from the northern boundary of the Rockvale Granodiorite, suggests that their status is still equivocal. Several reasons contribute to the difficulty in assigning an accurate palaeontological age for these fossil fragments: (a) their deformed nature; (b) presence only of moulds; (c) absence of other fauna in these beds; and (d) absence of correlative sediments in their vicinity.

The second and equally important aspect to this problem is the accepted assumption that the metamorphism of this fossil bed is attributable solely to intrusion of the Rockvale Granodiorite. Based on combined critical field evidence and additional unpublished isotopic work this assumption cannot be sustained. An alternative and more adequate explanation of this metamorphism rests with the intrusion of a linear belt of monzonitic and more mafic bodies some of which are barely unroofed (in addition to numerous coeval dykes and sills) into the sediments immediately to the west and north of the Rockvale Granodiorite during the Mid to Late Permian, at a time in which the geotherms were already raised following the intrusion of the voluminous New England Suite.

For these reasons it is believed that no serious conflict exists between the isotopic age of the Hillgrove Suite whose lower limit is 302 m.y. and the fossil fragments described above. It is quite conceivable that a short-lived marine transgression deposited fossil-bearing sediments unconformably on older Devonian strata either directly or by turbidity flow [bearing in mind the possibility of a megathrust sheet in this area (Korsch, 1980)], even at a time of magma generation at lower levels in the crust. This interpretation nevertheless implies that the fossil fragments at Rockvale may be slightly older than previously thought.

3.7.5 Metasedimentary Rocks Associated with the Hillgrove Suite

Because there is strong evidence that the Hillgrove Suite granitoids have been derived by partial melting of sedimentary rocks which are not significantly different in chemical composition to those which presently surround the plutons, it is obviously important to establish the relationship between these sediments and the granitoids in terms of Sr isotopes. Accordingly, Sr isotopic analyses of total-rocks and minerals were carried out on metasediments from mainly two areas, Wongwibinda and Moona Plains.

(a) Wongwibinda

Sr isotopic data for 22 total-rock samples from the Wongwibinda Complex (Binns, 1966) and from the Sandon Association sensu stricto (Korsch, 1977) are presented in Table 3.20 and plotted on a conventional isochron diagram (Fig. 3.13). Two isochrons were fitted to the data. Isochron II was fitted to data

Table 3.20 Rb-Sr data for Wongwibinda metasediments and calculated values of $^{87}Sr/^{86}Sr$ at 320 m.y.

Sample	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ (320 m.y.)	Mica age*
ISOCHRON I						
WB 20	95.0	420.0	0.653	0.70825	0.70528	
WB 24	81.7	356.7	0.661	0.70792	0.70494	
RV 8	92.9	373.2	0.719	0.70897	0.70570	**
WB 30	116.3	280.4	1.198	0.71087	0.70537	
WC 39	139.1	330.7	1.2015	0.71085	0.70541	
RMIG	115.7	253.0	1.320	0.71229	0.70632	**
RSCH	114.0	248.0	1.328	0.71111	0.70508	**
AB 12-7	111.8	231.7	1.394	0.71234	0.70601	
WB 183	113.3	227.2	1.440	0.71236	0.70598	
T10	132.9	255.2	1.504	0.71283	0.70600	
WB 4	268.3	143.9	1.550	0.71421	0.70717	**
Biotite	627.5	8.149	241.79	1.60289		261
duplicate	625.2	8.140	241.32	1.61127		264
Muscovite	256.6	28.83	25.966	0.81326		293
duplicate	256.6	29.26	25.574	0.80881		285
AB PEG	50.0	89.0	1.623	0.71324	0.70587	
D 28	116.0	201.0	1.667	0.71338	0.70581	
WB 3	134.0	203.5	1.903	0.71489	0.70624	
Biotite	478.9	11.43	126.43	1.16611		256
WB 63	169.5	246.6	1.987	0.71521	0.70627	
AB 11	163.3	118.1	4.001	0.72661	0.70857	
Biotite	578.3	6.518	282.29	1.74810		260
F 20	163.4	97.1	4.870	0.73070	0.70857	
ISOCHRON II						
AB 12-2	3.915	213.1	0.053	0.70739	0.70678	
AB 12-4	4.060	193.0	0.061	0.70692	0.70664	
AB 12-3	5.543	171.6	0.093	0.70712	0.70670	
AB 12-1	7.902	169.5	0.135	0.70739	0.70678	
AB 12-5	14.74	220.5	0.193	0.70776	0.70688	
AB 12-6	43.02	236.6	0.525	0.70898	0.70659	

* Calculated using 0.7050 as the initial $^{87}Sr/^{86}Sr$ of the total rock.
** Deleted from regression.

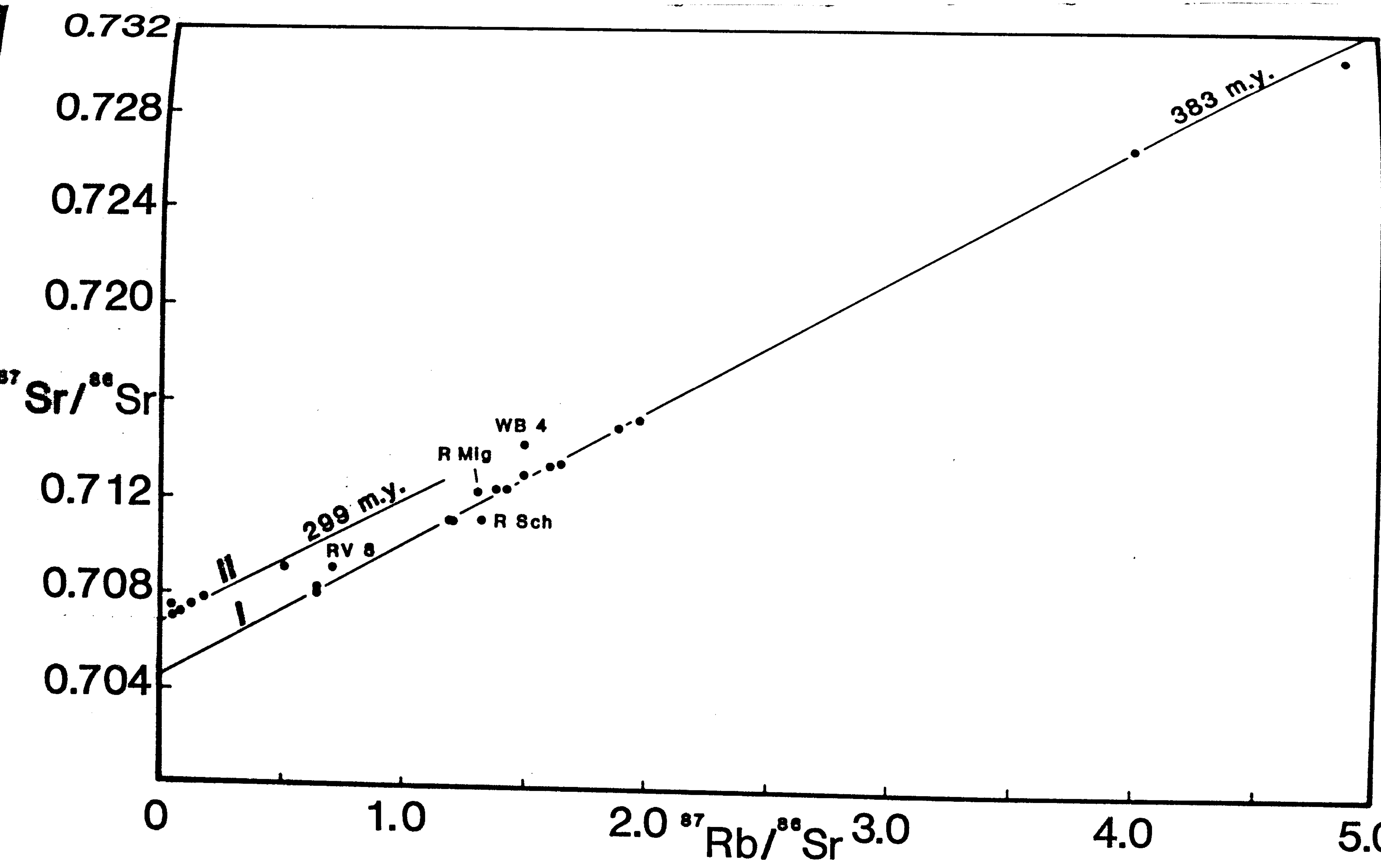

Figure 3.13 Isochron diagram for metasediments from the Wongwibinda Complex. Numbered samples deleted from regression (see text).

