first of our studies was that there is no simple correlation between the apparent 'cleanliness' (e.g. enclave content) and bulk-rock composition of *either* the Tom Groggin or Geehi samples in this area. This is attributed to the dispersal of solid residues in the magma such that even rocks with a low enclave content preserve significant restitic material as individual grains or aggregates of crystals scattered throughout the matrix. For example, in all rocks examined, two types of quartz are preserved. The first comprises clean, regularly-shaped grains, that snap to extinction under crossed polars. The second type consists of irregularly shaped individual grains (< 0.5 mm across) ranging up to aggregates of 3-4 mm across which consist of 3 or 4 sub-grains connected by triple junctions and exhibiting undulose extinction.

It is important that quartz is a significant restite phase in both suites. Most models view the 'evolution' of granite magmas as proceeding from mafic to felsic compositions. Our observations indicate that restite-rich granites might well have enhanced SiO_2 levels owing to the abundance of restitic quartz. Thus at least for the samples of these two studies, much of the compositional spread within and between the two suites can be attributed to variations in both the metasedimentary source-rocks and distribution of solids in the final magmas.

Geehi at Ournie Creek

Building upon the results of the first study, a single, apparently simple pluton of Geehi affinity was selected for more detailed investigation. Here, bulk-rock granite and enclave analyses were performed, and the mineral chemistry of biotite and plagioclase was examined.

An important aspect of this study was to examine the mineralogy and mineral chemistry of mafic microgranular enclaves and the host granite at a number of sites within the pluton. In short, both these enclaves and their host granite share very similar mineralogies (e.g. abundant cordierite and sillimanite). However, plagioclase grains have higher CaO contents in the enclaves compared with the granites, and biotites in the enclaves are generally more MgO-rich. Thus, the mafic microgranular enclaves display broad characteristics that might be expected from early-formed cumulates. These compositions are also co-linear with the rare restite-poor samples, as might be anticipated for a crystal fractionation (*sensu stricto*) trend.

References

CHAPPELL B.W. 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia, *Philosophical Transactions of the Royal Society of London* **A310**, 693-707.

MUNKSGAARD N.C. 1988. Source of the Cooma Granodiorite, New South Wales – a possible role of fluid-rock interactions. *Australian Journal of Earth Sciences* **35**, 363-377.

PIDGEON R & COMPSTON W. 1965. The age and origin of the Cooma Granodiorite and its associated metamorphic zones. *Journal of Petrology* **6**, 193-222.

WHITE A.J.R. & CHAPPELL B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

WYBORN L.A.I. 1977. Aspects of the geology of the Snowy Mountains region and their implications for the tectonic evolution of the Lachlan Fold Belt. PhD thesis, Australian National University, Canberra (unpubl.).

CRUSTAL TOMOGRAPHY OF OLD OROGENS: A GRANITIC PERSPECTIVE

John P. Hogan[1] & A. Krishna Sinha[2]

[1]Department of Geology & Geophysics, University of Missouri-Rolla, Rolla, MO 65409-0410, USA
[2]Department of Geological Sciences, Virginia Tech, Blacksburg, VA 24061, USA

Mapping the extent and geometry of terrane boundaries in the lithosphere is critical to resolving the kinematics of terrane accretion in complex ancient orogenic belts. Geophysical methods are extensively employed in imaging the present subsurface structure of the crust. However, structural and spatial information pertinent to unravelling the kinematics of terrane accretion during older orogenic events are commonly obscured by strain associated with younger plate motions. In contrast, the spatial distribution of granite plutons can be used to "image" the spatial distribution of distinct basement terranes in the middle to lower crust at the time of granite genesis (White *et al.* 1976; Chappell *et al.* 1988). Thus, mineralogical and geochemical studies of granite suites provide geologists with a means of seeing through the effects of younger tectonic events in order to reconstruct the structure of the crust during the associated orogenic event.

In this way, we have utilised I- and S-type granite plutons of the Coastal Maine Magmatic Province to construct a Mid-Palaeozoic image of the structure of the crust underlying a portion of the Caledonide Orogen in northern New England, USA. Granite plutons were subdivided into four suites using field, textural, mineralogical, and compositional criteria. Initial Pb isotopic compositions of these suites define two distinct fields in a $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram and overlapping fields in a $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram. Granites of the peraluminous granitic suite (PGS) and granite stocks of the weakly peraluminous to metaluminous granite suite (WPGS-S) define a composite field that yields a $^{207}Pb/^{206}Pb$ age of 2.0 ± 0.5 Ga. This field overlaps the isotopic composition of basement gneisses of the Avalon Composite Terrane. Granite batholiths of the weakly peraluminous to metaluminous granite suite (WPGS-B) and granites of the metaluminous granite suite (MGS) define a separate composite field with a $^{207}Pb/^{204}Pb$ age of 1.3 ± 0.5 Ga, and lower $^{206}Pb/^{204}Pb$ at the same $^{207}Pb/^{204}Pb$. These granites originated from a different basement terrane, presumably the Gander Terrane. The spatial distribution of granite suites identifies the presence of both basement terranes beneath the proposed surface terranes in coastal Maine. Thus, faults separating terranes at the surface do not persist as fundamental boundaries in the middle to lower crust. This implies that the surface terranes must have been assembled and thrust over the Avalonian basement along a basal décollement prior to initiation of granite magmatism in the early Silurian. Sparse geochronology suggests that granites derived from Gander Terrane basement may be restricted to the Devonian and Carboniferous, allowing for the possibility that the Gander Basement Terrane was thrust beneath the Avalonian Composite Terrane subsequent to the Silurian magmatic event but prior to magmatism that began in the middle Devonian.

References

CHAPPELL B.W., WHITE A.J.R. & HINE R. 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

WHITE A.J.R., WILLIAMS I.S. & CHAPPELL B.W. 1976. The Jindabyne Thrust and its tectonic, physiographic and petrogenetic significance. *Journal of the Geological Society of Australia* **23**, 105-112.

BORON ISOTOPE GEOCHEMISTRY OF S-TYPE GRANITE AND PEGMATITE

Shao-Yong Jiang[1,2]

[1]State Key Laboratory for Mineral Deposits Reseach, Nanjing University, Nanjing 210093, China
[2]School of Earth Sciences, Melbourne University, Victoria 3010, Australia

In recent years, the isotopic composition of the volatile element boron, which is a major constituent of tourmaline, has been used as an innovative geochemical tracer in studies of petrogenesis. Boron is an incompatible element in most common rock-forming minerals and tends to be preferentially enriched in late exsolved volatile-rich fluids during magma evolution. The exsolution of these fluids may lead to depletion of boron and other 'fluid mobile' elements in the granite, and to formation of tourmaline-rich metasomatic halos in the nearby country rocks. Tourmaline represents the only important mineralogical sink for boron in granitic systems, and the study of tourmaline boron isotope compositions can provide important insights into the magma sources, magma-volatile relationships, magmatic-hydrothermal evolutions, and the origin of granitic rocks, particularly the S-type peraluminous leucogranites and pegmatites.

Tourmaline from S-type granite and pegmatite shows a wide variation in $\delta^{11}B$ from -33‰ to +9‰. The lowest $\delta^{11}B$ values have been found from the Lavicky leucogranite in Czech Republic and the Keketuohai pegmatite of Xinjiang, China, and the highest $\delta^{11}B$ values were obtained from a pegmatite dike in the Liaoning borate deposit of China. Most of the $\delta^{11}B$ data from granite and pegmatite cluster between -15‰ and -5‰. It is suggested that the boron isotopic compositions of tourmaline from granite and pegmatite are largely controlled by the composition of the magma source, magma evolution and magmatic degassing, and the P-T conditions of tourmaline formation. The pre-melting history of boron mobilisation and its redistribution in granite source rocks may have pronounced effects on boron concentrations and the $\delta^{11}B$ values of the magma. Three possible sources of boron in the granitic magma are distinguished. Since tourmaline has a wide P-T stability and can persist in metasedimentary rocks up to conditions of anatexis, that mineral represents a most likely reservoir of boron for S-type granitic magmas. Most common rock-forming silicate minerals contain only minor to trace amounts of boron, but muscovite can contain up to several hundred ppm B, and its high modal abundance in clastic sediments may make it a significant boron inventory for granitic magmas in some cases. It is possible that non-marine evaporites could be a significant source of boron for magmas that evolved to produce granites and pegmatites with relatively high boron contents. In this case, the tourmaline tends to show very light boron isotopic compositions. During magmatic degassing, ^{11}B is preferentially partitioned into the vapor/fluid phase, leading to lower $\delta^{11}B$ values in magmatic tourmalines relative to the exsolved hydrothermal fluids.

THE LEUCOSOMES OF METAPELITIC MIGMATITES: SOURCE OR FEEDERS OF S-TYPE GRANITES?

W. Johannes

Institut für Mineralogie, Welfengarten 1, 30167 Hannover, Germany

The metapelitic migmatites of the Turku area (southern Finland) have been investigated in order to elucidate their petrogenesis and possible relations between their leucosomes and adjacent garnet- and cordierite-bearing granites.

The leucosomes are different in shape and size. The extreme cases are metre-thick leucosome sills, and small centimetre-thick patches, lenses and layers called *in situ* leucosomes. Intermediate in volume between these two types are centimetre to decimetre thick layers associated with melanosomes and dark, restite-rich schlieren.

The leucosomes are considered to be the result of dehydration melting. The amount of melt formed by this reaction at peak metamorphic conditions (P = 600 ± 50 MPa; T = 830 ± 30 °C) is estimated from experimental data to be 15 ± 5 wt%. A mass balance calculation based on the composition of restite minerals and the assumption that the leucosomes were pure melts results in 20 wt% melt. The partial melts contained approximately 4 wt% H_2O, they were water-undersaturated, and a_{H2O} was around 0.3 at peak metamorphic conditions.

According to Hölttä (1986) and Van Duin (1992) metamorphism of the Turku area followed a clockwise P-T path for which the retrogressive part may meet the H_2O-saturated solidus at 300 Mpa and 650°C. A few degrees above these conditions approximately 50% of the melt would have been crystallised. Separation of melt and crystals was an important process during cooling of the Turku migmatites.

All leucosomes and garnet- and cordierite-bearing granites are of similar modal composition. The main difference between these lithologies is the fraction of garnet or cordierite. It may be high in the *in situ* leucosomes and is always low in the leucocome sills.

A comparison of the chemical compositions of the leucosome sills and granites shows great similarities. There are only a few systematic differences: The K_2O content is higher in the leucosome sills (6.5 wt%) compared to the granites (5.7%), and the FeO and Mg values are lower in the sills (0.4 and 0.1 wt%) in comparison to the granites (1.9 and 0.5%).

The most striking differences between leucosome sills and granites become visible in their REE patterns. The pattern for the granites is typical for S-type granites, having relatively high contents of light REE, lower portions of heavy REE and a clear negative Eu-anomaly. The REE-pattern of the leucosome sills is contrary to this observation: The content of light REE is low, the portion of heavy REE especially low and the Eu-anomaly is positive.

Different models are given in the literature to explain the special REE patterns of leucosomes. Some authors attribute these patterns to disequilibrium melting (Carrington & Watt 1995; Jung *et al.* 1999), while other authors regard the leucosomes of metasedimentary migmatites as cumulates crystallised from anatectic melts (Sawyer 1987; Ellis & Obata 1992). The importance of the geochemistry of anatectic migmatites for the formation of granite is still under debate (White & Chappell 1990).

A simple model explaining the formation of Turku and migmatites and adjacent cordierite- and garnet-bearing S-type granites can be presented:

- High grade metamorphism produced partial H_2O-undersaturated melts of granitic composition (peak P-T conditions were around 830 °C and 600 MPa).
- The partial melts segregated during synmetamorphic deformation; they were collected and transported within sills (dykes).
- Fractional crystallisation occurred during cooling of the migmatite complex. Quartz and especially alkali-feldspar formed cumulates, the melt portion (?50%) became enriched in H_2O and moved further on.
- The final water-enriched melt crystallised at H_2O-saturated condition and formed the cordierite- and garnet-bearing S-type granites of Turku area.

References

CARRINGTON D.P. & WATT G.R. 1995 A geochemical and experimental study of the role of K-feldspar during water-undersaturated melting of metapelites. *Chemical Geology* **122**, 59-76.

ELLIS D.J. & OBATA M. 1992. Migmatites and melt segregation at Cooma, New South Wales. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 95-106.

HÖLTTÄ P. 1986. Observations on the metamorphic reactions and P-T conditions in the Turku Granulite Area. *Bulletin of the Geological Survey of Finland* **339**, 43-58.

JUNG S., HOERNES S., MASBERG P. HOFFER E. 1999 The petrogenesis of some migmatites and granites (Central Damara Orogen, Namibia): evidence for disequilibrium melting, wall-rock contamination and crystal fractionation. *Journal of Petrology* **40**, 1241-1269.

SAWYER E.W. 1987. The role of partial melting and fractional crystallization in determining discordant migmatite leucosome compositions. *Journal of Petrology* **28**, 445-473.

VAN DUIN J.A. 1992. The Turku Granulite Area, SW Finland: a fluid-absent Svecofennian granulite occurence. PhD thesis, University of Amsterdam, 233 pp.

WHITE A.J.R. & CHAPPELL B.W. 1990. Per migma ad magma downunder. *Geological Journal* **25**, 221-225.

HIGHLY FRACTIONATED CRETACEOUS S-TYPE GRANITES IN THE OGCHEON BELT, KOREA

Yong-Joo Jwa

Department of Earth & Environmental Sciences, Gyeongsang National University, Chinju, 660-701, Korea

Cretaceous granites are widely distributed in the central Ogcheon Belt, Korea. They show specific petrographical features such as micrographic intergrowths and abundant miarolitic cavities, which are indicative of shallow depths of emplacement. The chemical composition of the granites is close to that of haplogranites, and represents water saturated to slightly undersaturated minimum melt composition at less than 200 MPa.

The granites have very restricted SiO_2 contents, mostly between 74 and 78%. Major oxide contents of the granites show slight variation with fractional crystallisation, but trace and rare earth element contents exhibit very well-defined variation trends. Rb, Y, Nb, Th, Ta and heavy REE contents increase, but Ba, Sr and light REE contents decrease with fractionation. Increase of Rb and decrease of Ba and Sr can be explained by feldspar fractionation. The strongly negative Eu anomaly is another indicator of feldspar fractionation. Heavy REE and high field strength element such as Y, Nb, Th, Ta seem to have behaved incompatibly during fractionation. P and Zr contents remain constant with fractionation. These chemical characters suggest that the granites are of a highly fractionated facies.

The granites are of peraluminous ($1.0 < ASI < 1.3$) and contain up to 2% of normative corundum. The Sr initial ratios of the granites are higher than 0.714. Thus they can be discriminated as fractionated S-type.

The Cretaceous granites in the Ogcheon Belt are considered to have been emplaced at the hinterland of the Eurasian continental margin during the post-orogenic stage of the Jurassic Honam Shear Zone. The source materials of the granites would have been the supracrustal sedimentary rocks. Low temperature partial melting of the source produced the parental granitic magma whose composition was close to the minimum melt composition. This S-type magma underwent continuing fractional crystallization and was finally emplaced at shallow depths in the belt.

THE ROLE OF ANATECTIC PROCESSES IN GENERATING COMPOSITIONAL DIVERSITY IN METASEDIMENT-DERIVED GRANITIC ROCKS

A.I.S. Kemp

GEMOC, Department of Geology, The Australian National University, Canberra, ACT 0200, Australia

Variable separation of a residual source component ('restite') is commonly invoked to account for the intrinsic petrochemical diversity of supracrustally-derived ('S-type') granitic rocks. But how much restitic debris is actually entrained by granitic magmas upon migration from the source, and, even more important, is this capable of engendering the observed large compositional range? What is the nature of this material, and what factors control its incorporation or otherwise? Although these remain open questions, they are most likely to be resolved by examination of anatectic phenomena in the source regions of granites, rather than by studies of upper-crustal plutons.

