*Terra Antartica*
2001, **8**(4), 481-489

# History of Oligocene Erosion, Uplift and Unroofing of the Transantarctic Mountains Deduced from Sandstone Detrital Modes in CRP-3 Drillcore, Victoria Land Basin, Antarctica

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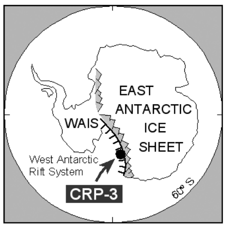
*Received* 26 October 2000; *accepted in revised form* 23 April 2001




**Abstract** - Detrital modes determined on 68 sandstone samples from CRP-3 drillcore indicate a continuation of the dynamic history of uplift-related erosion and unroofing previously documented in CRP-1 and CRP-2/2A. The source area is identified very strongly with the Transantarctic Mountains (TAM) Dry Valleys block in southern Victoria Land. Initial unroofing of the TAM comprised removal of much of a former capping sequence of Jurassic Kirkpatrick basalts, which preceded the formation of the Victoria Land Basin. Erosion of Beacon Supergroup outcrops took place during progressive uplift of the TAM in the Oligocene. Earliest CRP-3 Oligocene samples above 788 metres below the sea floor (mbsf) were sourced overwhelmingly in Beacon Supergroup strata, including a recognisable contribution from Triassic volcanogenic Lashly Formation sandstones (uppermost Victoria Group). Moving up-section, by 500 mbsf, the CRP-3 samples are depauperate quartz arenites dominantly derived from the quartzose Devonian Taylor Group. Between *c.* 500 and 450 mbsf, the modal parameters show a distinctive change indicating that small outcrops of basement granitoids and metamorphic rocks were also being eroded along with the remaining Beacon (mainly Taylor Group) sequence. Apart from enigmatic fluctuations in modal indices above 450 mbsf, similar to those displayed by samples in CRP-2/2A, the CRP-3 modes are essentially constant (within a broad data scatter) to the top of CRP-3. The proportion of exposed basement outcrop remained at < 20 %, indicating negligible uplift (*i.e.* relative stability) throughout that period.

## INTRODUCTION

The Cape Roberts Drilling Project used a sea ice platform to drill the western margin of the Victoria Land Basin in McMurdo Sound, to obtain fundamental knowledge of Cenozoic palaeoclimates and tectonic history of the Ross Sea region. The background to the project, its detailed aims, methods used and results so far are summarised in Cape Roberts Science Team (1998, 1999, 2000) Hambrey & Wise (1998) and Barrett & Ricci (2000a, b). In this paper, the results of a study of sandstone detrital modes on samples from CRP-3 are described and interpreted. The modes reveal a continuing dynamic history of erosional unroofing and accompanying uplift of the Transantarctic Mountains adjacent to the CRP-3 drillsite.

## METHODS

Sixty eight CRP-3 samples were selected for modal analysis. A mean sample distribution of about one every 10 m was achieved for most of the core. The upper 300 m is most poorly sampled, with a mean sample interval of about one every 15-20 m. Twenty two sandstone samples from the Beacon Supergroup were also analysed modally, for comparative purposes. Sample treatment included resin impregnation of weak samples, and staining for feldspars (method of Houghton, 1980). For each sample, 300 sand grains were counted using the Gazzi-Dickinson method (Dickinson, 1970). In reporting the results, all of the detrital modes are recalculated to exclude matrix (<30 µm). Counts for lithic sedimentary grains (Ls) in the CRP-3 samples were also excluded by recalculation, because they appear to be intraformational and thus do not preserve provenance information (Smellie, 2000). However, Ls forms only a tiny part of the grain population in those samples and the recalculations to exclude Ls have only a trivial effect on the modes. Grain types are described in detail by Smellie (1998). There is no obvious systematic influence of grain size on the CRP-3 sample modes, other than possibly to increase the data scatter (Cape Roberts Science Team, 2000; see also Smellie, 1998, 2000). However, the use of the Gazzi-Dickinson method and focus on modal indices (particularly ratios) that are unaffected by grain size, should minimise that scatter (Ingersoll et al., 1984; Smellie, 2000). As in CRP-1 and CRP-2/2A, the dominant influence on modal variations is likely to be provenance.

## RESULTS OF THE DETRITAL MODES

The CRP-3 samples are quartzofeldspathic sandstones similar to sandstones in CRP-1and CRP-2/2A. Most are subarkoses (*sensu* Pettijohn et al., 1973). A smaller proportion are arkoses, and several samples, mainly between 500 and 600 mbsf, are quartz arenites (Tab. 1). In addition, a few samples have mud matrix exceeding 15 % and are arkosic wackes; all are situated above 330 mbsf (see Tab. 1 in Wise et al., this volume). The mean value for quartz (Q) and feldspar (F) is 92.3 % (Q+F), and 32 % of samples (22 samples) have ≥ 95 % Q+F. These values are significantly higher than for any previous Cape Roberts Project modes (*cf.* Smellie, 1998, 2000). Q and F vary antithetically. Q values show a gradual down-core increase to 98 % at 500 mbsf, falling more steeply to 56 % at 700 mbsf before recovering slightly, to about 70 % at the base of the core (Fig. 1). Ratios of rounded to angular quartz grains (Qr/Qa) fluctuate widely (0.04-1.3) and the values are commonly higher than observed in CRP-1 and CRP-2/2A (Smellie, 1998, 2000). The ratios are highest at 525 mbsf, falling sharply thereafter to much lower values (0.08-0.1) at the base of the core. In most of the samples, plagioclase (P) is more abundant than alkali feldspar (K). K exceeds P in samples between 400 and 620 mbsf, corresponding generally to those samples poorest in F and richest in Q. P and K abundances apparently show no covariation, except for the section between 500 and 650 mbsf, where the indices broadly vary sympathetically. K/Q ratios are low (mainly < 0.1; Fig. 1) and are similar to those encountered in the basal 300 m of CRP-2/2A. They broadly vary antithetically with Qr/Qa ratios, as also observed in CRP-2/2A, and show a significant steady increase in samples below 500 mbsf.