points for 6 thin (< 10mm) slabs of compositionally banded, high-grade calc-silicate metasediment. Although the 'age' for these slabs (299 ± 54 m.y.) was quite predictable, the high initial $^{87}Sr/^{86}Sr$ ratio (0.70679 ± 0.00018) was rather surprising indicating that these calc-silicate samples were probably deposited in sea-water. It follows that they should therefore have equilibrated isotopically with the sea-water. However, the initial ratio of 0.70679 is somewhat lower than documented results (~ 0.7080) for Upper Devonian carbonates (Veizer, 1975) suggesting less than total equilibration. How this may be achieved is not entirely clear; however, the most plausible explanation for this apparent discrepancy relates to the environment in which they were deposited. At this time rapid erosion of an active volcanic arc was dumping enormous quantities of detritus into what may have been a marginal sea or even a large and possibly land-locked basin. The obvious effect of this is to drastically lower the $^{87}Sr/^{86}Sr$ ratio of the sea-water.

The high error of the regression is clearly a function of the very limited dispersion of Rb/Sr. Whether the associated (confining) mica schist (Ab 12-7) should be included in this regression is debatable in view of its unquestionable similarity and consanguinity with other analyzed mica schists from the Wongwibinda Complex. Furthermore, its inclusion in such a regression may lead to erroneous results because of the undue weighting that is given to samples with relatively high Rb/Sr ratios.

The total-rock samples which comprise Isochron I range from very low grade metagreywackes [Zone of Transitional Schists (Binns, 1966)] to uppermost amphibolite facies garnet-cordierite, orthoclase-sillimanite schists adjacent to the Abroi Granodiorite. Psammo-pelitic samples adjacent to the Tobermory Adamellite (north) and Rockvale Granodiorite (south) have also been included in this regression because it has been concluded from other lines of evidence (petrographic, chemical and mineralogical) that these rocks are probably part of the same sedimentary association (Sandon ?) as those of the Wongwibinda Complex. Four samples have been omitted from the regression: one (RV8) is a pelite associated with felsic veinlets which emanate from the Rockvale Granodiorite, two (R Mig and R Sch) are from the aureole of the mafic Mornington Tonalite (Chapter 7) and the other (WB4) is a cordierite rock close to Tertiary basalt.

The regression of the 13 total-rock samples yields a McIntyre Model 4 age of 383 ± 10 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70447 ± 0.00025. The fact that the statistical treatment prefers a Model 4 solution suggests that samples of slightly different age and initial ratio are included in this regression.

However, the very low MSWD (3.19) implies that these differences are indeed slight which infers that in this instance the approach of regional sampling was not inappropriate. The excellent fit of the points to Isochron I suggests that by sampling over such a scale it is possible to see through small-scale isotopic homogenizations which may have occurred at a later date. An excellent test of this assumption is by the Cameron *et al*. regression technique which assumes, as stated earlier, that some small scale isotopic homogenization has occurred since the initial closure of the Sr isotopic system. If all the scatter about the isochron is attributable to the last known metamorphic event (~ 250 m.y.) the free-line method gives a pre-metamorphic alignment equivalent to an age of $385 \pm {}^{16}_{14}$ m.y. and initial ratio of 0.70442 ± 0.00052. This is in excellent agreement with the McIntyre *et al*. method. It may be argued that the scatter is not due to a subsequent metamorphic event but is in fact due entirely to inherent igneous dispersion. Assuming the igneous provenance of the Wongwibinda sediments had an (unlikely) age of ~ 1600 m.y. the Cameron *et al*. regression technique gives an age which is essentially identical to the previous age. This illustrates that the alignment of the data is quite independent of the interpretation of the scatter.

The close approach of Isochron I to the present day Sr bulk earth point implies that the volcanics from which these sediments were derived do not have a previous crustal history, i.e. they show no evidence of recycling or contamination, a feature confirmed by Nd isotopes (Hensel 1980, 1981; unpublished data). On this basis the application of the Cameron *et al*. bulk earth model 2 method is entirely valid. The fact that the age ($391 \pm {}^{6}_{6}$ m.y.) and initial ratio (0.70423 ± 0.00001) by this method is indistinguishable from the free-line method, when coupled with the McIntyre *et al*. results, leads to the conclusion that the ages indicated for these sediments are in all likelihood the age of the volcanic provenance. However, in view of the type of sediments this is probably (within analytical error) the age of sedimentation also.

The Sr isotopic results for the minerals from the high-grade Wongwibinda metasediments (Table 3.20) are significant in two respects. Firstly, the age of WB4 muscovite (~ 289 m.y.) coincides with the age of Isochron II, and secondly, the biotite ages (254-264 m.y.) match the biotite ages of the Hillgrove Suite granitoids. This, in effect, suggests that two separate thermal and/or deformational events have been recorded in the Wongwibinda Complex, the first coinciding with the intrusion of the Hillgrove Suite granitoids and the second with a mild regional metamorphism which may have accompanied the intrusion of members of the New England Suite. The evidence that the second event was relatively weak, i.e. below ~ 450°C, is based on the preservation of the older age of the coarse-grained muscovite in sample WB4. In contrast to muscovite, the blocking temperature for the Rb-Sr system in biotite is much lower, i.e.

~280-300°C (Tetley, 1979) and hence biotite is readily reset during even mild metamorphism.

Table 3.20 also lists the total-rock $^{87}Sr/^{86}Sr$ ratios, recalculated for $\underline{t}$ = 320 m.y. These ratios show that on the basis of Sr isotopes several of the mildly metamorphosed samples could represent possible source rocks for the Hillgrove Suite granitoids. By comparison, some samples from the high-grade metamorphics, e.g. F20 and AB11, give recalculated $^{87}Sr/^{86}Sr$ ratios which on face value are clearly too high to have yielded the granitoids. This suggests possible redistribution of Rb during metamorphism, a phenomenon which may be supported readily by the number of quartzo-feldspathic veinlets found throughout these and other high-grade rocks. However, despite this apparent loss of Rb the regional distribution of Rb/Sr has not changed, hence validating the inclusion of these samples in the regional isochron.

(b) Moona Plains

The 15 total-rock samples from the Moona Plains area, which range in metamorphic grade from greenschist to amphibolite facies, define an isochron equivalent to an age of 351 ± 8.8 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70451 ± 0.00019. The statistical selection of Model III suggests that samples with slightly different initial ratios have been included in the regression. However, the low MSWD (3.84) implies that these differences were probably quite small. The fact that the Cameron et al. free-line method age of $352 \pm^{13}_{11}$ m.y. and initial ratio of 0.70449 ± 0.00022 is identical to the McIntyre et al. method leads to the same conclusion as that reached for the Wongwibinda sediments, i.e. that the indicated age for the Moona Plains metasediments represents the age of both the volcanism and the contemporaneously deposited sediments. Interestingly, there is a significant age difference between the sediments from these two areas. This suggests that volcanic activity in the New England region during the Devonian and Early Carboniferous may have migrated, in a way analogous to the migration of the volcanic centres of eastern Australia during the Tertiary.