Such a rare window into source-based processes is provided by the Cambro-Ordovician Glenelg River Complex, which exposes a range of strongly peraluminous granites close to their migmatitic metasedimentary protoliths. These phases, referred to as 'Harrow type' rocks, form dykes, plutons and sill-like bodies with abundant magmatic muscovite; the intimate field association with migmatites and the lack of mafic enclaves indicate exclusive derivation by anatexis of the host metasedimentary sequence. Two disparate subgroups are resolved, leucocratic adamellite to tonalite plutons, some of which have spessartine-rich garnet (hereafter felsic Harrow types), and relatively biotite-rich granodiorites, which commonly contain sillimanite (hereafter mafic Harrow types). The former are dominant and markedly heterogeneous on outcrop scale, typically with sheeted structures. Metasedimentary enclaves (mostly unmelted quartzofeldspathic schist) are common. Chemically, a pronounced and uniform depletion in ferromagnesian elements (FeO_t < 1%) is characteristic, along with a narrow silica range (~ 73-75.5%) and high Sr signature (> 230 ppm). Extreme variation in K_2O and Ba over the small silica range is a striking feature. Mafic Harrow types on the other hand contain numerous metasedimentary enclaves (commonly surmicaceous varieties), have distinctly higher TiO_2, FeO_t and Rb/Sr, and extend over a larger range of SiO_2 (~ 71.7-76.7%).

The key to the deciphering the origin of these contrasting subgroups lies with the surrounding migmatitic metasedimentary rocks. Felsic Harrow types are linked to leucosomes of well-segregated stromatic migmatites, generated by water-fluxed, muscovite-involved partial melting of quartzofeldspathic precursors, during which biotite was essentially refractory. Field and chemical evidence suggests that felsic plutons comprise an amalgamation of these leucosome-derived melts, transported from the source via sheet-like conduits and emplaced sequentially as individual, chemically-distinct 'batches'. The low TiO_2, FeO_t and Rb/Sr of felsic Harrow types reflects the minor participation of biotite in anatexis and the remarkably efficient segregation of partial melt from the biotite-rich residuum during melt extraction. Many felsic Harrow types are also undersaturated with respect to Zr and REE, despite sufficient concentration of these elements in the protolith. This is attributed to occlusion of accessory zircon and monazite by melanosome biotite.

The striking chemical heterogeneity across felsic Harrow type plutons, particularly in K_2O, Sr and Ba, therefore cannot be restite-controlled, but results from compositional differences between and within constituent magma batches. This in turn reflects poorly-blended melt contributions from different metasedimentary precursors, and implies that felsic Harrow types do not have a single, specific protolith composition. This aspect is only evident due to the lack of homogenisation between (and within) magma batches during pluton assembly, such that the chemical signature of each separate source component is preserved. In higher level plutons source-related heterogeneities tend to be erased by magmatic processes, so that the evidence for multiple protoliths is masked or obliterated.

In contrast, mafic Harrow type granodiorites are enveloped by melt-rich diatexite horizons and enclose large rafts of these rocks. Unlike stromatic migmatites, diatexites contain a large pervasive melt fraction, with minimal segregation of melt and residual components, resulting from a rapid and slightly higher degree of anatexis. Transitional boundaries, together with chemical and mineralogical similarities, clearly indicate derivation of mafic Harrow types by separation of unmelted residue from a mobilised diatexitic precursor, enhanced by shear-driven magmatic flow. Importantly, the clots, selvedges and schlieren of interwoven biotite-sillimanite ± muscovite that characterise mafic Harrow types are directly correlated with the melanosomes of flanking diatexites, and hence are of unambiguously restitic affinity. Much biotite is also residual, though chemically distinct euhedral grains were magmatically precipitated. With progressive removal of the restite component, mafic Harrow types become more melt-rich and converge towards the compositional field of the felsic Harrow types. Nevertheless, evolved mafic granodiorite variants retain a slightly more biotite-rich character, reflecting the more mafic partial melt of the parental diatexite compared to that of stromatic migmatites. Some fractionation of magmatic biotite may be required before complete chemical overlap between the two granitic subgroups is achieved.

This study shows that residue-poor and residue-replete granitic rocks may be generated from similar protoliths, under similar partial melting conditions during the same geodynamic episode. However, rather than representing end-members of a single magmatic lineage, this dichotomy manifests fundamentally different melt generation and segregation processes in the source, reflected by the development of contrasting migmatite types. Felsic plutons are complementary to stromatic migmatites, and demonstrate that batches of granitic magma may be extracted from chemically disparate protoliths at low melt fraction without wholesale entrainment of refractory material. The ponding of multiple, cleanly-segregated melt batches therefore results in the formation of restite-poor peraluminous plutons *near the source region*. This process strongly fractionates residue-compatible elements and maximises the geochemical signature of partial melting. At the opposite end of the petrogenetic spectrum, mafic Harrow type granodiorites are choked with restite, which was directly inherited from their poorly-segregated diatexitic precursors. Clearly, entrapment of unmelted residue is strongly favoured by the formation and subsequent mobilisation of diatexites.

THE S-TYPE LEINSTER GRANITE IN SE IRELAND

Pádhraig Kennan

Geology Department, University College Dublin, Ireland

The Caledonian granites of Ireland are all linked to the closure of the Iapetus Ocean. All were, with a few possible exceptions, emplaced at about 405-400 Ma. The major intrusions were all intruded into or close to, active shear zones. Diapirism and ballooning, sheeting, block stoping, cauldron subsidence are among the mechanisms involved in their emplacement. Compositional variations have been ascribed to fractionation, magma mixing and/or wall-rock contamination. In some intrusions, late hydrothermal alteration was significant. Mafic rocks (including appinites) of approximately the same age, occurring on the margins or in the envelopes of most of the intrusions, are relatively minor in volume. Interaction between the mantle and the lower crust along deep-going fractures has been suggested as causing and controlling magma generation, interaction and intrusion. This granite suite is not exceptional. Neither are the questions that are usually asked.

The Leinster Granite in southeastern Ireland, an assembly of five plutons separated by narrow screens of schist and gneiss, is the largest of all the Irish intrusions at the present level of exposure. Each of the individual plutons involves similar granite varieties. The typical granite is a two-mica, peraluminous rock characterised, in a patchy manner, by large, zoned microcline megacrysts. Whereas many of these are zoned phenocrysts, others are packed with inclusions. Large muscovite megacrysts are a defining feature of some granite varieties. The granite is ilmenite-bearing and magnetically featureless.

The Leinster Granite is the only major Irish granite routinely designated as S-type. With rare local exceptions, the enclaves are micaceous. Few could not be matched in the metapelitic and metapsammitic rocks of the exposed envelope. As these enclaves broke up, and as they progressively evolved into increasingly diffuse ghosts, they clearly contributed a significant if indeterminate proportion of the granite biotite. Hornblende is absent as are the mafic enclaves that are a feature of other Irish Caledonian granites. Zircons may be apparently pristine euhedral or recycled. The granite chemical composition reflects the variety of granite types distinguished on outcrop.

There are four aspects of the Leinster Granite that are distinctive and significant. The first is the mappable zoning of, in particular, the northernmost plutons. In these, a relatively dark quartz diorite occurs as a marginal variety and in extended curving screens in the interior. Contacts between this quartz diorite and various granodiorites are well defined. Porphyritic and non-porphyritic granodiorites are easily distinguished but difficult to map individually as discrete zones. Contacts between these and similar central rocks characterised by megacrystic muscovite are gradational over a hundred metres. For some time, these different granite varieties have been seen as reflecting a combination of fractionation below the present level of exposure, intrusion in discrete pulses, marginal contamination and, for the granites with megacrystic muscovite, pervasive hydrothermal overprinting. There is no explicit evidence for magma mixing.

The megacrystic muscovite is a second important and distinctive facet of the granite. Individual crystals are large (10 mm) and many are euhedral. Although similar muscovite occurrences have been described from other granites, the complex growth history they reveal seems not to have been recognised elsewhere. In each megacryst, compositional zoning provides a detailed record of oscillatory growth punctuated, at intervals, by corrosion events. The growth of sillimanite, biotite and zircon may be tied to intervals of corrosion or to particular zones. Perhaps, surprisingly, each individual megacryst appears to record a unique growth history. The observation that initial muscovite growth did not involve nucleation on a surface, though arguably favouring a magmatic origin, does not rule out late hydrothermal growth. What is certain is that this common granite mineral can more than match plagioclase in the detail of the growth record it retains – a record that is easily revealed. It is also certain, that in Leinster, hydrothermal muscovites characterise the best of building stones.

The third distinctive and, in the Irish context unique, feature of the Leinster Granite is the extent and variety of the mineralisation linked to it. Pb and Zn sulfides in granite-hosted quartz and carbonate veins, W and Sn enrichments in altered granite, Li in spodumene pegmatite, Ag, Au, Be etc., occur on and near the eastern margins of a number of the constituent plutons. Though previously tied to the granite crystallisation, these deposits are spatially associated with a horizon of distal volcanic-exhalative rocks in the granite aureole. The most distinctive of these rocks are coticule (manganese-garnet quartzite) and tourmalinite which, with the associated mafic meta-volcanic rocks, constitute a superb stratigraphic marker of, probably, lowermost Ordovician age.

Whole-rock Rb-Sr data provide a fourth perspective on the granite. In the apparently identical granodiorite(s) lacking megacrystic muscovite that make up the bulk of the intrusion, model initial $^{87}Sr/^{86}Sr$ ratios increase with depth - from the granite margin inwards. Sm-Nd data confirm this trend. This whole-rock progression continues into the spodumene-bearing pegmatites on and outside the granite margin. Low initial $^{87}Sr/^{86}Sr$ suggest that these are genetically linked, not with the supposedly most evolved granites of the main intrusion, but rather with the mafic and flux-rich coticule-bearing envelope rocks and with small diorite bodies occurring as satellites fringing the main intrusion.

The Sr-isotope variation in the Leinster Granite is just one element in a coherent and robust, regional Rb-Sr isotope pattern that is defined by all of the raw data available from many sources for the Irish (and British) Caledonian intrusions. For the Leinster Granite, as for many of the others, whatever happened at about 400 Ma clearly failed to homogenise the $^{87}Sr/^{86}Sr$. The regional pattern seems undisturbed by alteration and/or any erratic loss of radiogenic Sr but is easily blurred if calculated model or isochron initial ratios are used. Source inheritance seems to be reflected rather than the fractionation of magma. It is difficult to visualise the Leinster Granite, or any of the other intrusions, as having moved far from their source.

The Leinster Granite is just one S-type Caledonian intrusion. However, along with its mineralisation and its aureole, it occupies its own definable niche in a regional pattern involving continuity along strike. Northward and upward variation is reflected in the occurrence of granites of more I-type aspect. The coherency of a source for all on the margins of the Iapetus Ocean appears to be retained.

Acknowledgements
Thanks are due to Eileen Doyle, Mark Jones, Vincent Gallagher, Patrick Roycroft, Peadar McArdle, Peter Mohr, Susan Pyne, Aileen O'Brien and other students and colleagues at UCD for many useful debates.

VOLATILE EVOLUTION DURING MAGMA GENESIS: IMPLICATIONS OF CO_2 SOLUBILITY EXPERIMENTS ON ANDESITIC (DIORITIC) COMPOSITIONS

P.L. King[1,2] & J.R. Holloway[1,3]

[1]Geology Department, Arizona State University, Tempe, AZ 85287, USA
[2]Earth Sciences Department, University of Western Ontario, London, ON N6A 5B7, Canada
[3]Chemistry Department, Arizona State University, Tempe, AZ 85287 USA

Water and carbon dioxide are the major volatile species in igneous rocks and they dominate the gas emitted from active andesitic volcanoes (Symonds *et al.* 1994). Relative to H_2O, CO_2 has a high vapor pressure and rapidly forms a gaseous phase or low density fluid. For this reason, CO_2 solubility data are needed to model the physical properties of magmas, volcanic degassing and the formation of hydrothermal ore deposits.

We determined CO_2 solubilities in andesite melts with a range of compositions. Melts were equilibrated with excess C-O(-H) fluid at 1 GPa and 1300 °C in a piston-cylinder apparatus and then quenched to glasses. Samples were analysed using the electron microprobe (major elements), ion microprobe (C-O-H volatiles), and Fourier Transform Infrared spectroscopy (C-O-H species).

The effect of H_2O on CO_2 solubility

Since the amount of H_2O in igneous magmas generally exceeds the amount of CO_2, the effect of dissolved H_2O on CO_2 solubility in a melt is important. We examined how CO_2 solubility is affected by varying the melt H_2O content (a reflection of H_2O activity, a_{H_2O}, in the system). There is some dispute as to whether changing a_{H_2O} affects CO_2 solubility, and therefore whether CO_2 solubility is proportional to carbon dioxide activity (a_{CO_2}) and follows Henry's Law. Experiments have shown that CO_2 solubility is not readily described by Henry's Law at high pressure, but is at low pressure (Holloway & Blank 1994).

In anhydrous andesite (Mt. Hood ~ 60 % SiO_2), CO_2 solubility is ~ 0.4 wt% at 1300 °C and 1 GPa. If constant extinction coefficients are used for C-O species, then total CO_2 solubility increases by about 0.04 wt% per wt% of H_2O. As H_2O increases from 0 to 5 wt%, molecular CO_2 decreases (0.07 ± 0.01 wt% to ~ 0.01 wt%) and CO_3^{2-} increases (0.24 ± 0.06 wt% to 0.59 ± 0.08 wt%). Since total CO_2 solubility depends on H_2O content, Henry's Law does not readily describe CO_2 solubility. Specifically, CO_2 solubility increases with decreasing calculated mole fraction of CO_2 in the fluid (~ activity of CO_2 in the melt).

During decompression of a magma, the volatile species partition into a vapour or brine phase, dependent on factors such as pressure, initial volatile concentration, solubility and alkali saturation index. The findings of this study show that H_2O enhances CO_2 solubility in andesite melts at 1 GPa. Since CO_2 is more volatile than H_2O, it degasses at greater depth and may constitute the initial magmatic volatile phase if CO_2 is the most volatile species present. The initial degassing pressure will be lower for melts with higher H_2O contents, all other factors being equal. Also, because H_2O enhances CO_2 solubility, the quantity of CO_2 dissolved in the melt, at a given pressure, will be higher. Such a process means that bubble nucleation would occur at shallower levels and fluid production (Δ(mass of CO_2)/ΔP at constant temperature and composition) will be greater. If this is true, then degassing/fluid evolution models need to be re-evaluated.

The effect of melt composition on CO_2 solubility

Few studies of CO_2 solubility exist for intermediate melts, although they are volumetrically important rocks in subduction zones and span a range of compositions (e.g. low-K tholeiitic to high-K alkali andesites). We examined CO_2 solubility in andesite glasses with low H_2O contents (<1 wt%) and variable Ca, K, or Mg contents.

We found that CO_2 solubility is negatively correlated with (Si + Al) cations and positively correlated with cations with large Gibbs free energy of decarbonation (similar to Dixon 1997). Combining our andesite data with literature data (H_2O < 1 wt%), we find that: molecular CO_2 is more abundant in highly polymerised melts with ionic porosities greater than ~ 48% (ionic porosity=100*[1–(mol. vol. from ionic radii/(mol. vol.$_{melt}$ from Lange & Carmichael 1987))]) and high bridging oxygen/total oxygen (> 0.93). Carbonate dominates most silicate melts and is favoured in melts with low ionic porosities, low bridging oxygen/total oxygen (<< 0.93) and abundant cations with large Gibbs free energy of decarbonation.

The results of this study show that, among the andesites, high-Ca melts have the highest CO_2 solubility. This finding has implications for the evolution and genesis of andesites. If andesites are derived from melting a subducting slab, then a more Ca-rich slab will result in an andesite with relatively high CO_2 content. In contrast, if andesites are produced by volatile fluxing of the Ca-poor mantle then CO_2 solubility will be relatively low.