Pyroxene is the only other common framework-grain constituent, with abundances generally varying between 1 and 6 % (mean: 4.1 %). Highest abundances (9-12 %) occur in samples above 170 mbsf, diminishing to minimum values (< 1 %) at 500 mbsf, then rising to about 6 % at the base of the core (Fig. 1).

Minor framework minerals include hornblende (pale green, pale brown), brown biotite, muscovite, opaque oxide and coal, with a combined mode between 0.3 and 7 % (mean: 0.9 %). Of these, opaque grains (opaque oxide and coal) are commonest, as in CRP-2/2A samples (Smellie, 2000). The two opaque grain types can often be distinguished empirically: opaque oxide commonly occurs as an interstitial phase within dolerite grains, as fine granular aggregates or as individual small grains with angular shapes, whereas coal typically occurs as larger, single grains showing rounding. There are no clear down-core variations for the minor framework minerals and all are persistent (Cape Roberts Science Team, 2000a). However, below about 400 mbsf, biotite occurs mainly as small inclusions within quartz (note: only sand-size biotite grains or inclusions were counted for the modes; most biotite is sub-sand grade and only its presence is recorded in table 1, listed as an accessory phase). By contrast, muscovite occurs more commonly as free grains. Accessory minerals include zircon, bioclastic and possible inorganic carbonate, sphene, garnet, epidote (including clinozoisite) and possible celadonite (one occurrence; Tab. 1).

Lithic grains are a minor detrital component in all samples and usually form < 5 % of the mode (mean 2.7 %). They are dominated by fine volcanic types (Lv), typically forming > 90-100 % of the lithic population. Above 500 mbsf, most samples have < 3.5 % Lv, whereas below 500 mbsf, the proportion of Lv increases gradually to about 5 %, with some samples reaching 7-9 %. Four types were separately distinguished: (i) quartz–feldspar aggregates with graphic or myrmekitic textures; (ii) monomineralic or bimineralic quartz–feldspar aggregates with fine patchy (mosaic-like) or "snowflake" textures; (iii) fine lathy-textured grains formed mainly of decussate plagioclase, rarely with altered pyroxene and/or altered glass(?); and (iv) grains with feathery-textured plagioclase and/or pyroxene, sometimes with rod-like or dendritic opaque oxide, smectite(?)-altered glass or prismatic pyroxene. Graphic-textured (type (i) grains show relatively high abundances at four positions in the core: 0-250, 380-440, about 500 and below 580 mbsf (Fig. 1). Lathy-textured (type (iii) grains also show a weak peak at 380-400 mbsf, but no other significant variations with depth. Feathery-textured (type (iv) grains are more common above 440 mbsf and almost non-existent below that depth. By contrast, the quartzo-feldspathic mosaic grains (type (ii) show a striking increase below *c*. 550 mbsf (Fig. 1). It is principally the variation in the type (ii) grains that is responsible for the overall down-core increase in Lv noted above. Other lithic grains are uncommon. In addition to mudrocks, there are also sporadic occurrences of fine quartz-mica tectonite (Lm) and polycrystalline quartz (Qp). Dolerite and granitoid grains are also present but, because of the Gazzi-Dickinson methodology used, they are not counted as such (*cf.* Dickinson, 1970).

## PROVENANCE

All samples contain the same grain types, and none are diagnostic of individual parts of the section. Moreover, despite the presence of significant down-core variations in modal abundances, the data show

*Tab. 1* - Detrital modes for sand grains in samples from CRP-3.