The biotites from the two high-grade schists (K13) and B7) give identical ages to those recorded for biotites from the Argyll and Tia Granodiorites (275 m.y. and 269 m.y., respectively). This implies that both the metamorphic and igneous biotites were reset by a thermal event which was common to both groups of rocks.

Sr isotopic data for sediments from other parts of New England are too few on which to draw any significant conclusions.

Table 3.21

Rb-Sr data for sediments from southern New England

Sample	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	^{87}Sr/^{86}Sr (320 m.y.)	Mica age*
Moona Plains - Walcha District						
LH1	34.6	461.9	0.216	0.70557	0.70459	
K 13	114.6	556.4	0.595	0.70794	0.70524	**
Biotite	771.8	15.2	55.39	0.92231		276
W 5	80.7	360.3	0.647	0.70770	0.70475	
K 7	108.1	381.9	0.818	0.70881	0.70508	
ARG/GW	113.1	368.1	0.887	0.70900	0.70496	
MP 87	114.1	355.7	0.926	0.70902	0.70480	
MPTP	114.4	313.9	1.052	0.70951	0.70472	
MPGW 2	109.5	299.1	1.057	0.70942	0.70461	
B 7	161.0	398.1	1.168	0.71025	0.70541	
Biotite	882.3	47.0	155.4	1.29253		266
MP CONG 1	120.1	294.8	1.177	0.71070	0.70534	
HH 330	153.6	367.8	1.206	0.71088	0.70539	
K 11	105.9	246.5	1.241	0.71065	0.70500	
MP CONG 2	146.0	302.6	1.394	0.71167	0.70532	
HH 114 D	151.2	256.9	1.701	0.71295	0.70520	
MP MIG	156.5	91.0	4.974	0.72936	0.70671	
Hillgrove District						
HGW	91.4	244.6	1.079	0.70980	0.70490	
HGSH	217.3	116.7	5.039	0.73264	0.70815	
HC	123.7	282.3	1.273	0.71283	0.70695	

* Calculated using 0.7050 as initial ^{87}Sr/^{86}Sr of the total rock.

** Deleted from regression.

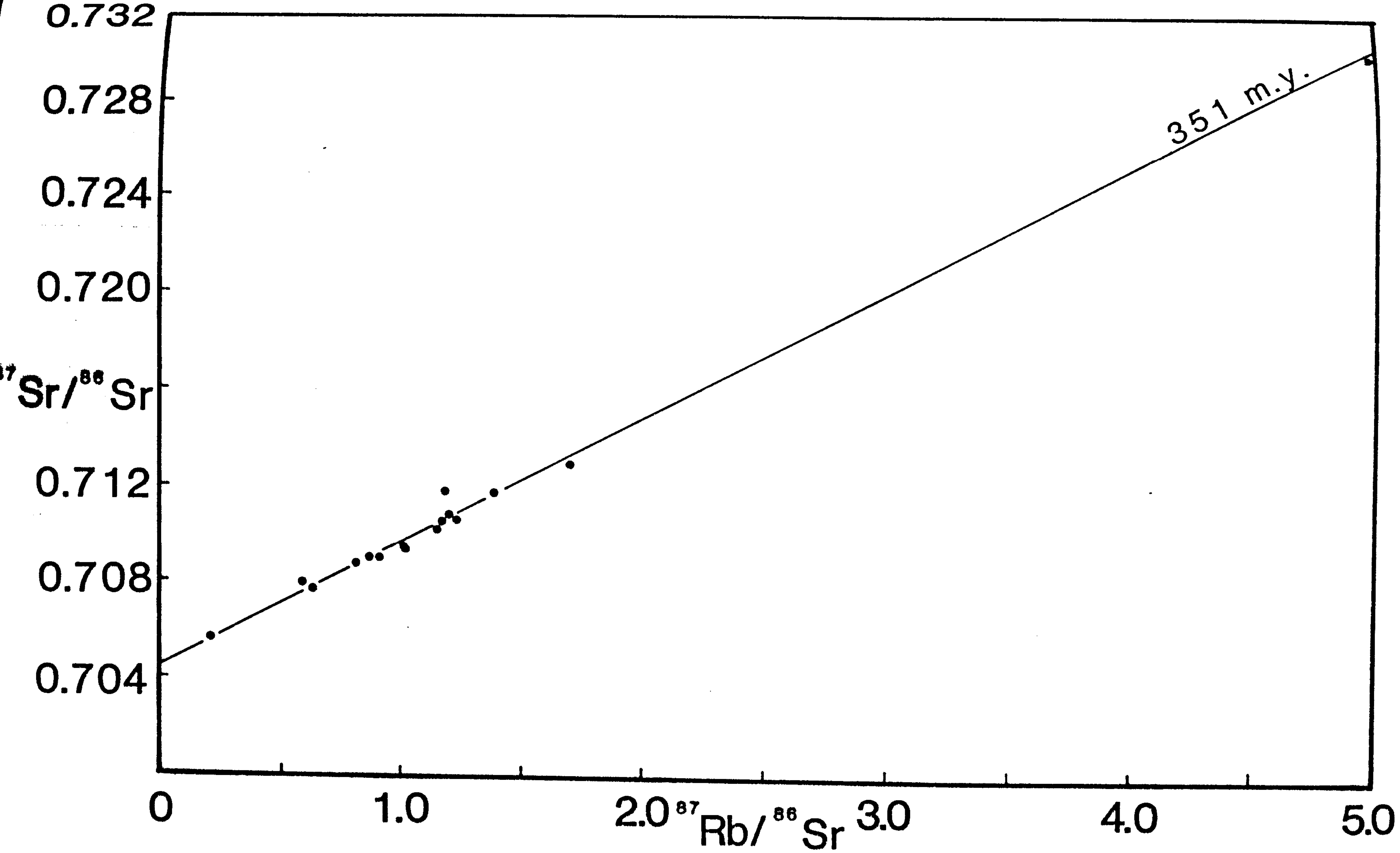

Figure 3.14 Isochron diagram for metasediments from the Moona Plains and Walcha districts.

3.7.6 Discussion

The 312 m.y. Rb-Sr total-rock age for the S-type Hillgrove Suite indicates that members of this suite predate the granitoids of the New England Suite by about 45 m.y. and thus, together with the S-type Bundarra Suite, represent the oldest known plutonic activity of the New England Batholith.

The initial $^{87}Sr/^{86}Sr$ ratio of the Hillgrove Suite (0.7053) is unusually low for S-type granitoids and is well below the lower limit of 0.708 suggested by Chappell and White (1974) to be representative of S-type granitoids. This discrepancy demonstrates the problems of using Sr isotopic ratios to evaluate the genesis of granitic rocks and emphasises the importance of the relationship between the granitoids and the source rocks.