In nature, the Ca content of andesitic melts is limited by precipitation of calcic plagioclase, clinopyroxene, and Ca-rich amphibole. Crystallisation of those minerals during cooling will decrease the Ca content of the melt, causing CO_2 saturation to be reached sooner than if Ca-poor phases crystallised. A consequence of crystallisation is that Ca-rich melt inclusions in clinopyroxene or plagioclase may have higher CO_2 contents that the melt that equilibrated after the mineral crystallised. This process may resolve the high CO_2 contents found in melt inclusions in some basalts (e.g. Johnson *et al.* 1994).

Our study shows no correlation between K_2O and CO_2 contents for the andesitic samples; this was also demonstrated for sea floor basalts (Johnson *et al.* 1994). One might expect that K-rich magmas would contain higher CO_2 contents based on 1) the correlation between K and CO_3^{2-} for literature samples; 2) abundant CO_2 in K-rich rocks (kimberlites, leucitites etc.); and 3) the high Gibbs free energy of decarbonation for K. In the samples we studied, it is possible that other cations (e.g. Ca) have a more influential role in coordinating CO_3^{2-} in the melt. Perhaps CO_2 solubility is enhanced in natural K-rich melts because K is the major cation coordinating CO_3^{2-} anions.

References

DIXON J.E. 1997. Degassing of alkalic basalts. *American Mineralogist* 82, 368-378.

HOLLOWAY J.R. & BLANK J.G. 1994. Application of experimental results to C-O-H species in natural melts. *In:* Carroll M.R. & Holloway J.R. eds. *Volatiles in Magmas*, pp. 187-230. Mineralogical Society of America, Washington DC.

JOHNSON M.C., ANDERSON A.T. & RUTHERFORD M.J. 1994. Pre-eruptive volatile contents of magmas. *In:* Carroll M.R. & Holloway J.R. eds. *Volatiles in Magmas*, pp. 281-330. Mineralogical Society of America, Washington DC.

LANGE R.A. & CARMICHAEL I.S.E. 1987. Densities of Na_2O-K_2O-CaO-MgO-FeO-Fe_2O_3-Al_2O_3-TiO_2-SiO_2 liquids: New measurements and derived partial molar properties. *Geochimica et Cosmochimica Acta* 51, 2931-2946.

SYMONDS R.B., ROSE W.I., BLUTH G.J.S. & GERLACH T.M. 1994. Volcanic-gas studies: methods, results, and applications. *In:* Carroll M.R. & Holloway J.R. eds. *Volatiles in Magmas*, pp. 1-66. Mineralogical Society of America, Washington DC.

HIGH TEMPERATURE FELSIC A-TYPE GRANITES: THE WANGRAH SUITE, LACHLAN FOLD BELT

P.L. King[1] & A.J.R. White[2]

[1]Department of Earth Sciences, University of Western Ontario, London, Ontario N6A 5B7, Canada
[2] Department of Earth Sciences, La Trobe University, Vic 3086, Australia

A-type granites are a minor but distinctive component of the granites of the Lachlan Fold Belt of southeastern Australia (Collins *et al.* 1982; Clemens *et al.* 1986; Whalen *et al.* 1987; King *et al.* 1997). They are felsic rocks with SiO_2 contents ranging from 69.7 to 77.1%, with an average of 73.8% (55 analyses). When unfractionated, as evidenced by high Ba contents, they are distinguished from felsic I-type granites by greater abundances of high field strength elements, such as Zr.

The Wangrah Suite contains a diverse association of A-type granites, comprising four main units with considerable textural variation. The Danswell Creek Granite is a white, equigranular, medium-grained, hornblende-annite monzogranite. The Wangrah Granite is a pink-grey to white annite ± hornblende monzogranite that is distinguished by a variably porphyritic texture and local rapakivi texture. The Eastwood Granite is a red annite monzogranite characterised by K-feldspar (< 25 mm long) and quartz (< 10 mm across), set in a fine- to medium-grained groundmass (> 75% of the rock). The Dunskeig Granite is a red, equigranular, medium-grained annite monzogranite. Biotite-muscovite aplites of varying texture and composition are found in all major granite bodies of the suite. Enclaves include both felsic and mafic microgranular enclaves and sedimentary xenoliths.

The least felsic granites from the suite (Danswell Creek Granite ~ 70% SiO_2) have compositional features that suggest that they represent parental magma compositions. The most felsic granites (Dunskeig Granite ~ 76% SiO_2) were derived from such compositions by fractional crystallisation. The Wangrah Suite granites were emplaced at shallow levels (~ 200 MPa), at high zircon saturation temperatures (> 830 °C) and relatively low water activity.

Geochemical trends do not support derivation of the granites via magma mixing or fractionation of the adjacent Jerangle basalts. We favour derivation of the Wangrah Suite from high-temperature partial melting of a refractory, H_2O-poor, quartzofeldspathic source region (Creaser *et al.* 1991; Landenberger & Collins 1996). The relatively refractory nature of the source rocks may have been due to limited H_2O content.

The compositionally variable Wangrah Suite differs from homogeneous A-type suites, such as the Gabo Suite to the southeast (Collins *et al.* 1982). Differences between A-type granite suites could be a function of magma ascent and emplacement processes. A-type granites from extensional settings are likely to form diapir-like intrusions that are melt-rich and cool before significant crystal fractionation occurs (e.g. granites from the Gabo Suite). In contrast, melt-rich granites that ascend relatively slowly in the crust may show chemical and petrographic evidence of fractional crystallization. In the case of the Wangrah granites, the magmas may have ascended in this manner, but late-stage emplacement, along a major fault at shallow levels, produced considerable textural variability.

References

CLEMENS J.D., HOLLOWAY J.R. & WHITE A.J.R. 1986. Origin of an A-type granite: experimental constraints. *American Mineralogist* **71**, 317-324.

COLLINS W.J., BEAMS S.D., WHITE A.J.R. & CHAPPELL B.W. 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. *Contributions to Mineralogy and Petrology* **80**, 189-200.

CREASER R.A., PRICE R.C. & WORMALD R.J. 1991. A-type granites revisited: assessment of a residual-source model. *Geology* **19**, 163-166.

KING P.L., WHITE A.J.R. & CHAPPELL B.W. 1997. Characterization and origin of aluminous A-type granites of the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* **36**, 371-391.

LANDENBERGER B. & COLLINS W.J. 1996. Derivation of A-type granites from a dehydrated charnockitic lower crust: evidence from the Chaelundi Complex, Eastern Australia. *Journal of Petrology* **37**, 145-170.

WHALEN J.B., CURRIE K.L. & CHAPPELL B.W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* **95**, 407-419.

SEDIMENT MATURITY AND THE FERTILITY OF S-TYPE GRANITE SOURCES: A LESSON FROM THE HILLGROVE SUITE, NEW ENGLAND BATHOLITH.

Bill Landenberger

School of Geosciences, University of Newcastle, Callaghan, NSW 2305, Australia

Most recent theoretical considerations and experimental investigations of water undersaturated (dehydroxylation) partial melting, contend that the water content of any given source rock is the overriding factor in melt fertility considerations. In these models, melt fertility may then be directly linked to the percentage of hydrous mineral phases in the source, and hence pelites, with their typically high modes of such phases, are regarded by many as the most likely sources of S-type granites. However, if any potential source rock is deficient in one of the primary low-melting constituents (quartz-albite-orthoclase), then the fertility at given P-T-a_{H_2O} condition will be restricted. For example, compared to typical granite compositions (and the ternary minimum) in the Q-Ab-Or system, many pelites are generally deficient in Ab, while greywackes may be deficient in either the Q or Or component, and quartz-rich psammites are deficient in both the Or and Ab components. If one or more of these components are depleted during partial melting, any further melting will deviate from the ternary Q-Ab-Or eutectic, and hence an increase in temperature is required.

In eastern Australia, granites of the Hillgrove Suite (New England Batholith) represent a more unusual group of S-type magmas that are more easily explained through the melting of fertile (volcanogenic) greywacke sources. Geochemical characteristics, combined with Sr and Nd isotopic compositions of the granites and various potential source rocks, provide tight constraints on possible sources. Only volcanogenic greywackes with compositions in the range of 64-67% SiO_2 overlap with the isotopic composition of the granites. Calculated melt fertilities of various potential source rocks, based on Q-Ab-Or compositions relative to the ternary eutectic at 500 MPa, also indicate that these greywackes are the most likely sources to produce large volumes of partial melt. Significantly, the isotopic characteristics and calculated melt fertilities preclude the involvement of pelites and more quartz-rich wackes (~ 70% SiO_2), which have previously been inferred as granite sources. The isotopic and chemical immaturity of these sediments ($^{87}Sr/^{86}Sr$ = 0.7048 to 0.7070, ε_{Nd} = +2 to -1, high Na_2O and low ASI), explains the unusual character of Hillgrove Suite granites, which are isotopically primitive ($^{87}Sr/^{86}Sr$ = 0.7040 to 0.7065, ε_{Nd} = -1 to +4), only mildly peraluminous (ASI = 1.00 - 1.15), and relatively high in Na_2O (3 - 4%) compared to most S-type granites. Major and trace element modelling indicate that the more mafic magmas of the suite (68-70% SiO_2) were produced by ~ 48% partial melting of the intermediate greywacke source, under water-undersaturated conditions involving biotite breakdown at granulite facies conditions and mid crustal depths (~ 500 MPa).

Hence, even though experimental and petrogenetic studies demonstrate that pelites are good sources for strongly peraluminous S-type granites, more sodic S-types that are only moderately peraluminous, such as those of the Hillgrove Suite, are more likely to have been derived from sources such as volcanogenic greywackes. Although few experimental data are available for the partial melting of greywackes, those of appropriate composition (i.e. near to the ternary minima) may constitute sources potentially more fertile than pelites. This also implies that the Q-Ab-Or compositions of potential source rocks may be just as (if not more) important than water content in melt fertility considerations.

THE CHEMICAL SIGNATURE OF S-TYPE GRANITIC MELTS

David London

School of Geology & Geophysics, University of Oklahoma, Norman, OK 73019, USA

White & Chappell (1983) recognised and delineated S-type granites on the basis of their chemical and mineralogical signature. The metallogeny of the S-types is also distinctive, with a Li-Cs-Ta (LCT) enrichment (Cerný 1991). In this paper, I review mostly experimental work performed by our research group at Oklahoma that elucidates how S-type melts acquire their chemical characteristics, and how that signature is amplified during fractionation to produce the LCT class of ore deposits.

Aluminum Saturation Index

Minimum melts in the system Ab-Or-Ms-Bt-Qtz are strongly peraluminous, with compositions for H_2O-saturated melts at 200 MPa represented by the wt% norm of $Ab_{30}Or_{30}Qtz_{34}Cor_6$ or $Ab_{30}Ms_{20}Or_{15}Qtz_{35}$. The Aluminum Saturation Index (ASI) of this H_2O- and muscovite-saturated melt is ~ 1.35; ASI values of granitic melts saturated in other peraluminous minerals at the same P_{H2O} and 800 °C vary as follows: tourmaline (1.45) > cordierite (1.30) = sillimanite (1.30) = kyanite (1.30) > andalusite (1.20) = corundum (1.20). Preliminary results of corundum- or tourmaline-saturated melts at the same P and T indicate that a reduction of a_{H2O} leads to reduction in ASI. This results from an increase in the activity of alumina, e.g. by a schematic melt reaction $Al_2O_3 + H_2O\downarrow \Leftarrow 2\ AlO(OH)$. Kinetic effects related to dissolution and diffusion of corundum and aluminosilicate components may also play a part in generating S-type partial melts with ASI values lower than expected. At 200 MPa H_2O and 800 °C, the ASI of melt in corundum-melt diffusion couples changes almost instantly via long-range diffusion of alkalis to a narrow boundary layer at the corundum-melt interface. The ASI of the initially metaluminous bulk melt shifts to 1.1 and persists close to this value. At 5 mm distance from a corundum-melt interface, which simulates two corundum grains in rock separated by a melt column 1 cm in length, the ASI of melt increases as a power function of time. Extrapolated to an equilibrium ASI of 1.20, this melt column would require ~ 100 years to achieve equilibrium with the corundum grains by diffusion.

Mafic components

The mafic (Fe + Mg) content of hydrous S-type melts is low at minimum-melting conditions with ~ 1 wt% total mafic oxides, and increases to only ~ 2.5 wt% oxides at 850 °C. This low mafic content, which corresponds to ~ 5 norm wt% of Bt, Crd, Gt, etc., helps to identify granites or leucosomes that may contain mafic restite. Mn is less compatible than the other mafic components in crystalline silicates and oxides, and hydrous near-minimum peraluminous melts can accommodate ~ 1 wt% MnO before achieving saturation in spessartine.

Rare alkalis and alkaline earths

The distributions ($D_i^{mineral/melt}$) of rare alkalis (Li, Rb, Cs) and alkaline earths (Be, Sr, Ba) between RFM (micas, feldspars, cordierite) and partial melts have been calibrated experimentally. Though measured partition coefficients are variably T-dependent, crystal structure (i.e., the crystallographic limits on solid solution) plays the dominant role in the distribution of these trace elements. For the dark micas, the experimental partition coefficients are ≥ 1 for Li (1.7 to 1.0), Rb (~ 2.0), and Ba (~ 14 to 6), and < 1 for Be (~ 0.46), Sr (~ 0.04), and Cs (~ 0.4). Partition coefficients for white micas are similar: Li (~ 0.8), Rb (1.6), Cs (0.3) and Be (0.96), Sr (0.05), and Ba (3-6). For the alkali feldspars, distributions of Ba and Rb vary with Or content: $D_{Ba} = 0.07 + 0.25(Or)$, and $D_{Rb} = 0.03 + 0.01(Or)$, where Or is in mole %. Values of D_{Sr} are between 10 – 14, D_{Be} from 0.13 (Or) to 0.19 (Ab), and $D_{Cs} = 0.13$. Cordierite is notable for the compatibility of Be (D_{Be} = 7-188) with D values varying inversely with *T*. These data can be used to predict the rare alkali and alkaline earth signatures of peraluminous magmas during anatexis and crystallisation. The tendency of S-type melts to carry a distinctive enrichment in Li and Cs (and relative depletion in Rb, Sr, and Ba) follows from anatectic reactions in which white mica persists beyond the solidus temperature of the metapelite and then breaks down to Or + Als or Cor, from which restite the melt eventually separates. This scenario promotes the generation of small volumes of melt that may contain relatively high and distinctive LILE contents from the outset. Be-enriched melts (starting at ~ 6-8 ppm Be) that generate beryl-bearing pegmatites cannot originate or crystallise in the presence of Crd. Micas also can sequester Li and Rb, but only when coupled with F.

Volatiles and fluxing components

S-type melts are hydrous but probably H_2O-undersaturated at source, and the ubiquitous presence of graphite ensures a high aCO_2 that probably saturates melts in a fluid phase (though low in H_2O) early in the history of ascent. Combinations of F, and especially B and P, however, distinguish S-types from most other granite groups. F is regulated by its compatibility in micas (D_F = 1.5-2.5, $D_F^{Bt/Ms} \approx 1.3$) but is largely unbuffered during melt fractionation. Monitors of F in LCT pegmatites (e.g., amblygonite-montebrasite solid solutions) indicate that these melts rarely exceed 1-2 wt% F, even at the most advanced stages of crystallisation. B derived from the breakdown of tourmaline and micas increases during fractionation to tourmaline-saturating equilibria involving Bt, Crd, Gt, or Spl. The low mafic content of S-type melts, however, means that this reaction is quickly exhausted and B increases unbuffered, perhaps past several wt% B_2O_3 in highly fractionated leucogranites and pegmatites. In contrast, various silicate-phosphate equilibria buffer the accumulation of P in melt to values not likely exceeding 1-3 wt% P_2O_5. The compatibility of P in alkali feldspars at high ASI of melts also moderates the increase of P with differentiation.