| Sample (mbsf) | Mean grain size | Qa | Qr | PL | K | PyroxTOT | AmphTOT | Biot | Musc | Qp | Ls | Lv[graphic] | Lv[mosaic] | Lv[feathery] | Lv[lathy] | Lm | Glass | Opq | Other | [Matrix/cement%] | Accessory minerals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.32 | VF-F(-M) | 59 | 8 | 12 | 7 | 11 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.7 | 0.0 | 23 | hbl?, biot? |
| 33.30 | (VF-)F | 58 | 7 | 18 | 2 | 13 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 1.0 | 0.0 | 0.0 | 1.0 | 0.0 | 6 | hbl? |
| 67.06 | VF-F(-M) | 55 | 11 | 15 | 5 | 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.7 | 1.3 | 0.0 | 0.7 | 0.3 | 0.0 | 0.3 | 0.0 | 26 | biot, sph |
| 74.85 | VF-M | 60 | 10 | 7 | 9 | 11 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 2.7 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 28 | hbl, sph, zirc |
| 89.50 | silty VF-F(-C) | 56 | 4 | 18 | 8 | 12 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 34 | musc, gt, sph, clinozoisite?, bioclastic carb |
| 139.87 | VF | 67 | 4 | 10 | 6 | 11 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 1.3 | 0.3 | 20 | hbl, biot?, sph? |
| 151.25 | VF-F | 64 | 6 | 13 | 6 | 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | 0.7 | 0.3 | 24 | sph? |
| 177.22 | VF-F | 61 | 19 | 7 | 4 | 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 1.7 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 16 | hbl, biot, zirc, epid, opq |
| 183.69 | VF-F | 68 | 15 | 6 | 4 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.3 | 0.0 | 0.7 | 0.0 | 0.0 | 0.3 | 0.0 | 10 | hbl, zirc |
| 202.59 | F | 75 | 10 | 5 | 5 | 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 0.0 | 7 | hbl, biot, musc, gt, sph |
| 226.42 | F-M | 45 | 26 | 17 | 2 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.3 | 1.7 | 0.7 | 0.0 | 0.0 | 1.0 | 0.0 | 18 | biot?, musc |
| 235.50 | F | 70 | 10 | 6 | 6 | 6 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 9 | biot |
| 249.67 | F | 64 | 21 | 5 | 4 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 0.7 | 0.0 | 0.0 | 0.3 | 0.0 | 18 | hbl, biot, musc, zirc, detrital carb?, gt |
| 256.66 | VF(-F) | 63 | 16 | 5 | 9 | 3 | 0.7 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.7 | 1.0 | 14 | musc, bioclastic and detrital? carb, zirc, gt, sph |
| 270.99 | M | 56 | 24 | 7 | 4 | 2 | 0.3 | 0.3 | 0.7 | 0.0 | 0.7 | 0.0 | 0.0 | 2.0 | 0.3 | 0.0 | 0.0 | 2.3 | 0.0 | 1 | all micas occur within Ls grains |
| 279.68 | VF | 68 | 11 | 7 | 7 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 10 | biot?, musc, epid |
| 286.17 | VF | 68 | 3 | 10 | 11 | 4 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 2.3 | 0.3 | 12 | musc?, sph?, clinozoisite?, zirc, gt |
| 315.77 | VF-M | 62 | 17 | 5 | 6 | 6 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 2.7 | 0.0 | 21 | musc, bioclastic carb, zirc |
| 326.77 | M | 73 | 16 | 7 | 2 | 1 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 17 | hbl, biot, musc?, zirc, sph, gt |
| 335.96 | VF-F | 67 | 9 | 7 | 6 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.7 | 0.7 | 0.0 | 3.0 | 0.0 | 0.3 | 0.0 | 12 | hbl, biot, musc?, zirc, sph, gt |
| 345.76 | F-M | 61 | 30 | 5 | 1 | 1 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 5 | hbl?, biot, musc, zirc |
| 358.95 | F | 63 | 10 | 12 | 7 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 1.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 14 | hbl, biot?, zirc, gt, epid |
| 369.64 | VF-F | 55 | 13 | 17 | 3 | 7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.7 | 1.0 | 0.7 | 0.0 | 0.0 | 1.0 | 0.0 | 13 | hbl, biot, epid |
| 375.32 | F-M | 55 | 33 | 5 | 2 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.7 | 0.3 | 0.0 | 0.0 | 0.7 | 0.3 | 12 | biot, zirc, gt |
| 383.76 | F | 62 | 21 | 5 | 3 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 1.3 | 0.7 | 1.7 | 0.0 | 0.0 | 0.3 | 0.0 | 22 | musc, zirc? |
| 387.46 | F-M | 72 | 19 | 6 | 1 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.3 | 9 | hbl, zirc, gt, opq, sph, epid? |
| 396.58 | F-M | 53 | 29 | 4 | 5 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.3 | 0.7 | 0.7 | 1.0 | 0.0 | 0.0 | 0.3 | 0.3 | 12 | hbl, zirc |
| 405.75 | VF | 58 | 3 | 8 | 21 | 1 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.3 | 0.0 | 0.0 | 7.0 | 0.0 | 19 | hbl, biot?, musc, zirc, gt, epid, sph? |
| 415.94 | VF-F | 67 | 12 | 4 | 12 | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.7 | 0.3 | 0.0 | 0.0 | 0.0 | 2.3 | 0.3 | 17 | hbl, musc, gt, zirc, sph?, detrital carb? |
| 426.77 | F | 65 | 21 | 3 | 7 | 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 10 | hbl, biot, opq, zirc |
| 437.12 | VF | 69 | 7 | 6 | 16 | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 19 | hbl, gt, sph, zirc |
| 449.73 | F | 64 | 28 | 2 | 3 | 1 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.7 | 0.0 | 24 | hbl, musc, gt, sph? |
| 455.81 | VF | 66 | 16 | 6 | 8 | 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 9 | hbl, biot, musc, zirc, sph, gt |
| 460.13 | VF-F | 73 | 13 | 4 | 7 | 2 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 16 | biot, musc, zirc, sph, gt |