Peterman _et al_. (1967) and Kistler and Peterman (1973) showed that because granitoids inherit the Sr isotopic composition of their source rocks, those derived by partial melting of volcanogenic detritus may possess isotopic ratios which reflect the upper mantle composition of this source material. Two obvious but important constraints to this generalization are (a) that the time periods between volcanism and sedimentation and between sedimentation and granite formation be small, i.e. < 200 m.y., and (b) that the contribution to the sedimentary pile did not include an old terrigenous component. For example, although the Cooma Granodiorite, southern New South Wales, was probably formed by _in situ_ anatectic melting of only slightly older enclosing sediments (Pidgeon and Compston, 1965), its high initial $^{87}Sr/^{86}Sr$ implies that these sediments were derived, at least in part, from a moderately radiogenic, presumably Precambrian source. This was confirmed recently by zircon studies on a number of associated S-type granitoids (Williams, _pers.comm._).

In view of the relatively low initial ratios of the Hillgrove Suite granitoids it can be confidently concluded that the contribution of old radiogenic material to the New England sedimentary pile was negligible at most. Two factors particularly to which the low initial ratios of the Hillgrove Suite may be attributed are (a) the contemporaneity of volcanism with sedimentation (McKelvey, 1974) and (b) the small age difference (< 80 m.y.) between sedimentation and granite formation.

The biotites from all Hillgrove Suite granitoids have Rb-Sr ages which are younger than the total-rocks. This may indicate that the biotites have:

(a) cooled very slowly, from the closure of the Rb-Sr total-rock system near the solidus temperature of the pluton, to below 300°C and thus closure of the Rb-Sr system in biotite; or

(b) cooled normally to below 300°C, then reset by a subsequent thermal event.

It is difficult to find consistent evidence for slow cooling. Williams et al. (1977) and Compston and Chappell (1977) believed that the cooling history of plutons from the Berridale Batholith, southern New South Wales, was short. It follows, by analogy, that most of the Hillgrove Suite plutons, with their fine grainsize, have also cooled rapidly. Certainly there appears to be a close relationship between the biotite ages and the type of contact between the granitoids and the country rocks. For example, plutons with sharp contacts and small thermal aureoles have the smallest differences between total-rock and biotite ages and are interpreted to have moved vertically more than those with contacts which are gradational into high-grade metamorphics. In contrast, the Hillgrove Suite plutons which have an envelope of migmatites and high-grade metamorphics, namely the Abroi, Argyll and Tia Granodiorites, appear to have been confined to a high-temperature environment for some time, and thus cooled more slowly. These plutons show the largest difference between total-rock and biotite ages.

The precise relationship between the high-grade (regional) metamorphic rocks and certain members of the Hillgrove Suite has been debated for some time. Binns (1966), Leitch (1968, 1974, 1977) and Gunthorpe (1970) believed that regional metamorphism and granitoid emplacement in the Wongwibinda and Tia Complexes were essentially synchronous, culminating at ~250 m.y. This close spatial association between the metamorphic rocks and the granitoids is matched by their identical biotite ages. However, these ages are not consistent with recent textural and structural interpretations (Korsch, 1977) nor with muscovite and total-rock isotopic data. These data show that an earlier, high-grade thermal event was recorded by muscovite in two-mica schists from the Wongwibinda Complex and by small (< 10 cm), compositionally banded calc-silicate sediments close to the Abroi Granodiorite. Therefore, this close similarity in biotite ages must reflect an additional thermal event which was extensive, deep-seated, and of only moderate intensity but which equally affected both the granitoids and their metamorphic envelopes.

It may be coincidental that the New England Suite intruded adjacent to the Hillgrove Suite between 245 and 265 m.y. (Chapter 4). However, the relatively large volumes of its members in close proximity to the Hillgrove Suite probably provided sufficient heat to reset the Rb-Sr system in both the metamorphic rocks and their associated Hillgrove Suite granitoids. It must be stressed that only the biotites from deep-seated granitoids appear to have been fully reset. Those granitoids which do not have an envelope of metamorphic rocks and which were previously interpreted to have risen further in the crust, do not show a resetting of their biotites, presumably because they were effectively isolated from the general rise in crustal temperatures resulting from the intrusion of the New England Suite.

Strong evidence to support this hypothesis may be gained from the close age correlations between certain members of the New England and Hillgrove Suites. For example, the total-rock age for the New England Suite plutons north of Armidale (261 ± 8 m.y.) is identical to the biotite ages for the Abroi, Rockvale, Tobermory and Wollomombi plutons (259, 269, 256 and 259 m.y. respectively). Furthermore, where members of both Suites are adjacent, both tend to display the same biotite age, e.g. the Wards Mistake and Henry River Adamellites have matching ages of 246 and 245 m.y., respectively.

This isotopic study on the Hillgrove Suite and associated metamorphic rocks therefore concludes that:

1. the age of the sediments surrounding the Hillgrove Suite granitoids is Early to Late Devonian and thus ~70-90 m.y. older than previously believed;
2. a derivation of the Hillgrove Suite from the surrounding sediments is consistent with Sr isotopes;
3. the Hillgrove Suite was the result of a single co-ordinated event of magma formation at ~312 m.y.;
4. the granitoids are isotopically homogeneous and of the same age along strike;
5. the granitoid isochron did not commence on a positive slope;
6. the biotites are all consistently younger than the total-rock age of the pluton;
7. variations in the biotite ages of the granitoids reflect differences in the amount of vertical movement of the granitoid from the zone of magma generation; and
8. the majority of biotites have been reset to ages mostly between 245 and 270 m.y., presumably in response to the intrusion of the New England Suite.

3.8 PETROGENESIS

3.8.1 Application of Experimental Phase Relations to the Genesis of the Hillgrove Suite Granitoids

Recent data on hydrothermal sediment-granitoid melt compositions (von Platen, 1965; James and Hamilton, 1969; Winkler and Lindemann, 1972; Winkler *et al*., 1975; McKenzie, 1976) have demonstrated that phase relations in the system $Qz-Ab-Or-H_2O$ (Tuttle and Bowen, 1958) may be inadequate when applied to granitoids because they fail to include the small but nevertheless significant An component. The Hillgrove Suite granitoids contain from 2% to 20% An (see Table 3.12) and hence, may not be feasibly related to An-free "granite" systems. Direct comparisons between specific compositions in An-bearing experimental systems and granitoids may be made *only* if it is assumed that the bulk granitoid compositions represent melt compositions, an assumption which cannot be readily supported from petrographic evidence.

On the Qz-Ab-Or projection of the "granite" system (Fig. 3.15) compositions of the Hillgrove Suite granitoids plot in a wide field within the 4-7 kb PH_2O thermal trough for Ab/An ratios of 2.9 (von Platen and Höller, 1966). The rather wide scatter of points, away from the ternary minima at both 4 and 7 kb PH_2O and towards the Qz-Ab join, is somewhat surprising considering the similar modal compositions of all the granitoids. The scatter may well reflect a compositionally variable source or crystal-liquid disequilibria during melt generation and accumulation. However, a more likely reason for this scatter is that the granitoid compositions represent a mixture of minimum or near-minimum melt *plus* residual phases, i.e. phases which have remained stable during and after ultrametamorphism and granitoid formation, e.g. quartz and plagioclase, thus providing an explanation for the tendency of the Hillgrove Suite granitoids to plot away from the Or apex at pressures up to 7 kb PH_2O.

Some felsic variants of the Hillgrove Suite granitoids (see Table 3.12) have very high Thornton and Tuttle differentiation indices (> 92), very low An (< 3%) and consequently very high Ab/An ratios. Therefore, they should not be projected together with the adamellites and granodiorites on a Qz-Ab-Or plot based on Ab/An ratios of 2.9. In the absence of suitable data for higher Ab/An cotectic lines at 4, 5 or 7 kb PH_2O, the felsic rock compositions with high Ab/An ratios may be compared more appropriately to the experimentally determined piercing point for Ab/An ratios of 10.4 at 1 kb PH_2O (James and Hamilton, 1969) or the 2 kb PH_2O "eutectic" of von Platen (1965), in the Qz-Ab-Or system. However, as shown on Figure 3.15 the felsic variants plot in a small field away from these experimentally determined points, towards the Qz-Or join.