Rare-element LCT pegmatites

Crystal fractionation in S-type magmas can generate pegmatite-forming melts that may contain up to ~ 2 wt% Li_2O (saturated in spodumene or petalite), 0.1 wt% BeO (at beryl saturation), 4.5 wt% Cs_2O (at pollucite saturation), 1-3 wt% each of F and P_2O_5 (moderated by micas, feldspars, and phosphates), and ≥ 2-4 wt% B_2O_3 (at or beyond the tourmaline saturation reaction). Such liquids are capable of dissolving large quantities of H_2O, which forestalls vapor separation, and lithophile HFSE – together promoting small but highly concentrated ore deposits at the end of the magmatic cycle. Exotic LCT pegmatites cannot originate directly by anatexis; crystal fractionation in excess of 95% is needed to bring even enriched S-type anatectic melts to ore grade. Restite separation, followed by multiple stages of crystallisation and efficient extraction of residual melts (from batholiths to apical plutons to pegmatites), are required to produce these rocks from initially large batches of magma.

References

CERNÝ P. 1991. Fertile granites of Precambrian rare-element pegmatite fields: is geochemistry controlled by tectonic setting or source lithologies? *Precambrian Research* **51**, 429-468.

WHITE A.J.R. & CHAPPELL B.W. 1983. Granitoid types and their distribution in the Lachlan fold belt, southeastern Australia. *In:* Roddick, J.A. ed. Circum-Pacific Plutonic Terranes, pp. 21-34. *Geological Society of America Memoir* **159**.

ARE S-TYPE GRANITES CONTAMINATED I-TYPES ? THE DEVONIAN COBAW COMPLEX, CENTRAL VICTORIA

Roland Maas[1], Tod. E. Waight[1,2], Ian A. Nicholls[3] & James A.C. Anderson[1,4]

[1] Department of Earth Sciences, La Trobe University, Vic 3086, Australia
[2] Danish Lithosphere Centre, Copenhagen, Denmark
[3] Dept. of Earth Sciences, Monash University, Vic 3168, Australia
[4] Johnson's Well Exploration N.L., Leonora, WA 6438, Australia

Two competing end-member models for S-type magma genesis pervade the literature: (i) S-type magmas are derived solely from melting of crustal (sedimentary) rocks; (ii) S-type magmas are produced via large-scale hybridisation and/or crustal assimilation processes and contain mantle-derived components. In southeastern Australia, Cooma-type granites come closest to the crustal melting end-member process but the isotopic compositions of the much more abundant Bullenbalong-style S-type granites can be explained in terms of either model.

The problem of S-type magma genesis has been explored in the Cobaw Complex ca 100 km north of Melbourne. Cobaw is a rare example of a zoned intrusion: a central hornblende-bearing I-type granite, the Baynton Granodiorite (375 km^2) is surrounded by a 1-6 km wide rim of the cordierite-bearing S-type Pyalong Adamellite (225 km^2). The complex is undeformed and stitches the Heathcote Fault Zone which separates low-grade turbidites of Ordovician (west) and Silurian age (east). The fault zone itself exposes Cambrian greenstones and shales. Field observations at Cobaw support a model of simultaneous emplacement of contrasting but genetically related felsic magmas (Fermio 1984). In this model, invasion of hot I-type magma (with a mantle-derived magma component) into mid-crustal metasediments produced S-type magma. Upwelling of the more primitive granite magma into the anatectic zone, followed by joint emplacement and high-level ballooning produced the gradational, convoluted contacts between, and the concentric arrangement of, the two granite phases. K-Ar, Ar-Ar and SHRIMP U-Pb data support essentially simultaneous emplacement at 367 ± 2 Ma. The complex therefore appears suitable for exploring possible genetic links between the two granite types; these may in turn be used to test if some S-type magmas could indeed be produced by large-scale crustal contamination of a more mafic, metaluminous magma.

Cobaw forms part of the Late Devonian Central Victorian Magmatic Province (CVMP) which differs in many aspects from the better-known granite batholiths in the eastern portion of the Lachlan Fold Belt. For example, the Pyalong, like the much larger Strathbogie Complex 50 km to the northeast, is typically higher in SiO_2, more reduced, and was emplaced at shallower level. All CVMP rocks, including the I-types, are high in Ba (up to >1000 ppm; Phillips *et al.* 1981; White & Chappell 1988). Initial Sr-Nd isotopic compositions for Baynton ($^{87}Sr/^{86}Sr$ 0.7085, ε_{Nd} −3.5) are similar to those for Pyalong (~ 0.7105, -4.5), and at least the latter shows very limited isotopic variation. Mafic enclaves occur in both granite phases and form chemical and isotopic mixing arrays with their respective hosts. This suggests at least local magma mixing during emplacement. High-grade metasedimentary enclaves in Pyalong, ranging from unmelted paragneisses to melt-depleted biotite-rich types, have distinctly higher $^{87}Sr/^{86}Sr$ and lower ε_{Nd} (0.711-0.723; -7.2 to −10.8) than their host (Anderson 1997). Their chemical and isotopic compositions substantially overlap those of high-grade enclaves in other S-type granites and those of the Ordovician/Silurian turbidites exposed at the surface. High-grade enclaves of this type may represent unmelted and/or residual material from the granite source. However, the considerable isotopic contrast between the enclaves and their host does not support this; the enclaves are either accidental xenoliths or represent only part of the magma source.

Despite differing mineralogy and bulk composition, the I- and S-type components of the Cobaw Complex show some interesting similarities, e.g. their Nd-Sr isotopic ratios, high Ba contents and their relatively low Fe^{3+}/Fe^{2+}. These may be related either to similar source rocks or to syn-magmatic processes (magma mixing or assimilation of Pyalong-type source rocks into the Baynton magma). The isotopic data can be accommodated in a simple mixing model using a variety of end-member compositions. We chose the metasedimentary enclaves as a possible crustal end-member. They represent lithologies present in the mid crust at the time of anatexis, and their average Rb/Sr systematics approximate the inferred crustal end-member for CVMP granites proposed by Gray (1990). The other end-member is a magma of tonalitic composition with the isotopic characteristics of the Heathcote Cambrian greenstones (broadly following Collins 1996). The models indicate that Baynton contains ~40% and Pyalong ~50% crust. As usual, the chemical data are not easily reconciled with such mixing. Compared to Pyalong, most mixtures are too high in Fe, Ti, Mg, Ca, Cr and Ni, and too low in K. However, the magma is likely to have undergone some fractional crystallisation after mixing which would drive magma compositions towards those observed in Pyalong. High Ba could have been derived from the source lithologies of the enclaves; the latter carry between 450-4500 ppm Ba mostly hosted in alkali feldspar (Anderson 1997). Silicic melts from such rocks would therefore be an adequate source of Ba. Syn-magmatic mixing processes, followed by a degree of fractional crystallisation, therefore appear to be capable of producing both Pyalong and Baynton compositions, supporting syn-magmatic mixing models proposed for the Lachlan Fold Belt granites in both central Victoria and southeastern New South Wales (Gray 1990; Collins 1996). However, zircon inheritance data for Pyalong (Anderson 1997) are not readily accommodated in such a mixing model. Instead, they support a purely Cambrian source. Volcano-sedimentary rocks of Cambrian age are known to underlie the Ordovician in Central Victoria. The more primitive Nd isotopic composition of these source rocks would explain the relatively high ε_{Nd} of Pyalong and other CVMP S-type complexes and would remove the need for significant syn-magmatic input of more primitive magma. Distinguishing between these competing models is not straightforward at present and will require further isotopic (e.g. single crystal zonation) and zircon inheritance data for the CVMP.

References

ANDERSON J.A.C. 1997. PhD thesis, La Trobe University, Melbourne (unpubl.).

COLLINS W.J. 1996. S- and I-type granitoids of the western Lachlan fold belt: products of three-component mixing. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 171-181.

FERMIO S.J. 1984. BSc Honours thesis, Monash University, Melbourne (unpubl.).

GRAY C.M. 1990. A strontium isotopic traverse across the granitic rocks of southeastern Australia: petrogenetic and tectonic implications. *Australian Journal Earth Sciences* **37**, 331-349

PHILLIPS G.N., WALL V.J. & CLEMENS J.D. 1981. Petrology of the Strathbogie Batholith – a cordierite-bearing granite. *Canadian Mineralogist* **19**, 47-63.

WHITE A.J.R. & CHAPPELL B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

THE PETROGENESIS OF MAFIC S-TYPE MAGMAS : QUENCHED MELT INCLUSIONS IN PHENOCRYSTS OF A SILURIAN DACITE (LACHLAN FOLD BELT)

Roland Maas[1], Vadim Kamenetsky[2], Ian A. Nicholls[3] & David Steele[4]

[1] Department of Earth Sciences, La Trobe University, Vic 3086, Australia
[2] CODES, University of Tasmania, Tas 7005, Australia
[3] Department of Earth Sciences, Monash University, Vic 3168, Australia
[4] Central Science Laboratory, University of Tasmania, Tas 7005, Australia

The restite model (White & Chappell 1977; Chappell *et al.* 1987) ascribes most compositional variation in southeastern Australian granitic and volcanic suites to the unmixing of magmas composed of undissolved, relatively mafic source material (the restite) and a felsic melt. Critics of the model advocate a greater role for large-scale crustal assimilation, magma mixing and fractional crystallization (e.g. Collins 1996).

One of the more contentious aspects of the restite model is the identity of restite minerals. Definitive evidence to support a restitic origin for rock-forming minerals in granites is very limited, in part due to modification of original signatures of the restite in a plutonic environment. Volcanic rocks, in particular S-type volcanics, may offer a better chance to examine potential "restite" crystals. We have studied a reasonably well-preserved phenocryst population in a crystal-rich (ca 56% crystals) peraluminous dacitic (S-type) lava of the Silurian Hawkins Volcanics north of Canberra (Cowra excursion stop 2, Wyborn *et al.* 1991, Hutton-2 excursion guide). The volcanics are thought to be extrusive equivalents of the widespread mafic S-type Bullenbalong Suite of granites. The entire phenocryst population (17% quartz, 19% plagioclase An_{51}, 10% biotite Mg_{55}, 4% orthopyroxene Mg_{48}, 5% cordierite Mg_{65}, trace garnet Mg_{25}) of this dacite has been interpreted as erupted (metamorphic) restite that experienced only limited magmatic processing prior to quenching (Wyborn & Chappell 1986). The dacite was believed to represent a primary magma produced by wholesale mobilization of partially (e.g. 40%) melted mature greywacke.

Crystal and melt inclusions are common in phenocrysts of quartz, orthopyroxene ($Mg_{45.6\text{-}50.7}$), cordierite, plagioclase, and also in apatite. For example, quartz phenocrysts contain euhedral inclusions of plagioclase ($An_{50\text{-}73}$), orthopyroxene, apatite and biotite. Quenched melt inclusions in quartz and orthopyroxene are composed of silicate glass and a shrinkage vapour bubble. Sulfide globules occur within silicate melt inclusions, or scattered through host phenocrysts. Melt inclusions in plagioclase and cordierite are often altered but those in quartz and orthopyroxene are fresh. The silicate melt inclusions provide the only preserved derivative of the dacite's melt phase; the (once glassy?) groundmass is altered.

Compositions of melt inclusions in quartz and orthopyroxene are similar, with SiO_2 75-79%, Al_2O_3 13-15%, FeO_t 0.1-1%, <0.1% MgO, CaO 0.5-1%, Na_2O 2.4-3.1%, K_2O 5-7%, P_2O_5 0.03-0.2%, A/CNK 1.14-1.22. By comparison, the bulk dacite has 68% SiO_2, 4.4% FeO_t, and 2.1% MgO.

Quenching of trapped silicate melt droplets occurs during very fast cooling which explains why melt inclusions are ubiquitous in volcanic and absent in most plutonic rocks. The presence of quenched melt inclusions in the major phenocryst types of the Hawkins dacite therefore supports a shallow-level igneous rather than restitic (metamorphic) origin for these crystals. Trapping of high-SiO_2 melt within magmatic rims on restitic cores cannot explain why these inclusions are found even in the cores of their host crystals - a fully igneous origin is much more plausible. Subtle variations in melt inclusion composition can be explained by fractional crystallization, consistent with evidence from trapped mineral inclusions. This suggests that fractional crystallization played a significant role in the petrogenesis of these dacites. If an igneous origin is accepted for the major phenocryst types, the amount of possibly restitic material in the dacite reduces to perhaps 5% or less. This is a remarkably low figure for a mafic S-type; such a small amount of restite would severely limit the role of any restite unmixing in producing compositional variation in granite and volcanic suites.

References

CHAPPELL B.W., WHITE A.J.R. & WYBORN D. 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

COLLINS W.J. 1996. Lachlan Fold Belt granitoids: products of three-component mixing. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 171-181.

WHITE A.J.R. & CHAPPELL B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

WYBORN D. & CHAPPELL B.W. 1986. The petrogenetic significance of chemically related plutonic and volcanic rock units. *Geological Magazine* **123**, 619-628.

WYBORN D., WHITE A.J.R. & CHAPPELL B.W. 1991. Enclaves in the S-type Cowra Granodiorite. Second Hutton Symposium Field Guide. *Bureau of Mineral Resources Geology and Geophysics Australia, Record* **1991/24**.

A COMPARISON BETWEEN S-TYPE/I-TYPE (AUSTRALIA) AND ILMENITE-SERIES/MAGNETITE-SERIES (JAPAN), IN VIEW OF THE GASES OCCLUDED IN GRANITES

Koichiro Nagamine[1], Masami Araki[2], Ryuichi Sugisaki[3] and Bruce W. Chappell[4]

[1]Graduate School of Human Informatics, Nagoya University, Nagoya, Japan
[2]Department of Earth and Planetary Sciences, Nagoya University, Nagoya, Japan
[3]Department of Teacher Education, Meijo University, Nagoya, Japan
[4]Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia

Introduction

Chappell & White (1974) defined two granite types in Australia, those derived from a source which had undergone a cycle of sedimentation (S-type) and those derived from purely igneous source rocks (I-type). On the other hand, Ishihara (1977) defined magnetite (Mt) series and ilmenite (Il) series granites on the basis of the presence or absence of magnetite. We have compared these definitions from another chemical viewpoint, the composition of gas species, especially CH_4 and CO_2 that are released from granitic rocks upon crushing. These gas features are expected to reflect the oxidation state of the source magma.

Materials and methods

We collected 108 samples of S-type and 59 of I-type granite in southeastern Australia. All samples were roughly crushed into small fragments about 5 mm in diameter, and 5 g of these were loaded into the crushing apparatus. This was heated at 110 °C and the inside air of the apparatus was replaced by Ar gas before crushing. Samples were crushed at 12 MPa, and subsequently the released gas in the apparatus was introduced into an FID gas chromatograph for the analysis of hydrocarbons (CH_4, C_2H_6, C_3H_8) and carbon oxides (CO, CO_2). In regard to the gas features of Mt- and Il-series granitic rocks, we refer to the data of granite samples in Japan which we previously analysed, 67 of Il-series and 46 of Mt-series.

Results and discussion

Takahashi *et al.* (1980) argued that all Mt-series are indeed I-types but Il-series include both S-types and I-types. We examined the relation between S/I types and Il/Mt series in terms of their gas features. The Il-series in Japan is clearly discriminated from the Mt-series on the basis of the gas compositions; the former is dominated by CH_4, and the latter by CO_2. This character with respect to the predominant C-bearing gas species is as expected because both ilmenite and CH_4 tend to be produced under a reducing conditions during magma genesis. Furthermore, C_2H_6 is present exclusively in CH_4-enriched samples of the Il-series. The occurrence of C_2H_6 probably indicates highly reducing condition in the magma.

The S-type granites including carbon inherited from parental sediments are inferred to be more reducing than are the I-type, and hence, the former is expected to be enriched in CH_4. However, correspondence between S/I types and Il/Mt series did not clearly emerge from these gas features. Samples from Jillamatong (S-type) show CH_4-dominant, but those from Dalgety, Numbla Vale, and Cowra (S-type) show CO_2-dominant, whereas those from Moruya and Jindabyne (I-type) are enriched in CO_2. Thus, it is noted that each batholith suite has individual gas compositions independent of the type (S/I), which correspond to those shown by either Il-series (CH_4-enriched) or Mt-series (CO_2-enriched). This suggests that the gas features are controlled by magma processes within each suite. For example, samples categorised as S-type from Dalgety and Numbla Vale areas show Mt-series character in their gas contents. This may be related to the genesis of the granites in that area; that is, both are accompanied by I-type granites (White & Chappell 1983). The inconsistency between S/I types and Il/Mt series may be derived from the different criteria for the discrimination of the granites. On the basis of the sulfur isotope data in granites, Coleman (1979) also pointed out that the association of S-type with ilmenite and I-type with magnetite does not apply to the batholith suites discussed above. As far as the present gas data are concerned, the Il-series corresponds to S-type and the Mt-series include both I-type and S-type.