| 473.61 | (F-)M | 61 | 25 | 3 | 8 | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 14 | hbl, sph |
| 480.68 | F-M | 60 | 26 | 6 | 2 | 4 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.7 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.3 | 0.0 | 20 | hbl?, zirc |
| 486.03 | F | 56 | 34 | 4 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.3 | 0.0 | 4 | hbl, musc |
| 495.15 | F-M | 55 | 43 | 0 | 1 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | hbl, biot, musc, opq |
| 500.21 | F-M | 52 | 46 | 0 | 1 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | biot, zirc, gt |
| 509.36 | F | 55 | 32 | 4 | 5 | 1 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.7 | 1.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 7 | hbl |
| 513.17 | F(-M) | 54 | 40 | 2 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 5 | hbl, opq, zirc |
| 525.36 | M | 41 | 53 | 1 | 1 | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.7 | 0.3 | 0.0 | 1.0 | 0.0 | 0.0 | 0.7 | 0.0 | 17 | biot, zirc |
| 533.26 | M-C | 51 | 40 | 1 | 5 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4 | hbl, biot, musc, zirc, gt, opq |
| 543.87 | VF-F | 58 | 18 | 7 | 11 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 1.3 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19 | hbl, zirc, opq |
| 550.03 | VF-F | 66 | 12 | 5 | 9 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 21 | hbl, biot, zirc |
| 562.65 | (F-)M | 58 | 38 | 2 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 18 | |
| 571.80 | F | 67 | 29 | 2 | 1 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.3 | 0 | hbl, musc, gt, opq |
| 578.24 | F | 59 | 26 | 6 | 6 | 2 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 20 | hbl, zirc, gt |
| 585.75 | (VF-)F(-M) | 71 | 11 | 7 | 5 | 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 2.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 11 | hbl, biot |
| 595.16 | VF-F(-M) | 69 | 9 | 4 | 8 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 3.7 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.3 | 12 | hbl, zirc |
| 610.95 | F | 67 | 14 | 6 | 6 | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 4.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 4 | hbl, musc, zirc |
| 615.37 | VF(-F) | 68 | 13 | 5 | 9 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 1.7 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.3 | 7 | hbl, clinozoisite?, sph?, gt, opq |
| 626.18 | (VF-)F | 61 | 25 | 2 | 4 | 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.3 | 2.7 | 0.3 | 0.7 | 0.3 | 0.0 | 0.0 | 0.0 | 11 | hbl, biot, musc, zirc, opq |
| 630.38 | F | 66 | 15 | 6 | 4 | 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 2.3 | 0.3 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 20 | hbl, biot, zirc |
| 643.11 | F-M | 63 | 13 | 6 | 7 | 8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.3 | 0.3 | 0.0 | 0.3 | 0.0 | 1.0 | 0.0 | 21 | hbl, biot, zirc, clinozoisite? |
| 655.86 | VF | 54 | 5 | 16 | 12 | 4 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 1.3 | 5.3 | 0.0 | 0.7 | 0.3 | 0.0 | 0.3 | 0.0 | 21 | hbl, musc, zirc |
| 664.03 | F | 62 | 11 | 12 | 7 | 2 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.7 | 2.3 | 0.0 | 0.7 | 0.0 | 0.0 | 2.3 | 0.0 | 13 | hbl, biot, musc, gt, epid, sph |
| 673.28 | VF-F | 55 | 17 | 13 | 9 | 2 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 1.3 | 1.3 | 0.0 | 0.7 | 0.0 | 0.0 | 0.7 | 0.0 | 23 | hbl, biot, musc, clinozoisite, sph, gt, zirc |
| 681.02 | VF(-F) | 51 | 12 | 10 | 8 | 7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 7.3 | 0.0 | 0.3 | 0.0 | 0.0 | 1.3 | 0.0 | 26 | biot, musc, sph? |
| 686.52 | F | 58 | 21 | 9 | 5 | 3 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.3 | 2.3 | 0.3 | 0.3 | 0.3 | 0.0 | 0.3 | 0.0 | 18 | hbl, biot, musc, sph?, epid |
| 696.77 | VF-F | 49 | 8 | 23 | 11 | 4 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.7 | 3.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.7 | 0.0 | 25 | hbl, epid? |
| 715.48 | F-M | 44 | 13 | 16 | 5 | 14 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.7 | 3.7 | 0.0 | 0.3 | 0.3 | 0.0 | 0.3 | 0.3 | 13 | musc, sph, zirc, gt |
| 724.08 | VF-F | 52 | 11 | 15 | 10 | 7 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 1.7 | 2.7 | 0.0 | 0.7 | 0.0 | 0.0 | 0.7 | 0.0 | 32 | hbl, musc, zirc, gt, sph |
| 730.87 | VF | 61 | 9 | 11 | 10 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 22 | hbl, biot, epid?, zirc, sph |
| 737.35 | VF-F | 53 | 11 | 16 | 9 | 6 | 0.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.3 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 21 | hbl, musc, sph, zirc |
| 750.02 | VF | 58 | 5 | 18 | 12 | 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.3 | 0.0 | 0.0 | 0.0 | 0.0 | 2.3 | 0.0 | 22 | hbl, biot, musc, sph, zirc |
| 770.26 | VF(-F) | 55 | 7 | 14 | 8 | 7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 2.3 | 0.3 | 1.3 | 0.7 | 0.0 | 3.3 | 0.3 | 23 | hbl, musc, sph? |
| 787.66 | VF | 63 | 8 | 10 | 11 | 2 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 0.0 | 23 | biot?, musc, celadonite?, sph, zirc, gt |