Although the field of felsic Hillgrove Suite rocks falls close to the 2 kb PH_2O cotectic in the An-free experimental $Qz-Ab-Or-H_2O$ system of Tuttle and Bowen (1958) it is nevertheless still markedly displaced from the minimum (*m*; Fig. 3.15), towards the Qz-Or join. In a preliminary experimental study of the An-free

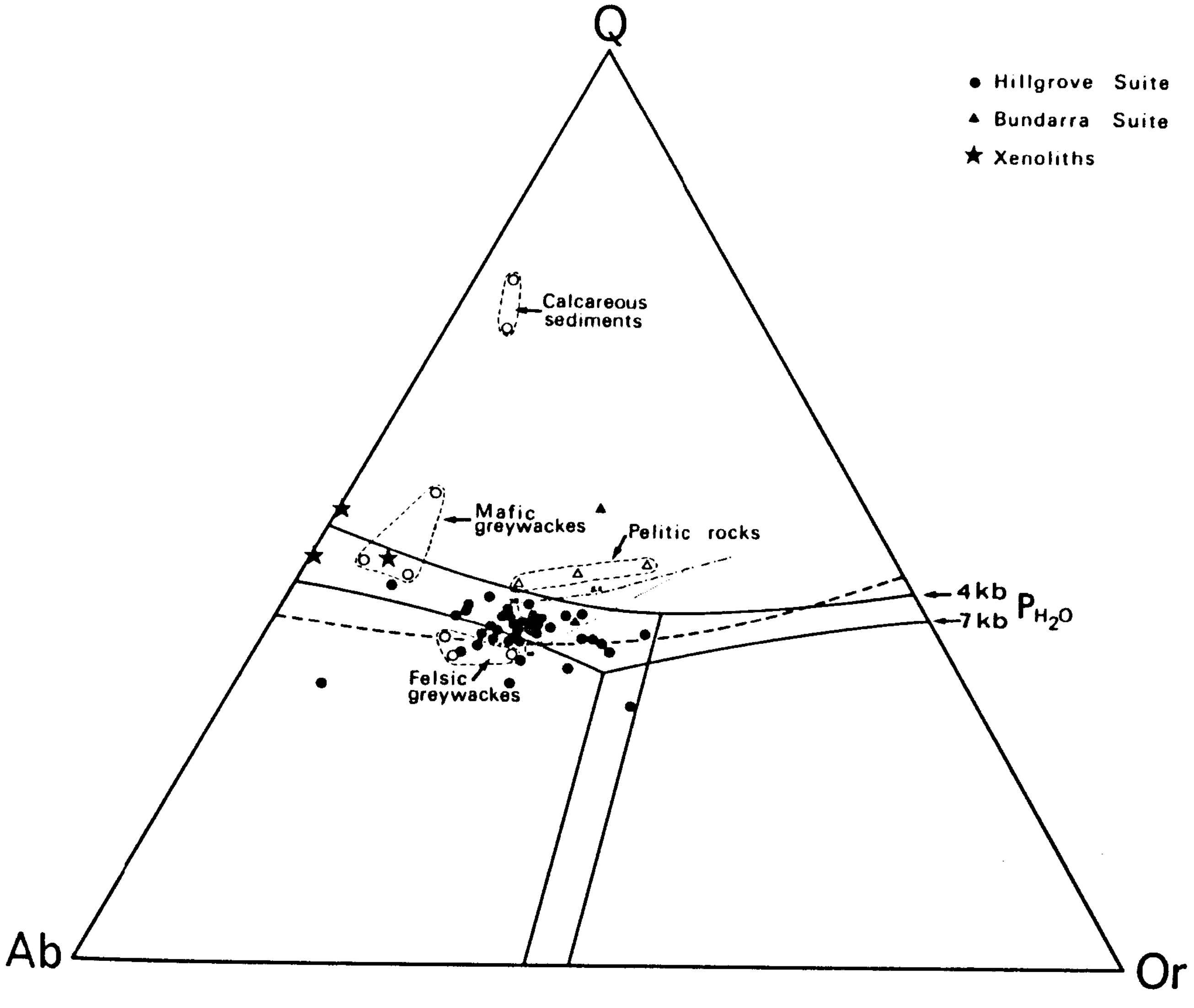

Figure 3.15 Mesonormative Q-Ab-Or proportions for granitoids (filled circles) and xenoliths (stars) from the Hillgrove and Bundarra Suites compared with the cotectic lines for water vapour pressures of 4 and 7 kb and Ab/An ratios = 2.9 (after von Platen and Höller, 1966). Also included are fields for certain New England sediments. Also plotted for comparison (thick dashes) is the cotectic line for 2 kb water pressure (after Tuttle and Bowen, 1958) in the An-free "granite" system; piecing points for various Ab/An ratios at 1 kb PH_2O (James and Hamilton, 1969; dotted line) and at 2 kb PH_2O (von Platen, 1965; dot-dash line).

system, McKenzie (1976) commented that the displacement of isotherms and minima towards the Qz-Or join was considerable, even with the addition of only small amounts (~ 5%) of An. Thus, the displacement of the felsic samples from the minima of both the An-free and the An-bearing systems may be due to the effect of volatiles or the fact that they may not represent minimum melts at all with respect to the Au-An-Qz-Or-H_2O system under geologically reasonable PH_2O or that the bulk compositions may be composites of minimum melt plus variable crystal fractions.

Von Platen (1965) investigated the effects of HCl on the minimum melt compositions and temperatures, and found that this component had a remarkable influence in moving the minimum melting composition away from the Qz apex and closer to the Or apex, and depressing minimum melting temperatures by up to 20° C. Other volatiles, e.g. F and B, have a similar effect (Wyllie, 1970). Since the first and last liquids of partial melting or fractional crystallization, respectively, approach minimum melt compositions, and are generally restricted in volume, there is a strong likelihood that these minimum melts will be saturated in H_2O and other volatiles. If this assumption is correct the field of felsic Hillgrove Suite samples would be *expected* to occupy an area on the Qz-Ab-Or projection slightly away from the piercing points of James and Hamilton and the 2 kb "eutectic" of von Platen, and closer to the Or apex (see Fig. 3.15). A further explanation for the displacement of the felsic rocks from the experimentally determined minima in the Qz-Ab-Or-An-H_2O system might be that because crystal-liquid equilibria probably represent the dominant mechanism in the formation of these rocks the activity of alkali feldspar, or alkali feldspar plus quartz, may be enhanced at either or both low temperature or water-saturated conditions (Tuttle and Bowen, 1958). Analytical data on aplitic rocks and granitoids approaching minimum melt compositions, from Europe, Africa, North America and other Australian batholiths, are similar to the felsic granitoids of the Hillgrove Suite, and plot towards the Qz-Or join, away from the ternary minimum.

As suggested above, one obvious reason for this displacement is the possibility that the felsic granitoids are not minimum melts. During partial melting the generation of non-minimum melt can follow only after the maximum amount of minimum melt has been generated from source material of a given composition. Although an increase in the temperature above that of minimum melting is essential to generate a non-minimum melt, this increase need not be very high since experimental data show that the coexistence of the equilibrium assemblage plagioclase-alkali feldspar-quartz-melt is restricted to a maximum range of about 50° C at 5 kb PH_2O (Winkler, 1976) or only about 30° C, according to Piwinskii and Wyllie (1970).