To examine the relationship between gas features and rock composition, we examined the published data on the chemical composition of the granites. The ratios of CH_4/CO_2 and FeO/Fe_2O_3 would decrease as oxygen fugacities increased in the source magma. The present samples showed a positive correlation between both ratios. This indicates that the oxidation state during the magma genesis constrains the composition of carbon-bearing gases as well as iron bearing minerals. From the viewpoint of oxidation-reduction conditions, the feature of carbon bearing gases could be another index to discriminate among granites.

Acknowledgments
We thank Dr K. Sugitani for his vigorous help in sample collection and Ms K. Muro'oka for her kind assistance in sample analysis. This study is supported by the Grant-in-Aid for Encouragement of Young Scientists of the Ministry of Education, Science and Culture, Japan (No 12740303).

References

CHAPPELL B.W. & WHITE A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

COLEMAN M. L. 1979. Isotopic analysis of trace sulfur from some S- and I-type granites. *Origin of Granite Batholiths, Geochemical Evidence*, Shiva Publications Ltd., 129-133.

ISHIHARA S. 1981. The granitoid series and mineralization. *Economic Geology, 75th Anniversary Volume*, 458-484.

TAKAHASHI M., ARAMAKI S. & ISHIHARA S. 1980. Magnetite-series/Ilmenite-series *vs* I-type/S-type granitoids. *Mining Geology Special Issue* **8**, 13-28.

WHITE A.J.R. & CHAPPELL B.W. 1983. Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia, *Geological Society of America Memoir* **159**, 21-34.

SIGNIFICANCE OF ENCLAVES IN THE DEDDICK AND COWRA GRANODIORITES

Ian Nicholls[1], Roland Maas[2] & Tod Waight[3]

[1] Department of Earth Sciences, Monash University, Vic 3168, Australia
[2] Department of Earth Sciences, La Trobe University, Vic 3086, Australia
[3] Danish Lithosphere Centre, Copenhagen, Denmark

The Silurian Deddick Granodiorite (SHRIMP zircon U/Pb age 430 Ma), a mafic S-type pluton in the southeastern Lachlan Fold Belt (Bullenbalong Supersuite), contains abundant centimetre to metre-scale angular to rounded enclaves. The most abundant types have clearly been derived from high-grade metasediments of pelitic-psammitic composition and migmatites are common. Among these, discrete fragments of melanosomes rich in cordierite, garnet, spinel and corundum represent residues from partial melting. However, evidence of reaction with host magma, plus their trace element compositions and Sr-Nd isotopic signatures, indicate that they are unlikely to represent restite in equilibrium with the melt component of the host, but were instead derived from a range of mid-crustal rocks which may have formed one source component for the magma, or may have been material incorporated into the magma at depths shallower than those of its dominant source regions (i.e. they are xenolithic). Pressure-temperature conditions of around 0.55 GPa and 840 °C estimated for *equilibration* of early-formed garnet-orthopyroxene clots in the granodiorite suggest that crystallisation of the magma began at temperatures > 900°C and depths at least as great as 20 km. Less precise estimates of equilibration conditions for the metasedimentary enclaves suggest temperatures of 820-750 °C at similar or slightly shallower depths. These observations lend support to the interpretation of the metasedimentary enclaves as xenolithic material of mid-crustal origin.

Three types of centimetre-scale microgranular enclaves with igneous textures may also be distinguished. The most common type are small rounded dark enclaves of tonalitic composition, often highly heterogeneous in mineralogy. Some contain large feldspar crystals which clearly were derived from the host magma, while others contain magnesian orthopyroxene (Mg^{85+}) which is most compatible with an origin from a high-Mg mafic-intermediate magma. Isotopic data for these enclaves form an array with ε_{Nd} extending from -6 to –12 and $^{87}Sr/^{86}Sr$ from 0.7130 to 0.7167. The host granodiorite shows a small spread of isotopic compositions around ε_{Nd} –10 and $^{87}Sr/^{86}Sr$ 0.715. These features are consistent with the formation of the tonalitic enclaves from globules of hybrid mafic-intermediate magma commingled with and contaminated by crystal-rich host magma.

Other igneous enclave types have similar mineralogy to the host granodiorite, but are much finer grained and poorer in aluminous minerals such as garnet and cordierite. A microgranodiorite group is isotopically less evolved than the host, and some of its members can be related to disrupted synplutonic dykes. A porphyritic granodiorite group is isotopically similar to the host and appears to represent a cogenetic marginal facies of the pluton.

The metasedimentary enclaves have chemical and Nd-Sr isotopic compositions broadly similar to those of psammitic-pelitic Ordovician-Silurian clastic sedimentary rocks exposed at granite emplacement level. SHRIMP U-Pb ages of detrital zircons in several enclaves show younger age cut-offs at 490-480 Ma, indicating earliest Ordovician depositional ages for their sedimentary precursors. Patterns of zircon inheritance in the enclaves show the ~ 500 and

1100-1200 Ma peaks commonly observed in Lachlan Fold Belt sedimentary rocks and many other Palaeozoic Gondwana margin sedimentary sequences in southeastern Australia, New Zealand and East Antarctica. U-Pb ages for metamorphic zircon rims and Sm-Nd dating of garnet indicate that metamorphism of enclave precursors was coeval with granitic magmatism at ca 430 Ma. The enclaves are most likely the metamorphic equivalents of Ordovician turbiditic sediments which had been tectonically transported to the mid crust (~ 20 km depth) during the very early Silurian. This is consistent with substantial crustal shortening via thrusting of Early Palaeozoic sediments in a convergent margin regime at that time.

The host granodiorite contains a significant component of disaggregated enclave material, made most obvious by the presence of 5-10 mm garnets which are much more Fe-rich than garnet crystallizing from the magma. Hence it is not surprising that zircon age spectra for the host show similarities with those of the enclaves. However, the granodiorite also shows a significant population of zircon ages at ~ 600 Ma which is poorly represented in or absent from enclaves. This observation again confirms that if the enclaves were derived from the source region of the magma, other source components were also involved. The 600 Ma "peak" in zircon age spectra of southeastern Australian Palaeozoic sedimentary rocks is best developed in those of the Mid-Late Cambrian Kanmantoo Fold Belt. These zircons are believed to have been derived from older terranes within present-day Antarctica (the Beardmore and Ross Orogens). The presence of the "Antarctic" zircon age population in the Deddick Granodiorite host suggests that the magma was either generated within or sampled during ascent crustal rocks other than (and probably deeper than) the earliest Ordovician Lachlan Fold Belt succession which was the source of its metamorphic enclaves.

The Cowra Granodiorite shows strong similarities in both host and enclaves to the Deddick Granodiorite, 400 km further south. Microgranitoid enclaves are again subordinate to metasedimentary varieties and may be subdivided into two groups according to mafic mineral assemblage: pyroxene microtonalites and biotite microgranites. No clear geochemical or isotopic distinction can be made between the two varieties. Petrographic evidence (quenched apatites, xenocrystic from the host granite) again suggests an origin as mingled more mafic magma globules which have been variably contaminated by the more felsic host magma, and this is supported by isotopic evidence. The microgranular enclaves have isotopic compositions ($^{87}Sr/^{86}Sr$ = 0.7095 to 0.7144, ε_{Nd} = -6.9 to -9.5) which are generally more primitive or similar to the host granitoid ($^{87}Sr/^{86}Sr$ = 0.7142, ε_{Nd} = -8.8). The spread in isotopic compositions is considered to reflect variable magmatic hybridisation followed by diffusive exchange between the felsic and more mafic magmas during slow cooling.

Several studied metasedimentary enclaves are not in isotopic equilibrium with the host granite and therefore cannot represent pristine samples of the latter's source region. Instead they are again interpreted as representing portions of a lithologically and compositionally diverse crustal source terrane or accidental xenoliths entrained during magma ascent.

CALCULATED PHASE EQUILIBRIA RELATING TO PARTIAL MELTING IN THE CRUST: GRANITES AND GRANULITES

Roger Powell[1], Richard White[1] & Tim Holland[2]

[1]School of Earth Sciences, University of Melbourne, Vic 3010, Australia
[2]Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK

A thermodynamic model has been developed for silicate melts in the system CaO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (CNKFMASH) (Holland & Powell 2000; White *et al.* 2001). In Holland & Powell (2000), the Holland & Powell (1998) internally-consistent thermodynamic dataset was extended via the incorporation of the experimentally-determined melting relationships in unary and binary subsystems of CNKASH. The predictive capability of the model was then evaluated via the experimental data in ternary and quaternary subsystems. In White *et al.* (2001) this model is extended by the addition of FeO and MgO, with the data for the additional end-members of the liquid being incorporated into the internally-consistent thermodynamic dataset. The resulting dataset, with the software THERMOCALC, Powell *et al.* (1998) can then be used to calculate melting relationships in rocks of pelitic and psammitic composition.

Calculated phase diagrams allow observations to be made about the processes involved in producing granulite facies rocks, particularly those relating to open system behaviour of rocks under such conditions. A fundamental conclusion from this work is that quantitative melt loss from granulite facies terranes is necessary for the preservation of the mineral assemblages we see, with the general absence of pervasive retrogression. Such melts, on being lost from their source, will contribute to granite intrusions at shallower levels in the Earth's crust. Such granites are predicted to have 70-75% SiO_2, for example, and might be expected to show geochemical features related to the residual minerals left behind in their source.

Such quantitative melt loss appears unavoidable in the granulite facies terranes that we have observed, for example with sedimentary layering and even sedimentary structures preserved, yet with unretrogressed granulite facies mineral assemblages. However there is another plausible mode of operation for the deeper levels of the crust, possibly on a variety of length scales. If the melt proportion becomes sufficiently large on a time scale that has not allowed melt extraction to take place (for whatever reason), then Rayleigh instability is likely to occur, and the melt with (a proportion of) its residue may ascend in the crust. What then may happen to such a mixture is difficult to ascertain. The geochemical signatures in this type of granite are harder to predict, depending on how the mixture behaves.

These two scenarios give end-member types of granite. Certainly we can now calculate mineral-melt equilibria in the source, given an original rock composition. We can also calculate the evolution of the magma during cooling, once any fractionation has ceased. In the absence of convincing forward modelling of the physics of the processes involved in progressing from melt-in-source to melt-in-magma at (much) higher crustal level, separating granite models looks difficult. Working out from a solid granite at the Earth's surface to what it looked like once it attained its current chemical composition is difficult enough, let alone constraining source and ascent processes.

References

HOLLAND T.J.B. & POWELL R. 1998. An internally-consistent thermodynamic dataset for phases of petrological interest. *Journal of Metamorphic Geology* **16**, 309-344.

HOLLAND T.J.B. & POWELL R. 2000. Calculation of phase relations involving haplogranitic melts using an internally-consistent thermodynamic dataset. *Journal of Petrology* (in press).

POWELL R., HOLLAND T.J.B. & WORLEY B. 1998. Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *Journal of Metamorphic Geology* **16**, 577-588.

WHITE R.W., POWELL R. & HOLLAND T.J.B. 2001. Calculation of partial melting equilibria in the system CaO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (CNKFMASH). *Journal of Metamorphic Geology* (in press).

GEOLOGY AND GEOCHRONOLOGY OF THE SOUTHEAST ASIAN S-TYPE GRANITES

Prinya Putthapiban

Geological Survey Division, Department of Mineral Resources, Rama VI Road, Bangkok 10400, Thailand

The granites of the Southeast Asian tin belt crop out as a north-south trending elongate zone more than 3,500 km long and 450 km wide through Southern China (Yunnan), Myanmar (Burma), Laos, Thailand, Malaysia and Indonesia. These granites can be grouped into three sub-parallel magmatic belts or provinces based on their field occurrence, and petrographic and geochemical characteristics. The Eastern Granites Province comprises small to large batholiths of zoned and unzoned plutons with a compositionally expanded range from gabbro to granite, but dominantly diorite and granodiorite. Volcanic rocks of expanded compositional range similar to those of the plutonic rocks are a common association within this terrane. The Central or Main Range Granites Province, however, comprises major batholiths and large complex plutons of restricted compositional range with a common association of migmatitic rocks in the northern part of the terrane. The Western Granites Province in general contains small to moderate batholiths and plutons of mainly restricted compositional range with a minor amount of the expanded type.

Whole rock geochemistry from Southeast Asia shows that most of the granites from the Eastern Province correspond approximately to the I-type category with subordinate plutons showing S-type characteristics, whereas those of the Central or Main Range Granites Province are exclusively S-type derived by partial melting of metasediments. Inherited Precambrian zircon populations in the granites from both provinces indicate that they were either underlain by, or situated adjacent to, Precambrian continental crust. The Western Granites Province comprises two contrasted granite suites with a majority of S-types and a minority of I-types.

Geochronological information suggests that granites from the Eastern Province perhaps represent the oldest episode of granite magmatism (264-200 Ma) and possess relatively low initial $^{87}Sr/^{86}Sr$ ratios of 0.705-0.715. The emplacement ages of granites of the Central or Main Range Province are 230-200 Ma with a variable initial $^{87}Sr/^{86}Sr$ ratio range of 0.725-0.730 for the northern Thailand migmatite-related suites and 0.710-0.727 for the others. The granites from the Western Province form the youngest suites of the Southeast Asian tin belt (130-45 Ma). The dominant S-type granites possess high to very high initial $^{87}Sr/^{86}Sr$ ratios of 0.719-0.744, whereas those of the I-types vary from 0.704-0.714. Cataclastic deformation together with hydrothermal activity and high grade metamorphism are the major mechanisms that explain the widespread resetting of mineral ages of the older granites in the region. However, slow cooling processes after granite emplacement are believed to be responsible for the younger mineral ages of the Cretaceous-Tertiary granites.

Tin mineralization is commonly associated with highly fractionated S-type granites characterized by high concentrations of SiO_2, K_2O, Rb, Th, U and Sn, whereas the concentrations of Fe_2O_3, MgO, CaO, Na_2O, Ba and Sr, as well as Fe_2O_3/FeO ratios, are low. Tin mineralized plutons exhibit high initial $^{87}Sr/^{86}Sr$ ratios and low magnetic susceptibilities.

S-TYPE CAPE GRANITES

R. Scheepers

Department of Geology, University of Stellenbosch, Private Bag X1, Matieland, 7602, Republic of South Africa

Introduction

The Cape granites are of Pan African age (560-510 Ma) and were emplaced in the Saldania belt in southern Africa. Investigations on Cape granites during the past 15 years has illustrated that the genesis of various Cape granite types was controlled by a combination of factors including source rock, level of emplacement, enclave composition and residence period, as well as material through which the granite moved during emplacement. In terms of the I-S classification scheme, some Cape granites have transitional properties. The fact that variations within S-type granitic plutons are linked to their generation and emplacement histories is emphasised.

Field relationships and mineralogy

The Cape granites were intruded into the metasedimentary Malmesbury Group in three tectonic terranes, the Tygerberg, Swartland and Boland terranes. As a general rule, S-type granites occur in the Tygerberg Terrane west of the Colenso Fault, the dividing line between the Tygerberg and Swartland terranes, whereas I-types are present east of that line. S-type granites may be subdivided into three types named Sa1, Sa2 and Sb, the latter also having some I-type properties. Sa1 granites are the oldest, least fractionated, granites with numerous metasedimentary enclaves and restite features. Sa2 granites are highly fractionated high level intrusions, often intrusive into Sa1 granites. Recrystallised ignimbrites and welded ash flow tuffs represent the volcanic counterparts of Cape granites with S-type features

Sa1 granites contain microcline perthite, plagioclase(An_{30-40}), biotite, pinitised cordierite in coarse grained phases and garnet, apatite, zircon, sphene, tourmaline, monazite, clinozoisite and Th-poor uraninite as accessory minerals. Sa2 granites are even-grained subsolvus microcline microperthite and albitic plagioclase-bearing granites, with both biotite and muscovite as well as rare garnet, tourmaline, zircon, apatite, monazite and uraninite as accessory minerals. The coarse grained varieties of Sb granites contain biotite as well as occasional hornblende. The leucocratic phases contain biotite and secondary muscovite. Accessory minerals are zircon, apatite, monazite and tourmaline in both coarse- and fine-grained varieties as well as sphene and clinozoisite in the coarse-grained phases.