Abbreviations: VF - very fine sand; F - fine sand: M - medium sand. Qa - angular quartz; Qr - rounded quartz; PL - plagioclase; K - alkali feldspar; Pyrox - pyroxene; Amph - amphibole; Biot - biotite; Musc - muscovite; Qp - polycrystalline quartz; Ls - sedimentary lithic grains; Lv - volcanic lithic grains; Lm - metamorphic lithic grains; Other - see list of accessory minerals. mbsf - metres below sea floor.

no distinctive (especially clear, step-like) variations that can be used as a basis for identifying petrofacies (*cf.* CRP-1 and CRP-2/2A; Smellie, 1998, 2000). The grain types are identical to those identified in CRP-1 and CRP-2/2A.

## MINERAL GRAINS

Mineral grain types in CRP-1, CRP-2/2A and CRP-3 samples are alike. The same provenance is interpreted for CRP-3 and inferred to be the Transantarctic Mountains (TAM), comprising coarse-grained plutonic rocks (Cambro-Ordovician Granite Harbour Intrusive Complex), quartzose sandstones of the Devonian–Triassic Beacon Supergroup, Jurassic dolerites and Kirkpatrick basalts, and minor metamorphic rocks (Upper Proterozoic metamorphic basement). The mineral grains are dominated by quartz and feldspar. Both are overwhelmingly derived from Beacon sandstone and pre-Beacon basement outcrops, but the high to very high Qr/Qa ratios strongly indicate an important to locally dominant Beacon sandstone source (Smellie, 1998, 2000). Minerals derived from a possible basement source (*e.g.* hornblende, micas, garnet, zircon) are persistent down-core, although present in small quantities (<< 1%). The presence of small quantities of basement (granitoid and metamorphic) clasts suggested to Cape Roberts Team (2000) that basement outcrops were exposed and being eroded right to the base of the core. However, it may be significant that all of the "basement mineral grains" are also present as detritus in Beacon sandstones, and the basement clasts identified by Cape Roberts Science Team (2000a) are mainly angular quartz and/or feldspar grains of granule grade, together with rarer pebbles. Clasts like those are also known within Beacon conglomerates, particularly in the St Johns Range (Turnbull et al., 1994). An origin by recycling from a Beacon source is possible for some or all of that debris.

Garnet, hornblende, biotite and muscovite may also be derived from metamorphic and/or granitoid (basement) sources. Below 375 mbsf, biotite is present almost entirely as tiny crystals within quartz (and hence has a likely plutonic origin), whereas muscovite occurs mainly as separate grains. However, garnet and micas are also present and locally common detrital components of the Beacon Supergroup (Taylor and Victoria groups for garnet, Victoria Group for micas), together with trace amounts of zircon (Korsch, 1973; Barrett et al., 1986; unpublished information of the author).

In the absence of grains sourced in the McMurdo Volcanic Group (see lithic grains, below), pyroxene is almost entirely derived from Ferrar Supergroup (probably mainly Ferrar dolerite; Kirkpatrick basalt may also be a minor source), and is thus a good proxy for the modal contribution from that rock group (*cf.* Smellie, 1998, 2000). Ferrar contribution is highest within the topmost 170 mbsf (Fig. 1), where clasts of Ferrar dolerite are also common (Cape Roberts Science Team, 2000; Sandroni & Talarico, this volume). Modal values diminish below, between 170 and 400 mbsf, reflecting diminished dolerite input, and are extremely low between 400 and *c.* 600 mbsf before recovering to higher values (similar to those between 170 and 400 mbsf) between 620 mbsf and the base of the core. These variations suggest that the proportion of Ferrar dolerite in the source terrain varied at different times during the depositional period represented by CRP-3, or else sediment transport paths varied through time (tapping different areas with differing proportions of Ferrar dolerite).

## LITHIC GRAINS

In contrast to previous CRP modal investigations, CRP-3 samples lack the alkalic volcanic lithic grains and ferromagnesian minerals characteristic of the McMurdo Volcanic Group (Smellie, 1998, 2000). The presence of fresh glass (brown, green and colourless), reported by Cape Roberts Science Team (2000) and interpreted as possible input from distal active alkalic volcanism in northern Victoria Land, is unconfirmed for the samples examined for detrital modes. Glass grains analysed by Pompilio et al. (this volume) have tholeiitic compositions and a likely Kirkpatrick basalt provenance.

Most of the lithic grains are volcanic-derived (Lv). Type (i) graphic- or myrmekite-textured grains resemble mesostasis derived from Ferrar dolerites (less commonly Kirkpatrick basalt), granitoid plutons or possibly grains recycled from the granitoid-sourced Beacon Supergroup; type (ii) quartzo-feldspathic aggregates are typical of recrystallised evolved lavas; type (iii) lathy-textured plagioclase-rich grains resemble relatively unevolved lavas; and type (iv) feathery-textured grains with rod- or dendritic opaques are fragments of basaltic lavas. The most likely source for types (iii) and (iv) basalt lavas is the Kirkpatrick Basalt Group (see also Pompilio et al., this volume), although similar textures occur more rarely within some Ferrar dolerites (*cf.* Elliot et al., 1995). The source of the type (ii) grains is less obvious. There are no known outcrops of evolved lavas in the TAM in south Victoria Land. However, fragments of identical lavas are common within parts of the Victoria Group (Lashly formation) and an origin by recycling through erosion of that source is a plausible explanation for type (ii) Lv grains. Similar fragments are also common in the Lower Jurassic Hanson Formation in the central TAM (Elliot, 1996), although arguments presented later suggest that the central TAM may be too distant a source area to have contributed significantly to CRP-3 sandstones. In addition, grains of polycrystalline quartz (Qp), metamorphic grains (Lm), dolerite and granitoid were