Supplementing the ternary Qz-Ab-Or diagram is the projection of the system onto the An-Ab-Or face of the "granite" tetrahedron. On this projection (Fig. 3.16) the Hillgrove Suite granitoids group into an elongate field approximately half-way between the thermal trough defined by Kleeman (1965) and the An-Ab join. This implies a range in the crystallization temperatures of these rocks even though the final crystallization of the minimum melt fraction may have occurred at roughly the same temperature. The felsic variants plot near and within the thermal trough which suggests a relatively low-temperature formation for these rocks, assuming saturation in H_2O. By comparison, rock compositions of the Bundarra Suite plot midway between the thermal trough and the majority of the Hillgrove Suite granitoids. Assuming similar degrees of water-saturation this infers that the Bundarra Suite crystallized at somewhat lower temperatures than the Hillgrove Suite.

3.8.2 Problem of H_2O in Melts

A vital aspect of melt generation is the availability of a fluid phase (usually H_2O). For example, if water-saturation is not achieved during partial melting, the amount of melt produced at a given temperature is severely restricted and further melting will not occur unless there is a rise in temperature. Unfortunately, detailed documentation of melting relations in water-undersaturated experiments at low temperatures is hindered by a number of experimental difficulties, e.g. nucleation, rate of reaction and metastability of phases etc. However, there is little doubt that the absence of free water during partial melting severely affects melting relations (James and Hamilton, 1969).

An important point in this problem is that the temperatures at which melting takes place in water-deficient systems are significantly different from those of saturated or near-saturated systems. For example, the experimentally determined solidus temperature of granite at $P = 2$ kb, in which the total amount of the fluid phase in the system is bound up in hydrous minerals, is about 875°C (Wyllie *et al.*, 1976), whereas solidus temperatures for the same rock will approach 1000°C under dry conditions (Piwinskii and Wyllie, 1968; Piwinskii, 1968; Robertson and Wyllie, 1971; Eggler and Burnham, 1973). On the other hand, experimentally determined *liquidus* temperatures for rocks with compositions identical to those of the Hillgrove Suite granitoids, will, even in the presence of excess water, approach 950°C (Piwinskii, 1968). This temperature is much higher than indicated by the mineralogies of both the Hillgrove Suite granitoids and their surrounding metamorphic rocks, which collectively suggest that the temperature range of partial melting was more likely to have been in the order 700-750°C. These relatively low temperatures imply that the melt composition

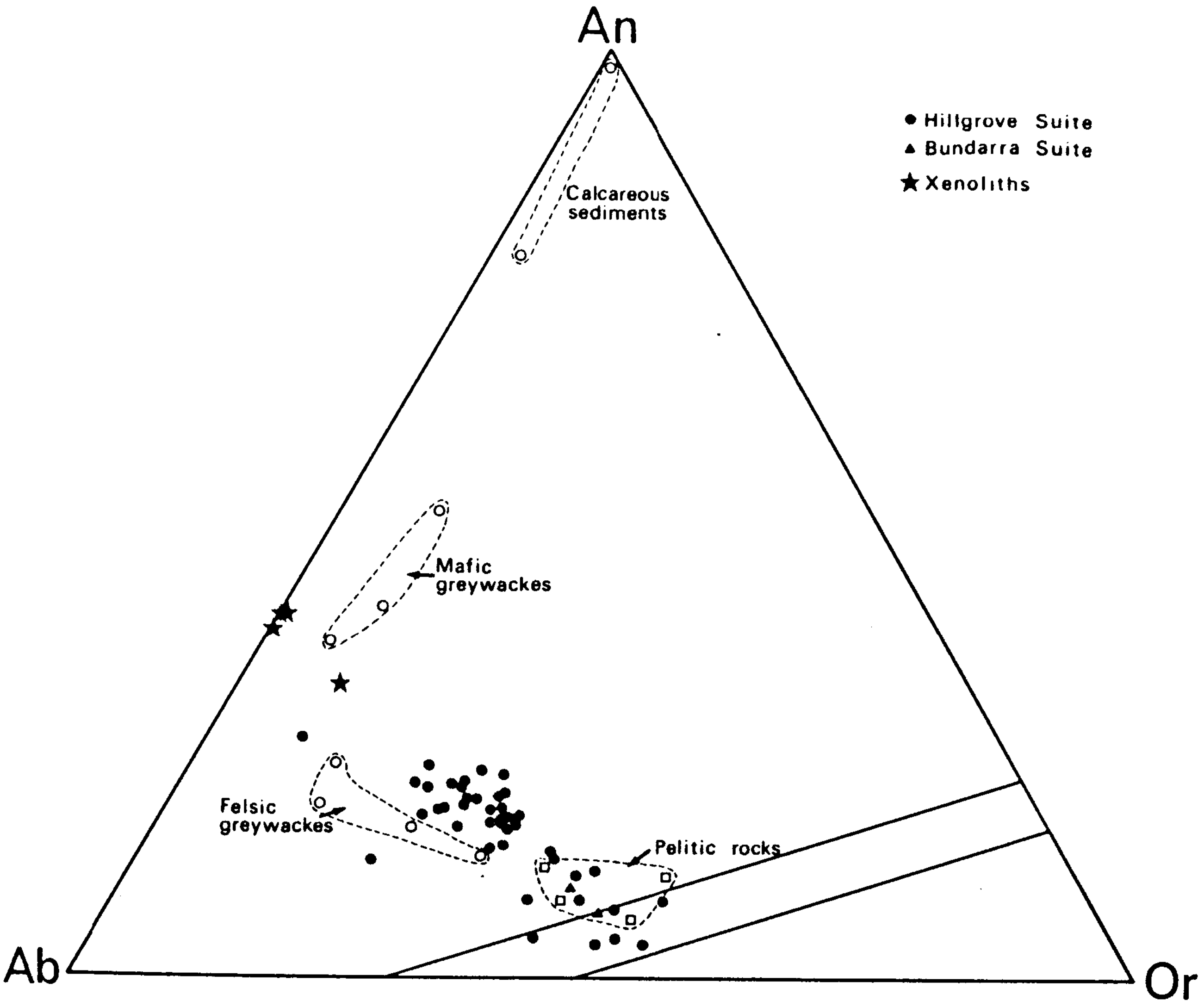

Figure 3.16 Mesonormative An-Ab-Or proportions for granitoids (filled circles) and xenoliths (stars) from the Hillgrove and Bundarra Suites compared with the thermal trough in the system An-Ab-Or-Qz (after Kleeman, 1965). Fields representing New England sediments are also included for comparison.

may have contained significant water so as to lower the solidus. Even though the melt phase may not have been *entirely* saturated it follows that water-saturated experimental systems may therefore be the most appropriate with which to compare the compositions of the Hillgrove Suite granitoids. Maaløe and Wyllie (1975) and Wyllie *et al.* (1976) argued strongly against this view, maintaining that granitic magmas are water-*under*saturated through most of their history. They suggested that, with the exception of early-formed liquids, which may have been water-saturated by virtue of their limited volume, batholiths could not feasibly have contained more than 1.5% H_2O.

Few constructive hypotheses have been advanced on this problem of saturation. The problem in fact is two-fold, requiring firstly the acquisition of large amounts of water necessary to promote relatively low-temperature melting, and secondly the dissipation of this large amount of water following crystallization. Four possible sources of this water include:

(a) connate water in the sediments;
(b) breakdown of hydrous minerals during prograde metamorphism;
(c) deeply circulating groundwater; and
(d) water in volcanic glass.