Geochemistry

S-type granites are low in Th and high in P_2O_5 whereas I- type Cape granites are high in Th and CaO and low in P_2O_5.

Sa1 granites range from TiO_2-rich to poor end-members decreasing in peraluminosity with increasing differentiation. The agpaitic index (Na+K/Al = 0.67) and the Rb/Sr value (2.70) of these granites are the lowest of the S-types but they have the highest Zr+Nb+Ce+Y (340 ppm) and MgO contents. Sa1 granites have a total REE content of 180 to 260 ppm, a moderately fractionated pattern (La_N/Yb_N = 0.6 to 0.9) and moderate Eu_N anomalies.

Sa2 granites are compositionally restricted to TiO_2-poor end-members increasing in peraluminosity with increasing differentiation. The agpaitic index (Na+K/Al = 0.83) and the extremely high Rb/Sr value (15.7) are the highest of the S-type granites. They have the lowest

Zr+Nb+Ce+Y (190 ppm) and MgO contents. U is particularly enriched, Th/U values are between 1 and 3 with an average of 1.9. Their total REE content varies between 212 and 230 ppm and they have a highly fractionated pattern (La_N/Yb_N = 46) and a moderate Eu anomaly (Eu_N = 0.6).

Sb granites vary from metaluminous to peraluminous. The agpaitic index (Na+K/Al = 0.79), Rb/Sr (3.91) and Zr+Nb+Ce+Y (310 ppm) values are intermediate between those of the Sa1 and the Sa2 associations. On the Whalen *et al.* (1987) discrimination diagrams granites of this association classify as unfractionated S- or I-type granites. Total REE values are between 167 and 291 ppm with La_N/Yb_N values of 5 to 6 for the leucocratic phases and 8 to 10 for the biotite-enriched varieties. The Eu_N values (0.39) for the leucocratic phases are considerably lower than for the types that contain biotite (Eu_N = 0.51 to 0.55).

S-type volcanic rocks

The volcanic equivalents of the granites with S-type features are present as a 188 m thick succession of recrystallised ignimbrites and welded tuffs. Compositionally, these rocks vary from rhyodacite to rhyolite. A subvolcanic intrusive phase varying between quartz porphyry and granite porphyry with a granitic composition also occurs. Both the volcanic and the subvolcanic phases are strongly peraluminous (ASI = 1.15 to 1.40). Biotite, cordierite and magnetite are present, and pyroxene is found in the subvolcanic rocks.

Petrogenesis

Cape granites with S-type features were generated from crustal material consisting of metasediments as well as meta-igneous rocks. Sa1 granites were generated with a low degree of partial melting and emplaced to an intermediate level in the crust. Reaction between melt and restite enclaves produced leucocratic granitic magma. Fractionation and emplacement of this second generation magma eventually developed into enclave-poor Sa2 granites and volcanic rocks. Sb granites were generated during higher degrees of partial melting and accordingly a higher ratio of meta-igneous to metasedimentary material. These granites were rapidly emplaced, this being ascribed to the depletion of high level magma chambers in Sa2 granites as a result of volcanism.

Conclusions

a) Partial melting of a mixture of metasediments and meta–igneous source materials (Namaqua–Natal belt) produced Cape granites with S-type features. Variation in degree of partial melting produced variations between these S- types.
b) Sa2 Cape granites were generated as a result of reaction between enclaves and melt at a high level in the crust, followed by fractionation.
c) High emplacement level enhances the separation of metasedimentary and meta-igneous enclaves, and also creates variation in S-type plutons and may even contribute to the I-S dividing line.

Reference

WHALEN J.B., CURRIE K.L. & CHAPPELL B.W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* **95**, 407-419.

LOWER CRUSTAL XENOLITHS FROM THE SUMIKAWA GRANODIORITE BODY, NORTHEASTERN JAPAN: ANATEXIS AND FORMATION OF HIGH-GRADE (SPINEL + QUARTZ) RESTITE

Toshiaki Shimura[1], Toshiko Kawai[2] & Shin-ichi Kagashima[3]

[1]Department of Geology, Faculty of Science, Niigata University, 8050, Ikarashi-2, Niigata, 950-2181, Japan.
[2]Hitachi INS Software Co., Nihon-ohdori 5-2, Naka-ku, Yokohama, 231-0021, Japan.
[3]Graduate School of Science and Technology, Niigata University, 8050, Ikarashi-2, Niigata, 950-2181, Japan.

High-grade metamorphic xenoliths in igneous rocks are sometimes thought to be restite of the host igneous rocks. We have found high-grade pelitic metamorphic xenoliths in a metaluminous granodiorite body. The metamorphic grade of the xenoliths reached granulite facies. We discuss their origin here.

Cretaceous-Tertiary plutonic-volcanic rocks are widely distributed in the Uetsu-area, northeastern Japan. The plutonic bodies intrude a pre-Cretaceous accretionary complex (Ahio Belt). The Iwafune granite (biotite granite, two-mica granite, and garnet two mica granite) occurs in the western part of this area, and is thought to be an S-type granite on petrochemical criteria. The Sumikawa granodiorite (hornblende-biotite granodiorite) intrudes the Iwafune granite as a small stock. The Sumikawa granodiorite is thought to be M-type or I-type. The isotopic age of the Iwafune granite is about 90 Ma (Kagashima 1999), whereas that of the Sumikawa granodiorite is 20 Ma (Agency of Natural Resources and Energy 1982; Kawai *et al.* 1999).

Various types of metamorphic rocks occur as xenoliths in the Sumikawa granodiorite body (Otsuka & Shimazu 1981; Kawai *et al.* 1999). These are subdivided to pelitic rocks, mafic-intermediate rocks, and calc-silicate rocks. Pelitic metamorphic xenoliths are dominant and can be grouped to sub-types by the mineral assemblage; (I) Bt-gneiss, (II) Grt-Bt-Sil gneiss, (III) Spl-Opx-Bt gneiss, (IV) Spl-Crd-Bt gneiss, and (V) Grt-Crd-Spl-Sil gneiss (Shimura *et al.* 2000). Type (V) granulite is the highest grade rock.

Type (V) rocks are poor in LIL or incompatible elements compared with type (I) rocks. Mass balance calculations and batch partial melting modeling indicate that the type (V) rocks are the restite of the type (I) rocks, and that the degree of melting degree was 40-60%. The range of initial Sr-isotopic ratios of all pelitic xenoliths is almost same as that of the Iwafune granite. Therefore, type (I) rocks, type (V) rocks, and the S-type Iwafune granite are thought to be original rock, restite, and melt, respectively.

A *P-T-t* path of type (V) granulite has been determined by textural evidence. These show the following reactions in the order:

Bt + Sil = Grt + Crd + melt ····· (1)
Grt + Sil = Spl + Crd ····· (2)
Spl + Crd = Bt + Sil ····· (3)

In the Fe-rich domain, sometimes the garnet porphyroblasts with sillimanite are cut by spinel + quartz, and the spinel is rimmed by cordierite. These textures show the reactions in the order:

Grt + Sil = Spl + Qtz ····· (a)
Spl + Qtz = Crd ····· (b)

The spinel + quartz assemblage is one of the famous assemblages of ultra-high temperature metamorphism (Harley 1998). We found the assemblage from type (V) rocks (Shimura et al. 2000). This sample has X_{Mg} (bulk) = 0.44, and is X_{Mg} (Grt) > X_{Mg} (Spl). The spinel composition in the spinel + quartz assemblage has a lower X_{Mg} (0.14-0.22) and X_{Zn} (0.01-0.02) than that in the spinel + cordierite assemblage (X_{Mg} = 0.16-0.32 and X_{Zn} = 0.02-0.05). Reactions (2), (a), (b), and Grt + Sil + Qtz = Crd made an invariant point in FMAS system. Adopting the thermodynamic model of Nichols *et al.* (1992), the spinel + quartz assemblage is stable at $T > 860$ and $P > 600$ MPa for this rock.

Type (V) rocks underwent a clockwise *P-T-t* path. The metamorphic event was caused by regional metamorphism in the lower crust, because the intrusive event of the Sumikawa granodiorite is a later stage. These stages can be described as:

M1 stage: prograde stage of main metamorphism.
M2 stage: main metamorphism, highest *T* conditions, partial melting and generation of S-type granitic magma (ca 90Ma?). Spinel + Quartz assemblage is stable in Fe-rich domain.
M3 stage: post-metamorphic conditions, decompression, cooling, and simple shear.
M4 stage: contact metamorphism by the Sumikawa granodiorite, xenolith incorporation into the granodiorite magma (ca 20 Ma?).

References

Agency of Natural Resources and Energy. 1982. *Report of regional geological survey of Uetsu Area (I).*

HARLEY S.L. 1998. On the occurrence and characterization of ultrahigh-temperature (UHT) crustal metamorphism. *In:* Treloar P.J. & O'Brien P.J. eds. *What Drives Metamorphism and Metamorphic Reactions?* pp. 81-107. Geological Society of London Special Publication **138**.

KAWAI T., SHIMURA T. & KAGASHIMA S. 1999. Lower crustal granulite facies metamorphism and generation of S-type granitic magma, in the Uetsu area, northern Japan. *Abstracts of Japan Earth and Planetary Science Joint Meeting* GB-P006.

KAGASHIMA S. 1999. Layered structure in the Iwafune granite, northeastern Japan and its isochron age. *Memoirs of the Geological Society of Japan* **53**, 261-268.

NICHOLS G.T., BERRY R.F. & GREEN D.H. 1992. Internally consistent gahnitic spinel-cordierite-garnet equilibria in the FMASHZn system: geothermobarometry and applications. *Contributions to Mineralogy and Petrology* **111**, 362-377.

OTSUKA T. & SHIMAZU M. 1981. Sillimanite-garnet gneiss xenolith in granodiorite of the Iwafune area, Niigata Prefecture. *Journal of the Geological Society of Japan* **87**, 833-836.

SHIMURA T., KAWAI T. & KAGASHIMA S. Metamorphism of lower crustal granulite xenoliths from the Sumikawa granodiorite body, Uetsu-Area, Northeastern Japan: first report of a spinel-quartz assemblage from the Japanese islands. *Eos* **81** *Western Pacific Geophysics Meeting Supplement*, V32B-10.

WHY ARE S-TYPE GRANITES FOUND WHERE THEY ARE, AND NOT FOUND ELSEWHERE WHERE ONE MIGHT EXPECT THEM?

Leon T. Silver

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA

The concept of I- and S-type granites (White & Chappell 1977; Chappell & White 1974) as reflectors of contrasting, partially melted source materials, i.e. igneous and/or sedimentary, has provided a valuable perspective on granite petrogenesis. This contribution examines that concept from a Cordilleran viewpoint.

Demonstrated in the granitic rocks of the vast Lachlan Fold Belt (LFB) of southeastern Australia, significant differences have been found between I-type and S-type suites of granitic rocks in the mineralogy, petrography, composition (major, trace, isotopic) and enclaves (Chappell & White 1992). High Aluminum Saturation Index, presence of cordierite (or altered equivalent), other aluminous phases, mafic textural aggregates of the micas, a correlation between colour index and abundance of dark micaceous metasedimentary enclaves, and some other diagnostic minerals help identify S-type granites, particularly in the more mafic rocks of a suite. I-type granites, commonly, are identified by their calcic to calcalkaline, metaluminous character, hornblende in the assemblage, hornblende-bearing enclaves, etc. For most suites, the more mafic the rock, the larger the fraction of unmelted material (restite) inferred to be derived from the sedimentary or igneous source regions. More leucocratic members of each type of suite tend to lack readily diagnostic characteristics, emphasising the importance of studying suites with compositional ranges, rather than individual rocks, in order to discriminate. In the LFB large plutons of each type and considerable abundance, have been identified convincingly. However, in many other great plutonic terranes (e.g. the American Cordilleras), the criteria developed in the LFB for recognition of S-type granites are rarely, if ever, clearly recognised and applied. White *et al.* (1986) challenged tentative identification of S-types in the American southwest (Miller & Bradfish 1980; Todd & Shaw 1985) and raised the question of whether *any* S-type granites existed in southwestern North America.

Nearly 15 years later, a large body of more recent literature from Alaska to Mexico suggests that very little S-type granite (*sensu stricto*) is present throughout the entire Mesozoic granite terranes of the North American Cordillera. A similar, less well-documented, assessment is possible in Central and South America. Some provisional S-type assignments have been made but none have really been put forward with the persuasive evidence required by White & Chappell. In contrast, I-types are everywhere in great abundance. But even here there appear to be differences between the Cordillera and the LFB. Tonalites characterise the former, more potassic granodiorites the latter. More generally, Pitcher (1982) referred to these as I-(Cordilleran) and I-(Caledonian) types.

The Peninsular Ranges batholith of southwestern North America displays beautifully regular spatial isotopic patterns. From west to east, the Sr, Nd and Pb isotopes become systematically more evolved, and $\delta^{18}O$ values heavier. It has been suggested that these changes resulted from a greater sedimentary component in the rocks of the eastern side, either in the source or resulting from higher level assimilation (e.g. DePaolo 1981). However, Silver & Chappell (1988) pointed out that there are small relative changes in major element abundances in that batholith, which is dominated throughout by tonalites, and argued that there cannot be a significant metasedimentary component in the rocks of the eastern side. An "S-type" component appears to be lacking.

A distinctive feature of the North American Cordillera, compared with many other fold belts, is that there is no significant Sn mineralisation associated with the granites of that region. Such mineralisation is associated with strongly fractionated S-type granites of the LFB.

What does all this imply? Were some necessary source materials for the more mafic S-type granites missing in the Cordillera? Were the thermal regimes inappropriate? Were the volatile endowments inadequate? In the largest sense, was the lithosphere and tectonic-thermal milieu that different between mid-Palaeozoic Australia and the Mesozoic western Americas?

On the east flank of each of the great North American batholiths are large regions of two-mica granites, some of them associated with I-type suites. Are some sedimentary protoliths involved in the production of these rock? Do we need another category (X-type), at least temporarily? Let us discuss this together. But "Cordilleran" and "Lachlan" do not appear to be comparable settings in some important ways that need more consideration.

References

CHAPPELL B.W. & WHITE A.J.R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

CHAPPELL B.W. & WHITE A.J.R. 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1-26.

DEPAOLO D.J. 1981. A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. *Journal of Geophysical Research* **86**, 10470-10488.

MILLER C.F. & BRADFISH L.J. 1980. An inner Cordilleran belt of muscovite-bearing plutons. *Geology* **8**, 412-416.

PITCHER W.S. 1982. Granite type and tectonic environment. *In:* Hsu, K.J. ed. *Mountain Building Processes*, pp. 19-40. Academic Press, London.

SILVER L.T. & CHAPPELL B.W. 1988. The Peninsular Ranges batholith: an insight into the evolution of the Cordilleran batholiths of southwestern North America. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 105-121.

TODD V.R. & SHAW S.E. 1985. S-type granitoids and an I-S line in the Peninsular Ranges batholith, southern California. *Geology* **13**, 231-233.

WHITE A.J.R. & CHAPPELL B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

WHITE A.J.R., CLEMENS J.D., HOLLOWAY J.R., SILVER L.T., CHAPPELL B.W. & WALL V.J. 1986. S-type granites and their probable absence in southwestern North America. *Geology* **14**, 115-118.