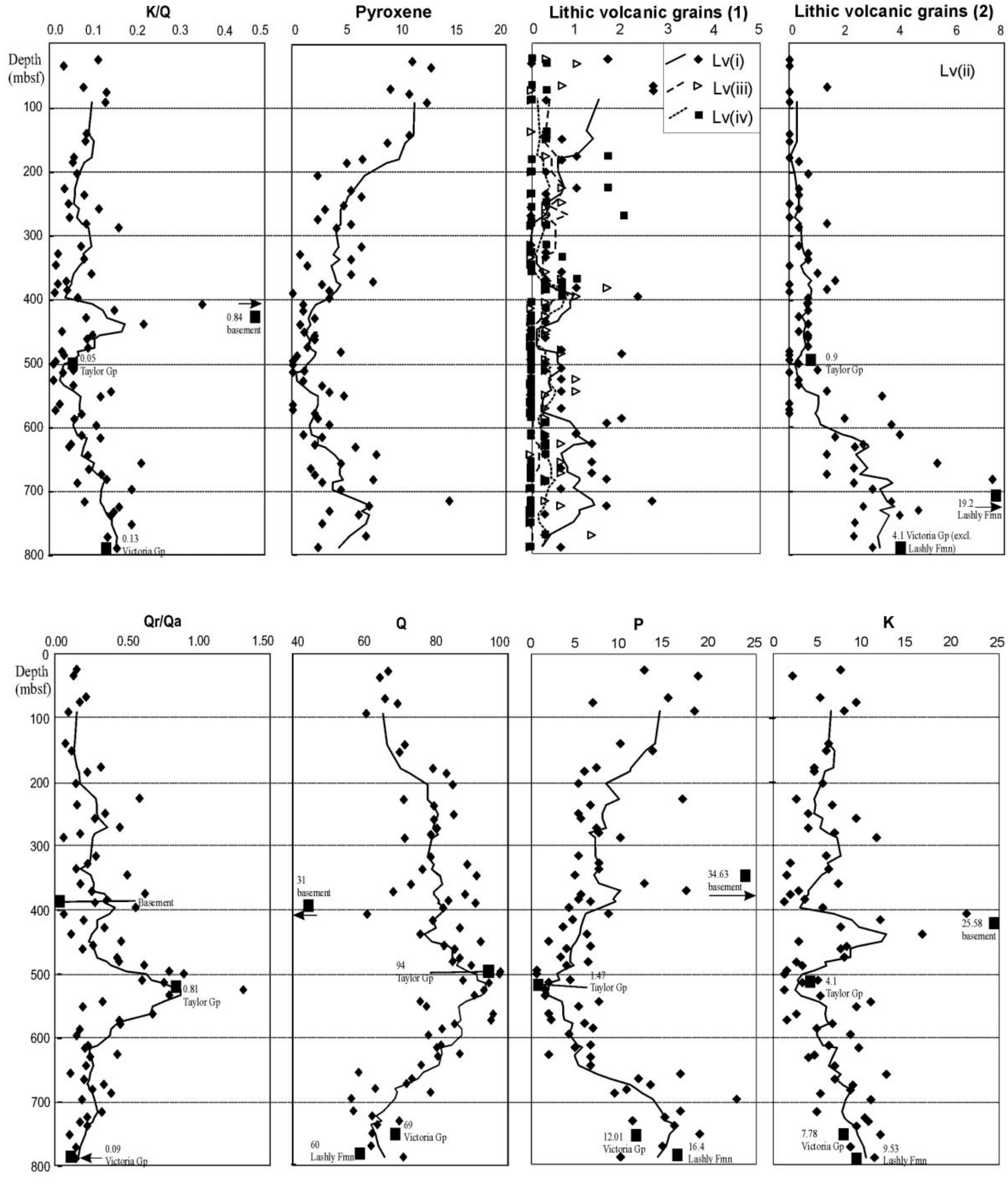



*Fig. 1* - Down-core distribution of selected modal indices for sandstone samples in CRP-3. All values plotted are percentages. Also superimposed are mean values determined for representative groups of samples from the different provenance types (Beacon Supergroup (Taylor and Victoria groups; unpublished modal data of the author) and basement (mainly granitoids; calculated from Talarico & Sandroni, 1998). Note that detritus derived from Ferrar dolerite will have no effect on these ratios but is the likely primary control on the pyroxene abundances shown. Curves drawn in each diagram are based on 5-point running averages. See Tab.1 for explanation of modal abbreviations. Lithic volcanic grain types (i-iv), and their provenance interpretation, are described in the text.

noted above, although dolerite and granitoid are too coarse-grained to be included in the modes. Together, they have a persistent down-core distribution (Cape Roberts Science Team, 2000). Only dolerite grains show a few obvious zones of greater abundance, located mainly within the upper 180 mbsf, but also at 370-400 and 480-540 mbsf (see also Sandroni & Talarico, this volume). Qp and Lm also occur as a detrital component in Beacon sandstones and need not indicate a basement provenance.

## DISCUSSION

### EROSIONAL HISTORY AND LOCATION OF THE SOURCE TERAIN

It is possible to estimate the relative contributions from the different lithological provenance "types" (*i.e.* granitoid and metamorphic basement, Beacon, Ferrar dolerite, Kirkpatrick basalt) by comparing the different modal contributions of those sources (*cf.*

Smellie, 2000). Qr/Qa ratios are a particularly useful discriminant. Because of the short distance between the TAM source terrain and the CRP-3 drillsite (30-100 km), angular quartz grains are unlikely to become significantly rounded by normal fluvial or glacial processes. Very short transport distances for CRP-3 sediments were also inferred by Atkins (this volume), based on clast shapes and surface features. Thus, rounded–well rounded quartz grains will be derived exclusively by erosion from Beacon sandstones. Moreover, only Beacon sandstones and basement granitoids will contribute angular quartz. In addition, there are significant differences in Qr/Qa ratios for different parts of the Beacon Supergroup: high Qr/Qa ratios are characteristic of the Devonian Taylor Group, with much lower ratios for Victoria Group sandstones (Fig. 1). Similarly, K/Q ratios are very low in the Taylor Group, higher in the Victoria Group and very high in basement granitoids (Fig. 1); neither Ferrar dolerites nor Kirkpatrick basalts contribute to K/Q ratios. Smellie (2000) used a combination of Qr/Qa and K/Q ratios to distinguish between Beacon and basement sources: basement sources have very low Qr/Qa ratios combined with high K/Q, whereas the converse is true for Beacon sources. In figure 1, modal data for the different sources are superimposed for comparison with CRP-3 samples. For Qr/Qa and K/Q ratios, there is excellent antithetic agreement. In particular, from the base of the core up to *c.* 500 mbsf, the dominant source apparently changes from dominantly Victoria Group to dominantly Taylor Group. This is also consistent with the observed decrease in evolved volcanic lithic grains from 800 to 500 mbsf, a trend that a basement source cannot emulate: the sole known source of evolved-Lv detritus (Lv type (ii), above) is by recycling from the upper Victoria Group. Above 500 mbsf, observed trends of (diminishing) Qr/Qa and (increasing) K/Q ratios either indicate an increasing influx of Victoria Group detritus or else detritus derived from basement rocks. However, the much lower and roughly unchanging proportion of evolved-Lv grains above 500 mbsf suggests that the trends are much more likely to be an effect of contributions from a basement source.