Circulating groundwater is potentially the most effective way of providing the large quantities of water required. Obviously, it is not known if groundwater systems existed in the source regions of the S-type granitoids at depths of 20-25 km. One example where large amounts of trapped ground water in sediments may have directly influenced the level of water-saturation in low-temperature partial melts is the Taupo Volcanic Zone (Rutherford and Heming, 1978). These authors suggested that widespread melting of the greywackes, due to andesitic and basaltic volcanic activity at relatively high crustal levels (4-7 km depth), may have been enhanced by the initiation of groundwater circulation systems within the large axial graben-like depression containing these sediments. Rutherford and Heming infer that this circulating water was sufficiently deep to enter the melt phase, maintain high water-saturation levels and thus promote more extensive partial melting.

Brown and Fyfe (1970) experimentally produced a range of granitic melts from starting material containing different hydrous phases, e.g. muscovite, biotite, phlogopite, amphibole. They found that the melts differed in composition according to the breakdown behaviour of the hydrous phases and suggested that melting of granitoid source rocks is initiated by the breakdown of a hydrous phase. Two major factors suggest that this model is unlikely to be singly applicable to the generation of the Hillgrove Suite granitoids:

1. The amount of water liberated by the breakdown of mica (maximum H_2O content ~ 5%), in source material of greywacke composition is very small (0.5 - 0.8 wt.%) and thus capable of producing only very small amounts of water-saturated melt. Even if the greywackes were extensive and the released water became concentrated (by an unknown mechanism) the volume of water-saturated melt would be small in relation to the actual volumes of the Hillgrove Suite granitoids.

2. Geologically unreasonable temperatures are required to produce granite melts if the water has to be derived from the breakdown of hydrous phases; for example, biotite (*mg* 36) is stable up to at least 770° C (Brown and Fyfe, 1970). Other experimental data (e.g. Wyllie *et al.*, 1976) show a wider range of biotite stability, depending on the *mg* number of the biotite. Wyllie *et al.* (1976) determined the upper stability limit of biotite in granitic rocks at 2 kb and at fO_2 appropriate to the Ni-NiO buffer, and found it to be at 880° C in water-saturated and 860° C in water-undersaturated conditions.

One important aspect of the breakdown of hydrous phases is the release of Cl and F. The importance of these volatiles in depressing the solidus of granitic melts has been stressed by numerous authors (e.g. von Platen, 1965; Wyllie and Tuttle, 1961; Wyllie, 1971; Holloway, 1976). In addition, the rate of volatile release during the breakdown of the hydrous phases, which is shown routinely by $^{40}Ar/^{39}Ar$ experiments to be steplike rather than instantaneous, is certain to significantly influence the rate of melting and the distribution of H_2O in the melt.

Connate water in sediments has traditionally been presented as a major factor in arguments that granitic melts are generated primarily in geosynclinal environments (Joplin, 1942). Water is supposedly trapped in the sediments and readily available when melting begins. Two points which do not favour this model include:

(a) During compaction and consolidation of sediments pore space is reduced and water expelled - it is therefore difficult to conceive large quantities of interstitial water being retained in the deeply buried sediments undergoing high-grade metamorphism.

(b) Because prograde metamorphism of sediments essentially involves dehydration reactions (Fyfe *et al.*, 1958) it is implicit that water moves away from the source of heat. Thus, high-grade metasediments typically contain less

H_2O than their low-grade equivalents. However, the reverse, i.e. movement of water by grain-boundary diffusion *up* the thermal gradient and *into* the zone of melting, is a fundamental premise in the interpretation of oxygen isotopes (Taylor, 1977, 1978).

An additional source of water, rarely alluded to, is from volcanic glass. Glass is often the dominant component of felsic volcanic rocks and may be present in significant amounts in immature volcanogenic sediments. It is known to contain up to 12% H_2O under experimental conditions (Helz, 1976), and up to 10% in natural pitchstones (Hatch *et al.*, 1961), the water in the latter apparently being incorporated at subsolidus temperatures (Carmichael, 1974). Two important points to consider here are:

1. the significantly greater wt.% of water in glass relative to hydrous minerals; and
2. the instability of this glass under prograde metamorphism.

Thick units of hydrated acid volcanics or greywackes containing 30-40 vol.% of glassy detritus are capable of containing vast quantities of water. However, it is well known that volcanic glass becomes unstable during metamorphism and transforms to clays, zeolites, chlorites and micas which also hold a comparatively large amount of water. If only a small amount of the water originally contained by the greywackes or volcanics remains in this source material during rapid ultrametamorphism, the potential contribution of water to a low-temperature melt is considerable and thus enhances the likelihood that these melts would be water-saturated.

Assuming only a relatively small amount of water is retained by a large volume of metasediment at partial melting, enormous quantities of water must have moved through the entire sedimentary sequence during progressive metamorphism and (a) liberated, (b) incorporated by the ensuing melt, or (c) relocated elsewhere. One possible way for water to escape is by shear zones and joints, particularly if there is a rising heat source such as an intruding granitoid (Roberts, 1970). However, without structural control, movement of water may be difficult, and confined largely to migration along grain boundaries. Elder (1966, 1968) presented a model, which is supported by stable isotope studies (Taylor, 1977), whereby liberated water is returned to the heat source by spontaneous convection. During the transport of water through a thick sedimentary pile the solutions generally become quite saline (Fyfe and Henley, 1973). If this convective method of water transport indeed operated in New England during the generation of the Hillgrove Suite granitoids, the salinity of the vapour phase may have lowered minimum melting temperatures (*see* von Platen, 1965) and promoted partial melting.

Burnham (1974) presented an interesting mechanism for explaining the presence and activity of water in silicate melts. He suggests that components in the melt are hydroxylized and H_2O in the melt becomes chemically reacted H_2O. This method has many advantages over other mechanisms dealing with the fluid phase in melts. For example, because chemically reacted water causes a marked depolymerization of the melt, melt viscosity is greatly affected (Shaw, 1965; Burnham, 1963, 1967, 1975). This provides a good explanation for phenomena such as magmatic flowage, layering and intrusive capacity in granitic rocks - phenomena which traditionally have been difficult to explain because of the assumed high viscosity of low-temperature melts. On crystallization, the chemically reacted water is presumably expelled (gradually) from the silicate structure with increased ordering, and may subsequently take part in subsolidus processes, e.g. re-equilibration, or exchange with meteoric or groundwater (Taylor, 1977).

The hydroxylization hypothesis also readily facilitates the second part of the problem of water-saturated melts, i.e. the dissipation of large quantities of water during crystallization. It has been established that at 6 kb PH_2O, 14 wt.% H_2O is required to saturate a granitic melt and about 6.5 wt.% at 2 kb PH_2O (Wyllie *et al.*, 1978). Even if the Hillgrove Suite granitoids crystallized at very low pressures (say 2 kb), at least twice as much water as is presently contained in the rocks would have to be dissipated. This may be achieved by venting or by the development of pegmatites. Pegmatites however, are rarely associated with the Hillgrove Suite or with sediment-derived granitoids in general (but cf. Fagan, 1979). A large (~ 1 sq.km) garnet-tourmaline pegmatite which occurs within the high-grade rocks adjacent to the Abroi Granodiorite appears to postdate the main period of metamorphism at Wongwibinda, and is therefore considered to be genetically unrelated to the stressed granitoids. Apart from some minor dykes and lit-par-lit injection veins associated with the Wollomombi portion of the Abroi Granodiorite, little additional evidence can be cited for the escape of a hydrous vapour phase from the granitoids. Of course it could be argued that rocks containing this vapour phase have been removed by erosion, since it is known that the stressed granitoids were being unroofed during the Miocene.