PER MIGMA AD MAGMA RELATIONSHIPS IN THE LACHLAN FOLD BELT: EVIDENCE FROM THE YABBA PLUTON AND ITS SOURCE

D.A. Steele[1] & R.C. Price[2]

[1] Central Science Laboratory, University of Tasmania, Tas 7005, Australia
[2] School of Science and Technology, University of Waikato, Hamilton, New Zealand

Granites with petrological characteristics that can be unambiguously related to particular sources are rare in the Lachlan Fold Belt (LFB) of southeastern Australia. Most LFB granites were emplaced as high level, contact aureole plutons or their volcanic equivalents far removed from source. The regional aureole S-type granites of the Cooma Supersuite (CS) are relatively few in number and small in areal extent but, importantly, some share spatial and chemical relationships with adjacent low P - high T high-grade migmatitic rocks. The CS granites provide information about granite sources, melt generation, and magma segregation processes that is not readily derived from other more common LFB granites. The CS granites are also argued to have played important roles in various petrogenetic models proposed for the voluminous S- and I-type granites of the LFB. They have been claimed to represent either magmas derived from the relatively infertile, Ordovician flysch of the LFB (the "restite model" viewpoint, e.g. Chappell 1984), or *the* crustal end member in 'multi-component' magma mixing models (e.g. Gray 1984; Collins 1996). Understanding the genesis of the CS granites therefore places constraints on more generally applicable petrogenetic models.

Migmatite-granite-enclave relationships

In their "*per migma ad magma*" paper, White & Chappell (1990) used the Cooma Granite as an example of a residue (restite)-laden, poorly segregated magma that became mobile. The Silurian Yabba pluton in the Wagga Metamorphic Belt, SE Australia, possesses characteristics similar to those of the Cooma Granite. Both are regional aureole, residue- and enclave-rich granites, with relatively low CaO and Na_2O contents. Both are highly peraluminous and have elevated initial Sr isotopic ratios (Steele 1993). The Yabba pluton offers better exposure, and a wider range of rock types (gneissic to felsic granites) and chemical variation than the Cooma Granite allowing a closer examination of *per migma ad magma* relationships.

The Yabba Granite is a three-phase, syn-tectonic pluton located between the migmatitic Gundowring Terrane and the lower grade Early Ordovician Lockhart Terrane (Fleming *et al.* 1985). The gneissic phase is structurally conformable with adjacent Gundowring Terrane whereas the main and felsic phases intrude the Lockhart Terrane. Systematic changes occur in enclave and mineral abundances and bulk and mineral chemistry from the gneissic to the felsic phase. In all phases the dominant minerals are quartz, K-feldspar, plagioclase, biotite, and sillimanite (qtz-kfs-pl-bt-sil) with minor late muscovite (mu), but pl dominates in the gneissic phase. Plagioclase compositions change from An_{25-35} (gneissic phase) to An_{10} (felsic phase). Pressure and temperature have been estimated at 700-800 °C and 0.5-0.7 GPa respectively, and relatively high water activities (> 0.8). Enclaves are abundant and are dominantly schistose bt-sil clots, massive to poorly layered qtz-pl-bt±kfs quartzofeldspathic gneisses, and calc-silicates nodules. Graphic intergowths of qtz-kfs and qtz-pl are common. Microgranular 'igneous textured' enclaves are rare.

The metasedimentary Gundowring Terrane comprises interlayered quartzofeldspathic (qfp) and pelitic gneisses and migmatites with minor calc-silicates. Bt-sil-qtz-kfs assemblages dominate the pelitic rocks. Cordierite-garnet assemblages are minor. The qfp gneisses display a spectrum of parageneses from qtz-$pl_{(An>40)}$-bt to 'semi-pelitic' qtz-$pl_{(An25-35)}$-kfs-bt-sil. Maximum P-T estimates are 800 °C and 0.5 GPa. Orthopyroxene is absent from rocks of the terrane.

With few exceptions the gneisses and leucosome/melanosome migmatite components of the Gundowring Terrane occur as enclaves in the Yabba pluton, supporting the hypothesis that the Yabba Granite was derived from the Gundowring Terrane and not from the Early Ordovician Lockhart Terrane flysch (Steele *et al.* 1992). The semi-pelitic qfp gneisses are not represented among the enclaves and are argued to represent a fertile source component.

Per migma ad magma model

The mineralogical and chemical variations in the Yabba pluton reflect the effects of two processes. Variation in the gneissic phase is attributed to partial melting and magma accumulation processes in the source region whereas trends defined by data for all three phases are attributed to homogenisation and fractionation during ascent.

Melting occurred in almost all Gundowring gneisses containing qtz-kfs-pl and water (from muscovite dehydration reactions) producing stromatic, ptygmatic and nebulitic migmatites. As heating of the terrane continued, melting ceased in 'infertile' rock types (i.e. those with insufficient Na, Ca or H_2O) but continued in 'fertile' semi-pelitic qfp gneisses and migmatites. Locally, as melt volumes exceeded critical melt percentages (25-35% - van der Molen & Paterson 1979), mobilisation and coalescence of the magma began. As a consequence, disaggregation of the layered gneiss-migmatite sequence and entrainment of adjacent migmatitic layers occurred, resulting in incorporation of leucosome (qtz-kfs, qtz-pl) and melanosome (bt-sil) components into the accumulating Yabba magma. Non- or partially-melted (infertile) rock types were entrained as enclaves.

Continuation of melting and magma accumulation resulted in a magma volume large and buoyant enough to escape its source. At this stage the 'bulk' composition of the magma was set ("source" composition of White & Chappell 1977). Field exposures of the Gundowring Terrane and the Yabba pluton record all stages of the *per migma ad magma* process. The model proposed is similar to those of Wickham (1987) and Obata *et al.* (1994) although the range of rock types exposed in the Gundowring Terrane and the Yabba Granite allow the construction of a more complete model that may be applicable to other metasediment-derived granites.

References

CHAPPELL B.W. 1984. *Philosophical Transactions of the Royal Society of London* **A310**, 693-707.
COLLINS W.J. 1996. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **88**, 171-179.
FLEMING P.D., STEELE D.A. & CAMACHO A. 1985 *Abstracts of the Victorian Lithosphere Symposium.* Geological Society of Australia, Melbourne, 14-15.
GRAY C.M. 1984. *Earth and Planetary Science Letters* **70**, 47-60.
OBATA M., YOSHIMURA Y., NAGAKAWA N., ODAWARA S. & OSANAI Y. 1994. *Lithos* **32**, 135-147.
STEELE D.A. 1993. *Petrological studies on gneisses and granites of the Tallangatta region, NE Victoria.* PhD thesis, La Trobe University, Bundoora (unpubl.).
STEELE D.A., PRICE R.C., FLEMING P.D. & GRAY C.M. 1992. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 500.
VAN DER MOLEN I. & PATERSON M.S. 1979. *Contributions to Mineralogy and Petrology* **70**, 299-318.
WHITE A.J.R. & CHAPPELL B.W. 1977. *Tectonophysics* **43**, 7-23.
WHITE A.J.R. & CHAPPELL B.W. 1990. *Geological Journal* **25**, 221-225.
WICKHAM S.M. 1987. *Journal of the Geological Society of London* **144**, 281-297.

AGE RELATIONS OF NEW ZEALAND PALAEOZOIC S-, I- AND A-TYPE GRANITE SUITES

Andy Tulloch[1], Dave Kimbrough[2], Nicholas Walker[3] & Andrew Allibone[4]

[1]Institute of Geological and Nuclear Sciences, Dunedin, NZ
[2]Dept of Geological Sciences, San Diego State University, California, USA
[3]Institute of Geological and Nuclear Sciences, Dunedin, NZ
[4]Dept of Earth Sciences, James Cook University, Queensland

The early Palaeozoic basement in New Zealand comprises two terranes separated by the north-south-trending Anatoki Thrust. The western, inboard Buller Terrane largely consists of relatively uniform quartz-rich turbiditic rocks. The eastern, outboard Takaka Terrane consists of a varied assemblage of siliciclastic, volcaniclastic, volcanic and carbonate rocks. Both terranes were extensively intruded by mid-Palaeozoic granite plutons. A wide range of crustal levels are exposed in the upper and lower plates of Cretaceous metamorphic core complexes, but any Palaeozoic volcanic rocks associated with mid-Palaeozoic granites have been removed. The Cretaceous plate margin thermal event has reset most radiogenic isotope systems in many rocks. Here we discuss mid-Palaeozoic granite suites (380-290 Ma) in the light of U-Pb ages on representative plutons.

S-type granites are of two distinct age groups. The older, voluminous, Karamea Suite (380-370 Ma) accounts for ~ 80% of Palaeozoic magmatism, and is restricted to the Buller Terrane. It consists of peraluminous tonalite-granodiorite-two mica granite; abundant brown-red biotite is characteristic but cordierite is rare. Subeconomic W-Sn mineralisation is present locally. SiO_2 ranges from 62-76%. The younger, less voluminous Ridge Suite (new name) (ca 345-335 Ma) is defined from the Takaka Terrane, but may also intrude the Buller Terrane and possibly should include a number of plutons previously assigned to the Karamea Suite. Ridge Suite is also peraluminous and characterised by red-brown biotite, but forms a more restricted range of tonalite to granite compositions (SiO_2 64-70%). With only one exception it has distinctly higher Na_2O/K_2O, CaO and Sr than Karamea Suite S-types, possibly reflecting the generally less mature nature of the Takaka Terrane metasedimentary rocks.

I-type granites are present in both terranes, and are also of two distinct age groups. Whereas 335-350 Ma I-types have an overlapping age relationship with the younger Ridge S-type granites, the 360-365 Ma Paringa Suite I-type granites are distinctly younger than the spatially associated Karamea Suite. SiO_2 ranges from 50-76%, and hornblende is common in rocks with < 68% SiO_2. Magnetite and titanite are common accessory minerals.

Inherited zircon and Sr, Nd isotopic compositions suggest that at least Ordovician sedimentary rocks and a mafic igneous component were involved in Karamea Suite genesis. However, the spatially associated I-type Paringa Suite is too young to represent the mafic igneous component, in contrast to the essentially coeval relationship between I- and S-type granite of the Lachlan Fold Belt. The Karamea S-type and Paringa I-type granites may be indirectly related via a convergent margin setting: convergence and terrane amalgamation led to crustal thickening in the Buller Terrane which produced the inboard S-type granites; subsequent subduction related to a trench east of the Takaka Terrane produced the I-types in both terranes. S-type plutonism of the Ridge Suite may have been more directly related to associated coeval I-types and subduction.

S- and I-type plutonism at 380-335 Ma was followed by relatively minor volumes of **A-type plutonism** in both terranes at ca 310-290 Ma. Most are peraluminous biotite-bearing granites; peralkaline varieties are rare. These A-type granites are too young to be related to the earlier S- and/or I-type plutonism.

The temporal and spatial distribution of S-type granite indicates that the Anatoki Thrust represents an I-S line at ~ 370 Ma. A second I-S line to the east at ~ 340 Ma suggests the presence of a cryptic, unexposed, relatively thin/primitive terrane to the east of the Takaka Terrane, which formed basement to voluminous Mesozoic arc magmatism.

Although the 380-360 Ma plutonism may have a correlative in the 380-365 Ma central Victorian granites of the Lachlan Fold Belt there is no sign of the major 430-400 Ma pulse that dominated magmatism in southeastern Australia. The A-type rocks may have formed during a period of post-orogenic extension possibly related to that observed in the New England Fold Belt of eastern Australia.

SIMILARITIES BETWEEN FRACTIONATED A-TYPE GRANITES AND SOME LOW-TI RHYOLITES FROM CONTINENTAL FLOOD BASALT PROVINCES

Simon Turner, Frances Garland & Chris Hawkesworth

Department of Earth Sciences, Wills Memorial Building, University of Bristol, Bristol BS8 1RJ, UK

A-type granites typically occur in bimodal magmatic suites and at least some can be shown to be the result of fractionation of accompanying basaltic magma or extraction of interstitial liquid from a gabbroic crystal mush. Many continental flood basalt provinces (CFB) are capped by rhyolites with "A-type" compositions and most studies have concluded that these higher silica rocks are crustal melts. However, although many of the low-Ti CFB exhibit a marked a silica gap from ~ 55-65% SiO_2, many incompatible element ratios, and the calculated eruption temperatures (950-1100 °C) are strikingly similar between the rhyolites and the associated basalts. Using experimental evidence, derivation of the low-Ti CFB rhyolites from a basaltic parent is shown to be a viable alternative to crustal melting. Comparison of liquid compositions from experimental melting of both crustal and mantle-derived (basaltic) source materials allows the two to be distinguished on the basis of Al_2O_3 and FeO content. The basalt experiments are reversible, such that the same melts can be produced by melting or fractional crystallisation. The effect of increased water content in the source is also detectable in the liquid composition. The majority of rhyolites from CFB provinces fall along the experimental trend for basalt melting/fractional crystallisation at relatively low water content. The onset of the silica gap in the rhyolites is accompanied by an abrupt decrease in TiO_2 and FeO^*, marking the start of Fe-Ti oxide crystallisation. Differentiation from 55-65% SiO_2 requires ~ 30% fractional crystallisation in which magnetite is an important phase, plus < 20% crustal contamination, to explain the observed increases in Sr isotopes and some incompatible element abundances. The rapid increase in silica occurs over a small temperature interval and for relatively small changes in the amount of fractional crystallisation; thus intermediate samples are less likely to be sampled. It is argued that the presence of a silica gap is not diagnostic of a crustal melting origin for A-type granites or CFB rhyolites, and models for crustal growth should take this substantial contribution from the mantle into account.

INHERITED ZIRCON IN GRANITES: GOLD MINE OR RED HERRING?

Ian S. Williams

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Inherited zircon (zircon significantly older than the igneous rock in which it occurs), is common in granitic rocks, including the Siluro-Devonian granites of the Lachlan Fold Belt (LFB). Limited data suggest that it is also abundant in the related volcanic rocks. Inherited zircon usually occurs, not as discrete grains, but as cores surrounded by an overgrowth of younger zircon precipitated from the melt phase of the magma. Its abundance ranges widely relative to the total zircon content of the host rock. It is extremely rare in the more mafic igneous rocks of the LFB such as gabbros and diorites, which are strongly undersaturated in Al (metaluminous), and only slightly less so in granites closely related to those mafic rocks. It is generally scarce but ubiquitous in other I-type granites, which are the dominant I-types of the LFB. These two groups, characterised by different patterns of zircon inheritance, correspond to, and define, the high- and low-temperature I-type granites of Chappell *et al.* (1998). In contrast, inherited zircon comprises a major fraction of the total zircon content of the S-type granites, which are always oversaturated in Al (peraluminous) and also formed at low magmatic temperatures. It is most abundant in the mafic S-type granites, in which virtually every zircon grain contains a large inherited core (Williams 1995).

These differences in abundance are governed by several factors, for example the abundance of zircon in the source rocks, the capacity of the magma to incorporate zircon-bearing country rock during its ascent, and the solubility of such assimilated zircon in the magma. High-temperature magmas have the greatest power to assimilate, but it is just such magmas in which assimilated zircon has the least chance of survival. Watson & Harrison (1983) showed that zircon has a high solubility in strongly metaluminous melts, particularly at higher magmatic temperatures. In contrast, low-temperature peraluminous melts become saturated in zircon at relatively low Zr contents, so zircon is relatively insoluble in such melts and zircon from the magma protolith has a greater chance of being preserved as inheritance in the resulting granite.

Detrital zircon in sedimentary rocks commonly survives high grade metamorphism, simply being overgrown by new zircon precipitated during the metamorphic event. If enough partial melt develops for a magma to mobilize, the former detrital zircon is preserved in that magma as inheritance. This process can be studied in regional metamorphic areas such as the Cooma Complex (Williams 2001). There it can be shown, by comparison between detrital and inherited zircon U-Pb analyses, that incorporation of zircon into an S-type magma had a negligible effect on the U-Pb isotopic systems in that zircon. An analogous example of metamorphism leading to the production of I-type magma has proved much more difficult to find. Currently the best test for the origin of inherited zircon in such magmas has been to compare the inheritance patterns in I-type magmas intruded into contrasting sedimentary sequences. Although the results show the inherited zircon to be derived from depth and not the near-surface country rocks, derivation of the inheritance from the magma source rocks has not been proven (Williams *et al.* 1999).