The low K/Q ratios (mostly < 0.08) compared to mean values for K/Q in granitoid basement (0.84) imply that the proportion of detritus contributed by basement was small, suggesting only a small basement outcrop. Antithetic fluctuations in Qr/Qa and K/Q ratios can also be interpreted to suggest that different periods experienced inputs of sediment with different source-proportions, very similar to the variable modes for those ratios observed in CRP-2/2A (Smellie, 2000). Applying a simple lever rule to the modal values suggests that the proportion of detritus derived from basement outcrops generally fluctuated between about 5 and 20 % in alternate periods of reduced and enhanced influx, respectively. Although evidence for a major influence of a Victoria Group source is lacking above 500 mbsf, the sporadic but persistent presence of Permo-Triassic palynofossils, coal debris and evolved-Lv (*cf.* Cape Roberts Science Team, 2000a) indicates that Victoria Group strata continued to be exposed, but that they formed only a small part of the outcrop being eroded.

Lithic grains derived from the Kirkpatrick basalts (Lv types (iii) and (iv), above) are slightly commoner (*c.* 2 %) above *c.* 430 mbsf, in a section of the core in which Kirkpatrick basalt clasts are also conspicuous (Cape Roberts Science Team, 2000a; Sandroni & Talarico, this volume). They become scarcer below that depth. However, they always form a minor part of the grain population (range of modal values: 0-2.3 %). The general paucity of detritus from that source suggests that the Kirkpatrick basaltic outcrop was largely removed at some time prior to the depositional period represented within CRP-3.

The modes for samples within CRP-3, particularly those obtained close to 500 mbsf, indicate a dominance of sand-grade sediment derived from a source dominated by the Taylor Group of the Beacon Supergroup. This implies that strata of the Taylor Group formed a major part of the source terrain. This conclusion provides a strong clue about the location of the source area that fed the Oligocene Victoria Land Basin. The TAM are divided into several crustal blocks on a range of scales, which probably experienced different rates and periods of uplift (*e.g.* Wrenn & Webb, 1982; Stump & Fitzgerald, 1992; Huybrechts, 1993; Fitzgerald, 1994; Busetti et al., 1999; van der Wateren et al., 1999). Major crustal lineaments probably exist at the sites of the Mackay and Ferrar glaciers. The Dry Valleys block in southern Victoria Land is the major outcrop area of the Devonian Taylor Group, which reaches thicknesses of 750-1100 m (Gunn & Warren, 1962; McElroy & Rose, 1987; Allibone et al., 1991; Isaac et al., 1996). The Taylor Group thins rapidly to the north, south and west (0-300 m in the central TAM, absent in northern Victoria Land; Barrett et al., 1986; Collinson et al., 1986). Moreover, outcrops in the Convoy Range, north of the Mackay Glacier, are dominated by Ferrar dolerite (Pocknall et al., 1994). Any significant sediment contribution derived from that source would thus have a dominant dolerite signature, which is not obvious in CRP-3 samples (except possibly the very high Ferrar-derived pyroxene input above 170 mbsf). Absence of lithologically distinctive metagreywacke and carbonate clasts and grains in CRP-3 sandstones is also a source terrain indicator. These are relatively uncommon lithologies in Victoria Land but are thickly developed and well exposed in the central TAM (Archaeocyathid-bearing Shackleton Limestone (*c.* 8 km thick; Cambrian; Byrd Group) and thermally metamorphosed greywacke and argillite of the Goldie Formation (*c.* 7 km thick; late Precambrian; Beardmore Group); Laird et al., 1971).

Finally, the virtual absence of low-grade metamorphic clasts and lithic grains in CRP-3 (and CRP-2/2A) samples suggest that the Proterozoic low-grade metamorphic terrain of the Skelton Group, which is restricted to the area between the Ferrar and Skelton glaciers, was also not contributing significant detritus to the CRP-3 sequence.

## UPLIFT AND UNROOFING HISTORY

The sequential trends for modal indices documented above are a clear indication of a dynamic evolving provenance, which, in the Ross Sea region, can be interpreted in terms of TAM uplift and erosion in southern Victoria Land. At least three episodes can be identified from the CRP-3 Oligocene sequence:

*Period 1 (pre-CRP-3)*. The paucity of distinctive detritus derived from a Kirkpatrick basalt source implies that the Kirkpatrick basalt outcrop had already been largely removed prior to the Oligocene period represented by CRP-3. The period of removal of the Kirkpatrick basalt outcrop may have coincided with the erosion of about 3 km of Beacon Supergroup strata, down to the lower few hundred metres at CRP-3 (P.J. Barrett, personal communication). This period of erosion is unrepresented in CRP-3 but presumably corresponds to a major phase of early, pre-Oligocene uplift and unroofing of the TAM.