3.8.3 Application of Experimental Phase Relations to New England Sediments

Since the weight of geochemical, mineralogical and isotopic evidence suggests a sedimentary parent for the Hillgrove Suite granitoids it is obviously necessary to examine the applicability of the phase data to anatectic melting of selected exposed metasediments. The two major groups of possible source rocks are (a) pelitic rocks and (b) greywackes. In the latter group three subdivisions can be recognized depending on their mafic index. The *most* mafic type of greywacke (Group A) is from the Baldwin Formation, a thick Tamworth Trough unit of Upper Devonian age, composed essentially of clastic, vitric and lithic greywackes. Although this unit is not exposed around the plutons, chemical evidence (*see* 3.6.5) suggests that it, or a chemically equivalent unit, may underlie the more-felsic greywacke units of the New England region.

On the Qz-Ab-Or projection (Fig. 3.15) the Baldwin greywackes plot on the Qz-Ab join close to the Ab apex. Other mafic greywackes (Group B) occupy a field between the 4 and 7 kb PH_2O cotectics, halfway between the Qz-Ab join and the Hillgrove Suite granitoids, while the felsic greywackes (Group C) plot adjacent to the granitoids.

Figure 3.15 also shows that although *individually* none of the sediment groups are ideally suitable for generating the Hillgrove Suite magmas, e.g. pelites are too rich in Qz and felsic greywackes too high in Ab, a *combination* of pelites and felsic greywackes conceivably could be the parent of most Hillgrove Suite granitoids. However, it appears that a high-An/low-Or sedimentary component is also required, in order to produce the remaining granitoids. This is more clearly illustrated on the Ab-An-Or triangle (Fig. 3.16), which highlights the An-deficiency in both the pelites and felsic greywackes. Thus partial melting of the pelites and felsic greywackes alone cannot produce the relatively An-enriched granitoids. If the xenoliths represent model sedimentary source material from which a proportion of melt has been removed, it follows that the compositions of the granitoids should lie between the source composition and the assumed minimum melt fraction (*see* Fig. 3.15). The variation in the Qz component of the granitoids matches the range of observed xenolith compositions, whereas the variation in the Or component (relative to Ab) can be attributed to various mixing ratios of minimum melt : residual crystals. The Ab-An-Or diagram (Fig. 3.16) clearly illustrates this simplistic geometrical relationship.

Progressive melting of greywackes under water-saturated experimental conditions has been described by Winkler (1976) and James and Hamilton (1969). Since the experimental greywackes are compositionally similar to the New England sediments, it may be reasonably assumed that the melting behaviour of the sediments, and therefore the compositions of any melt products, closely resemble the synthetic system. Thus, the first melt will probably form at about 670° C at PH_2O = 7 kb (Winkler, 1976) and fall somewhere on this cotectic line in the Qz-Ab-An-Or tetrahedron, its exact position determined by the composition of the plagioclase and alkali feldspar with which it is assumed to be in equilibrium. Once the melt has used up all the available Or component, no additional melt can be produced, regardless of the amount of water available, without a rise in temperature. If the temperature increases, the melt composition will leave the 7 kb PH_2O cotectic line and move up above one of the cotectic surfaces of the tetrahedron. It will now be a non-minimum melt.

In a sedimentary sequence having a wide range of Ab/An ratios it is therefore quite feasible to generate a range of chemically distinct partial melts each with its own specific restite mineral assemblage. Physical mixing of these melts during ascent through the crust is probably unavoidable and may be reflected by the heterogeneities now observed in many of the Hillgrove Suite plutons.

The relationship between the chemical compositions of the sedimentary source rocks and their partial melt products is obviously close. However, the generation of granitic melts is also directly dependent on the pre-melt mineralogy of the metasediment. Thus metasediments with little of one of the major components, i.e. quartz, plagioclase or alkali feldspar, can produce only a small amount of minimum melt. Similarly, metasediments with large quantities of mica but lacking alkali feldspar may not be capable of producing a minimum melt until the mica begins to break down incongruently and provides some Or component.

3.9 CONCLUSIONS

A comagmatic series of stressed granitoids, collectively named the Hillgrove Suite, flanks the eastern margin of the New England Batholith. Members of this Suite possess textural, mineralogical and chemical characteristics which distinguish them from other S-type granitoids of the New England Batholith and from their counterparts of southern New South Wales. Perhaps the most characteristic feature of the Hillgrove Suite plutons is their well-developed post-crystallization tectonite fabric. The development of this fabric, which is particularly eminent in some plutons, is directly related to a number of vigorous faults which truncate or transect many of the plutons.

Margins of plutons which are not faulted display sharp to complex intrusive relationships with the sedimentary country rocks. Where the contacts are sharp and the intruded sediments only weakly metamorphosed the plutons are interpreted as having moved some considerable distance from their sites of generation, in contrast to plutons which display complex contacts with closely associated high-grade metamorphics.

The Hillgrove Suite granitoids exhibit mineral assemblages which are characteristic of S-type granitoids but which nevertheless distinguish them from other S-types. For example, they contain almandine-rich garnet, coexisting reddish-brown and green biotites, coexisting blue and colourless quartz and less commonly, coexisting Fe-Mg and calciferous amphiboles; graphite is ubiquitous.

The major and trace element chemistry of the granitoids further indicates a derivation from sedimentary source rocks. However, many of the criteria established originally by Chappell and White (1974) to distinguish between S- and I-type granitoids in southern New South Wales are inappropriate for the Hillgrov Suite. This suggests that the compositions of the respective sedimentary source rocks were fundamentally different. Sr isotopic studies support this and show that the Hillgrove Suite granitoids have initial $^{87}Sr/^{86}Sr$ ratios which are much lower than their counterparts of southern New South Wales. The low initial ratios of this Suite and indeed other S-type granitoids from New England are consistent with a derivation from relatively young volcanogenic detritus. The isotopic data, when combined with field, mineralogical and chemical evidence, therefore lead to the conclusion that members of the Hillgrove Suite were generated more-or-less simultaneously at ~ 320 m.y. from parent material which was rather uniform in both Rb/Sr and $^{87}Sr/^{86}Sr$ characteristics, and crystallized over a short period (*cf.* Flood and Shaw, 1977). This conclusion is not supported by the biotites of both the granitoids and the surrounding metamorphic rocks, which show consistently younger ages. However, this discrepancy reflects a widespread but variable resetting of biotite ages by a mild thermal event during the Early and Middle Permian.

The constraints of the chemical data, especially the REE, preclude a derivation of the Hillgrove Suite granitoids by partially melting the type of volcanogenic sediments which surround the granitoids at the present erosion level. Calculations based mainly on trace elements show that the source material for the granitoids required an additional sedimentary (or volcanic) component containing more FeO, MgO, TiO_2 and CaO, but markedly less REE (particularly HREE), than the exposed sediments. Because greywackes of the Upper Devonian Baldwin Formation (a thick, sedimentary unit of the Tamworth Trough) approximate the required component, it is tentatively suggested that this unit (or its chemical equivalent) might underlie the more felsic volcanogenic sediments that are generally exposed in the New England region.

A comparison of experimental phase equilibria with Hillgrove Suite granitoid compositions suggests that the majority of plutons crystallized in the 4-7 kb PH_2O thermal trough of the Qz-Ab-Or-An-H_2O system (von Platen and Höller, 1966). However, despite this apparent limitation, the data points fall into a relatively wide field and thus exceed the scatter indicated by differences in their modal abundances. Therefore, the compositional variation of the granitoids, in relation to the experimental system, is probably due to a number of factors including source heterogeneity, variations in the degree of melting, physical mixing of minimum and non-minimum melts each with their own specific restite mineral assemblage and possibly also to differences in their water contents.