Having accepted that at least the inheritance in S-type granites is predominantly source-derived, the inheritance pattern in those granites becomes a guide to their possible source rocks. A feature of the S-type granites of the LFB, both regional- and contact-aureole types, is the close similarity between their inheritance patterns and the detrital zircon age patterns in the regional early Palaeozoic flysch (Williams 1992, 1995). One possibility is that part of the flysch sequence itself might be the source of the magmas, in which case the age of the youngest inherited component is of particular interest because it places an upper limit on the deposition age of the source metasediment. Young inherited zircon is rare, however, and there is always the question of whether the apparent ages of such grains have been reduced by partial loss of radiogenic Pb. There is also the question of whether individual analyses might represent a mixture of inherited and melt-precipitated zircon. These issues have been explored using cathodoluminescence-guided ion microprobe analysis of zircon from the Jillamatong Granodiorite, a member of the Bullenbalong Suite (White & Chappell 1988), one of the most mafic contact-aureole S-type granites of the LFB, and a rock type in which the inherited component is particularly abundant.

References

CHAPPELL B.W., BRYANT C.J., WYBORN D., WHITE A.J.R. & WILLIAMS I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* **48**, 225-236.

WHITE A.J.R. & CHAPPELL B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

WILLIAMS I.S. 1992. Some observations on the use of zircon U-Pb geochronology in the study of granitic rocks. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 447-458.

WILLIAMS I.S. 1995. Zircon analysis by ion microprobe: the case of the eastern Australian granites. *Leon T. Silver 70th Birthday Symposium and Celebration*, The California Institute of Technology, 27-31.

WILLIAMS I.S. 2001. The response of zircon, monazite and their U-Pb isotopic systems to low-P regional metamorphism, Cooma, NSW. *Australian Journal of Earth Sciences* (in press).

WILLIAMS I.S., STEPHENS W.E. & CHAPPELL B.W. 1999. Inherited zircon-a direct tracer for the provenance of granitic magmas. *In:* Barbarin B. ed. *Fourth Hutton Symposium Abstracts*, Document du BRGM **290**, 70.

WATSON E.B. & HARRISON T.M. 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* **64**, 295-304.

WHAT ASSOCIATED VOLCANIC ROCKS CAN TELL US ABOUT GRANITE GENESIS AND TECTONICS

Doone Wyborn

Department of Geology, Australian National University, Canberra, ACT 0200, Australia

The widespread Silurian to Devonian granites of the Lachlan Fold Belt are associated in time and space with felsic volcanic rocks of almost equivalent aerial extent. Compared to the granites, the volcanic rocks preserve higher temperature mineralogy, giving a greater chance of determining intensive parameters. Two types of volcanic rocks can be recognised, those associated with granites that evolved dominantly by fractional crystallisation, and those associated with granites that evolved dominantly by restite fractionation. These are equivalent to the high temperature and low temperature granites of Chappell *et al.* (1998).

The high temperature volcanic rocks are dominated by sparsely phyric (< 10% phenocrysts) rhyolites with minor associated andesites and basaltic andesites. They are exclusively I-type. The rhyolites were derived from felsic tops of magma chambers that evolved through convective fractionation (Wyborn *et al.* 2001).

The low temperature volcanic rocks are much more voluminous and are both S- and I-type. High abundances of phenocrysts (30-60%) provide a striking contrast with the high temperature volcanic rocks. Examples of the I-types include the Kadoona Dacite intruded by the Bega Batholith (Wyborn & Chappell 1986), and the St Marys Porphyry in NE Tasmania. Their primary mafic mineralogy is dominated by clinopyroxene and orthopyroxene, but this is replaced by hornblende and biotite in associated granite bodies.

S-type volcanic rocks are the dominant type of low temperate volcanic rocks, and are widespread in the area around Cowra, Yass and Canberra. Two eruption cycles of differing composition are present. The first cycle (Hawkins cycle) is strongly peraluminous with ubiquitous phenocrysts of cordierite, and there is chemical matching with the Bullenbalong Supersuite of granites (Wyborn *et al.* 1981). In this cycle, volcanism was initiated in a shallow water to terrestrial environment with many small eruptions of crystal-rich dacite lava and ignimbrite and uncommon crystal poor rhyolite. The cycle was ended by a climactic eruption of a widespread crystal-rich ignimbrite up to 600 m thick and overlain by a rhyolitic ashfall deposit. The ignimbrite is 80% crystals but contains magma blobs with around 50% crystals indicating the crystal-rich character of the magma. The second (Laidlaw) cycle (Wyborn 1990, 1993) is similar in that smaller eruptions are followed by the climactic Laidlaw ignimbrite of approximately 600 km^3. The Laidlaw cycle is only weakly peraluminous, and does not contain cordierite. These cycles are envisaged as periods during which plutons rising towards the surface bleed off small amounts of magma until they reached a critical level in the crust where the pluton erupted catastrophically.

Intensive parameter determinations for the volcanic rocks indicate temperatures ranging from 800 °C for the oldest strongly peraluminous S-type volcanic rocks through to over 1000 °C for the youngest high temperature I-type rhyolites. None of the volcanic rocks exhibit Y-depleted trace element patterns indicating they were generated within the crust at pressures less than 10 kilobars. A geotherm can be constructed that passes through the PT conditions determined for the Wagga Metamorphic Belt (Morand 1990).

Some important conclusions deriving from the volcanic rocks in the Yass-Canberra area include:

1. Most of the felsic magmas were derived from relatively shallow zones of partial melting and evolved by restite fractionation.
2. High-level granitic magmas are in equilibrium with anhydrous mafic minerals until they are substantially solidified.
3. Eruption cycles progressed with time from shallower to deeper and hotter source rocks during the Silurian and early Devonian.
4. A similar and high geothermal gradient was imposed on large parts of the Lachlan Fold Belt in the Silurian to early Devonian, giving rise to widespread melting of the mid to lower crust.
5. The main granitic batholiths and the main felsic volcanic eruptions occupy the same structural zones here termed magma upwelling zones.
6. The upwelling zones were topographically higher than the intervening downwelling zones so that subaerial volcanism above major batholiths sits adjacent to shallow marine basins relatively devoid of magmatism.
7. The upwelling zones are less deformed than the downwelling zones.
8. Major faults separate the upwelling and downwelling zones at the surface. These are unlikely to shallow out and detach, as they would then have to cut through the roots of the batholiths.
9. Passive heating and the resulting internal crustal rearrangement due to melting and upward migration of magma was the dominant cratonisation process in the Lachlan Fold Belt; externally imposed dynamic folding events are subordinate.

References

CHAPPELL B.W., BRYANT C.J., WYBORN D., WHITE A.J.R. & WILLIAMS I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* **48**, 225-236.

MORAND V.J. 1990. Low-pressure regional metamorphism in the Omeo Metamorphic Complex, Victoria, Australia. *Journal of Metamorphic Geology* **8**, 1-12.

WYBORN D. 1990. ICOG7 Excursion Guide B-2, Silurian Volcanics and the Geological Timescale. 7th International Conference on Geochronology, Cosmochronology and Isotope Geology, Canberra, A.C.T., Bureau of Mineral Resources, Australia, Record **1990/51**.

WYBORN D. 1993. Palaeozoic felsic volcanism in the Canberra district. IAVCEI Excursion guide. Australian Geological Survey Organisation, Record 1993/68.

WYBORN D. & CHAPPELL B.W. 1986. The petrogenetic significance of chemically related plutonic and volcanic rock units. *Geological Magazine* **123**, 619-628.

WYBORN D., CHAPPELL B.W. & JAMES M. 2001. Examples of convective fractionation in high temperasture granites from the Lachlan Fold Belt. *Australian Journal of Earth Sciences* (in press).

WYBORN D., CHAPPELL B.W. & JOHNSTON R.M., 1981. Three S-type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research* **86**, 10335-10348.

MIOCENE S-TYPE GARAM CHASMA LEUCOGRANITE, HINDUKUSH RANGE (TRANS-HIMALAYAS), NORTHWESTERN PAKISTAN

Mohammad Zafar[1], Mamoru Murata[1], Tahseenullah Khan[2], Hiroaki Ozawa[1] & Hiroshi Nishimura[1]

[1]Department of Geosciences, Faculty of Science, Naruto University of Education, Tokushima 772-8502, Japan
[2]Geoscience Laboratory, Geological Survey of Pakistan, Islamabad, Pakistan

Introduction

A majority of the post-collisional granitic rocks in the Indian-Nepal Himalayas occur in the Higher Himalayas (collision zone) and the Trans-Himalayas on the southern margin of the Asian Plate. The westernmost extension of the Himalayas is situated in northern Pakistan, where the granite activity was more complex than in the Indian-Nepal Himalayas because of the presence of the Kohistan-Ladakh palaeo-island arc, squeezed between the Asian and Indian plates. The Northern Suture that separates the Kohistan-Ladakh island arc from the Asian plate was developed at ca 100 Ma due to the closure of the Neotethys (Pudsey 1986; Petterson & Windley 1985). The arc is bounded in the south by the Main Mantle Thrust, which formed as a result of India-Asia collision at 55 to 40 Ma (Tahirkheli 1982; Coward *et al.* 1986; Rowley 1986). Therefore, the Trans-Himalayan I-type granitic rocks occur in the Asian plate and the Kohistan-Ladakh arc, and the Higher Himalayan S-type granitic rocks occur in the Nanga Parbat-Haramosh Massif of northern Pakistan.

The post-collisional peraluminous Garam Chasma granite in the Hindukush Range on the southern margin of the Asia Plate is different from other I-type granitic rocks in the Trans-Himalayas. Therefore, the petrological investigation of the Garam Chasma granitic rocks leads us to better understand the mountain building process of the Himalayas and adjacent terranes.

Garam Chasma granite

The Garam Chasma granite occurs about 30 km northwest of the Northern Suture, and intrudes discordantly into the Hindukush metamorphic complex of the Wakhan zone (Gaetani *et al.* 1996). It is an undeformed fine- to coarse-grained leucogranite with K-Ar biotite ages of 20 to 18 Ma (Zafar *et al.* 2000). The main minerals include muscovite, biotite, plagioclase, K-feldspar and quartz, with subordinate garnet and tourmaline. The accessory minerals include apatite, zircon, sillimanite and allanite. The Garam Chasma granitic rocks show a restricted range of SiO_2 contents (72 to 75%). Their alumina saturation index ranges from 1.03 to 1.25. The K_2O/Na_2O ratios of the rocks are higher than 1.0. The $\delta^{18}O$ values of four samples of those leucogranites range from 11.48 to 12.72‰. We conclude that the Garam Chasma granite is an S-type granite based upon its peraluminous character and the $\delta^{18}O$ values of higher than 10‰, a value that separates S-type and I-type granites of the Berridale Batholith (O'Neil & Chappell 1977). Initial $^{87}Sr/^{86}Sr$ ratios of the rocks range from 0.706 to 0.710 (Hildebrand 1997).

Discussion

The Garam Chasma S-type granitic rocks differ from the I-type Trans-Himalayan granitic rocks on the southern margin of the Asia Plate and the Kohistan-Ladakh island arc, in age, mineral assemblage, bulk chemistry and $\delta^{18}O$ values. The ages of post-collisional granites within the Asia Plate and Kohistan-Ladakh arc are 37-21 Ma and 104-26 Ma, respectively (Searle 1991; Petterson & Windley 1985), suggesting the older age of activity than that of the

Garam Chasma. The $\delta^{18}O$ values of the Kohistan-Ladakh granitic rocks are lower than 10‰ (Blattner *et al.* 1983; Zafar *et al.* 2000).

The Nanga Parbat-Haramosh Massif represents the westernmost extension of the Higher Himalayas in Pakistan. The three small plutons studied are composed of tourmaline two-mica leucogranite. Their U-Pb (zircon and monazite) ages range from 19 to 1 Ma (Zeitler *et al.* 1993; Schneider *et al.* 1999). The leucogranites show restricted SiO_2 contents (73 to 77%) and K_2O/Na_2O ratios higher than 1.0. Their major and trace element variation plots show similar trends to those of the Garam Chasma. The aluminum saturation index and $\delta^{18}O$ of the rocks range from 1.01 to 1.35, and 11.6 to 12.01‰, respectively.

Miocene S-type granitic rocks in Higher Himalayas in India, Nepal and South Tibet are tourmaline two-mica leucogranite ranging in age from 21 to 17 Ma (Stern *et al.* 1989; Searle *et al.* 1997). Their chemical characteristics and $\delta^{18}O$ values are also the same as those of the Garam Chasma. Therefore, we can conclude that the Garam Chasma granite, despite its exposure on the southern margin of the Asian Plate, is akin to the Higher Himalayan granites.

References

BLATTNER P., DIETRICH V. & GANSSER A. 1983. Contrasting ^{18}O enrichment and origins of High Himalayan and Transhimalayan intrusives. *Earth and Planetary Science Letters* **65**, 276-286.

COWARD M.P., WINDLEY B.F., BROUGHTON R.D., LUFF I.W., PETTERSON M.G., PUDSEY C.J., REX D.C. & KHAN M.A. 1986. Collision tectonics in the NW Himalayas. *In:* Coward M.P. & Ries A.C. eds. *Collision Tectonics*, pp. 203-219. Geological Society of London Special Publication **19**.

GAETANI M., LE FORT P., TANOLI S., ANGIOLINI L., NICORA A., SCIUNNACH D. & KHAN A. 1986. Reconnaissance geology in Upper Chitral, Baroghil and Karambar district (northern Karakoram, Pakistan). *Geologische Runschau* **85**, 683-704.

HILDEBRAND P.R. 1997. Leucogranite genesis in the Hindu Kush, Northwest Pakistan. *Proceedings of the 12th Himalaya-Karakoram-Tibet International Workshop*, 47.

O'NEIL J.R. & CHAPPELL B.W. 1977. Oxygen and hydrogen isotope relations in the Berridale batholith. *Journal of the Geological Society of London* **133**, 559-571.

PETTERSON M.G. & WINDLEY B.F. 1985. Rb-Sr dating of the Kohistan arc batholith in the Trans-Himalaya of N. Pakistan and tectonic implications. *Earth and Planetary Science Letters* **74**, 45-57.

PUDSEY C.J. 1986. The Northern Suture, Pakistan: margin of a Cretaceous island arc. *Geological Magazine* **123**, 405-423.

ROWLEY D.B. 1996. Age of initiation of collision between India and Asia: a review of stratigraphic data. *Philosophical Transactions of the Royal Society of London* **A326**, 229-255.

SCHNEIDER D.A., EDWARDS M.A., ZEITLER P.K. & COATH C.D. 1999. Mazeno Pass Pluton and Jutial Pluton, Pakistan Himalaya: age and implications for entrapment mechanism of two granites in the Himalaya. *Contributions to Mineralogy and Petrology* **136**, 273-284.

SEARLE M.P., PARISH R.R., HODGES K.V., HARFORD A., AYERS M.W. & WHITEHOUSE M.J. 1997. Shisha Pangma leucogranite, South Tibetan Himalaya: field relations, geochemistry, age, origin and emplacement. *Journal of Geology* **105**, 295-317.

STERN C.R., KLIGFIELD R. & SCHELLING D. 1989. The Bhagirathi leucogranite of the High Himalayas (Garhwal, India): age, petrogenesis, and tectonic implications. *Geological Society of America Special Paper* **232**, 33-44.

TAHIRKHELI R.A.K. 1982. Geology of the Himalaya, Karakoram and Hindukush in Pakistan. *Geological Bulletin, University of Peshawar* **15**, 1-51.

ZAFAR M., MURATA M., KHAN T., OZAWA H. & NISHIMURA H. 2000. K-Ar biotite ages from Miocene post-collisional Garam Chashma leucogranite, eastern Hindukush Range (Trans-Himalayas), northwestern Pakistan. *Journal of Mineralogical and Petrological Sciences* **95**, 101-106.

ZEITLER P.K., CHABERLAIN C.P. & SMITH H.A. 1993. Synchronous anatexis, metamorphism, and rapid denudation at Nanga Parbat (Pakistan Himalaya). *Geology* **21**, 347-350.