*Period 2 (788 to c. 450 mbsf)*. From the base of the CRP-3 core to *c.* 500 mbsf, progressive changes in the modal indices indicate that the source terrain changed from one dominated by Victoria Group strata, initially uppermost Victoria Group (Lashly Formation), to one dominated by the Taylor Group. At *c.* 500 mbsf, the modal trends alter direction (*e.g.* from higher to lower Qr/Qa ratios; Fig. 1). The change corresponds to an abrupt influx of detritus from the basement outcrop, which was either exposed for the first time, or else the area of basement outcrop available for erosion was significantly increased by uplift. As the change occurs within a period of rapidly varying modes caused by uplift, and the upper surface of the basement outcrop is a gently dipping homoclinal surface (Kukri Erosion Surface), the former seems more likely. The modes continue to change rapidly up to *c.* 450 mbsf, indicating an increasing contribution from the basement outcrops. In terms of simple homoclinal uplift of the TAM, a period of *progressive* upward movement and erosion is envisaged. Had it been abrupt uplift, exposing (for example) Victoria and Taylor groups more or less simultaneously along steep scarps, we would expect to see a more homogeneous mixture of detritus rather than the progressive modal trends observed. The up-core diminution of Victoria Group detritus also suggests that the Victoria Group strata were back-stripped by scarp retreat relative to the underlying Taylor Group strata. Using pyroxene modal variations as a proxy for Ferrar dolerite input, it also appears that the proportion of Ferrar dolerite in the source area diminished up-core during that period. In other words, from a source comprising Victoria Group intruded by sheets of dolerite, the source terrain changed to one dominated by Taylor Group largely lacking dolerite. In the Dry Valleys block today, mapping indicates that the Victoria Group contains about 50 % by thickness of Ferrar dolerite, whereas the Taylor Group is largely free of dolerite (Isaac et al., 1996). Conversely, the hinterland of Cape Roberts, crossed by the Mackay Glacier, contains abundant dolerite that would swamp the modes with dolerite-derived detritus, which is not observed. These observations are consistent with the modal data and also support interpretation of the TAM in southern Victoria Land as the likely CRP-3 provenance area. The subsequent up-core change (particularly above 400 mbsf) to much higher pyroxene contents could be correlated with the unroofing of the peneplain sill (also known as the upper sill: Turnbull et al., 1994). The sill is a laterally very extensive and thick (300-500 m) dolerite mainly emplaced along the Kukri Erosion Surface unconformity that separates the Beacon Supergroup from basement (Gunn & Warren, 1962; Turnbull et al., 1994; Isaac et al., 1996).

*Period 3 (above c. 450 mbsf)*. The modal indices also show a significant change at *c.* 450 mbsf. Above that depth, most of the indices show a comparatively wide scatter superimposed on only very gradual up-core variations (e.g. diminution in Q, antithetic increase in P). The scatter can be resolved statistically into a series of weakly-defined peaks and troughs, which may have importance for uplift and erosion. For example, Qr/Qa and K/Q ratios, and pyroxene modes, show several peaks, which cross-correlate (in the case of Qr/Qa and K/Q ratios, they correlate antithetically). Despite greater data scatter for CRP-3 samples, the patterns broadly resemble those previously described for CRP-2/2A samples (particularly below *c.* 300 mbsf in that core; Smellie, 2000). However, the origin of the CRP-2/2A modal variations is still enigmatic. It remains hard to ascribe the variations to an entirely sedimentological origin (e.g. by varying the transport paths between source and basin, to alternately tap lithologically different provenances). However, the peaks and troughs are superimposed on a more general pattern of only slight up-core provenance variation. The modes remain dominated by Beacon sandstone detritus (probably mainly Taylor Group), together with material shed from a relatively small basement outcrop representing probably < 20 % of the provenance area, and some Ferrar dolerite. The proportion of basement outcrop apparently changed little to the top of CRP-3, implying that uplift was either extremely slow or had possibly ceased during that period.

## CONCLUSIONS

Detrital modes were determined on 68 samples from the CRP-3 drillcore. For the Oligocene period, they reveal a continuation of the dynamic history of uplift-related erosion and back-stripping of the Transantarctic Mountains previously documented by detrital modes for younger sequences in CRP-1 and CRP-2/2A. The new data also give the clearest indication so far that the source region was almost certainly the Dry Valleys block of southern Victoria Land. The modal variations indicate that the earliest sediments were derived overwhelmingly from a Beacon source, initially Victoria Group strata (including a distinctive contribution from the Triassic Lashly Formation), whereas by *c*. 500 mbsf the source was almost entirely Taylor Group strata. Above 500 mbsf, an important contribution was introduced from a source identified as basement. The basement contribution increased upward to *c*. 450 mbsf, but thereafter the proportion of basement outcrop being eroded remained roughly constant (at < 20%) to the top of the core. Interpretation of the modal trends indicates that progressive rather than sudden uplift occurred during the period represented up to *c*. 450 mbsf, after which the remainder of the CRP-3 sequence accumulated in a period of relative stability or only slight uplift. Although not represented by samples in the CRP-3 sequence, it is also evident that a major episode of uplift and erosion of the TAM must also have preceded the formation of the Victoria Land Basin.

ACKNOWLEDGEMENTS - I am particularly grateful to Jim Collinson for Beacon sandstone samples, numerous reprints of papers on Beacon stratigraphy and petrology, and access to unpublished detrital modes of Beacon sandstones; to Bill Hammer and the late Ken Woolfe for additional reference samples of Beacon sandstones; to Massimo Pompilio and Hannes Grobe for help with obtaining CRP-3 samples; and to Stewart Bush and Mike Tabecki for making and staining thin sections from difficult core material. Finally, my grateful thanks are extended to all involved in the Cape Roberts Project, from inception to completion, for their invaluable help and constructive discussions during the course of three drilling seasons and workshops, and to all members of Scott Base and McMurdo Station for their unstinting hospitality. Constructive comments on this paper by Werner Ehrmann and David Elliot are also greatly appreciated.

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