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A STABLE CARBON ISOTOPIC STUDY OF TYPES 1 AND 2 CARBONACEOUS CHONDRITES

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Abstract: Fourteen C1 and C2 carbonaceous chondrites were studied by a technique of stepped combustion in order to distinguish differences in the abundance, distribution and isotopic composition of refractory ($600°<T<1300°C$) carbon fractions.

Specifically, the distribution and abundance of ^{13}C-rich carbonaceous matter was qualitatively investigated to provide data on diagnostic patterns and intergroup relations, and to identify possible differences between Antarctic and non-Antarctic C1 and C2 meteorites. The data reveal that the C1 and C2 groups possess different carbon isotope profiles, which could be useful as an aid to classification. Furthermore, the carbon isotope profiles for Antarctic and non-Antarctic C2 meteorites are dissimilar, suggesting fundamental differences in the sources sampled by the two groups, or alternatively, that an Antarctic weathering process has affected C2 meteorites residing within and on the ice sheets.

1. Introduction

It has been appreciated for some time that minute quantities of isotopically anomalous carbonaceous material are contained within carbonaceous chondrites. These carbonaceous components are distinguished by their refractory nature (resistance to oxidation and the ability to withstand temperatures of 600°C in an atmosphere of pure oxygen) and ^{13}C-enrichments which exceed values obtainable by known solar system processes (SWART *et al.*, 1983; YANG and EPSTEIN, 1984; McGARVIE *et al.*, 1985). Despite the discovery of extreme carbon isotopic enrichments in two or three samples, remarkably little is known concerning the extent to which carbonaceous chondrites host exotic carbon components, which have previously been recognised from measurements on samples extensively processed to isolate noble gas carriers (SWART *et al.*, 1983). In this paper we present the results of a comprehensive stable carbon isotopic survey of bulk C1 and C2 meteorites, treated only with HCl to eliminate carbonate minerals.

Although whole-rock carbon contents and $\delta^{13}C$ values are well known, it should be noted that the bulk carbon isotopic compositions camouflage a ^{13}C-rich component which is known to have a $\delta^{13}C$ value of at least $+1500‰$ obtainable by stepped combustion methods (SWART *et al.*, 1983; YANG and EPSTEIN, 1984), and possibly up to $+7000‰$ obtainable by ion probe methods (NIEDERER *et al.*, 1985; ZINNER *et al.*, 1986).

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For this reason a stepped combustion technique is employed to separate the isotopically normal carbon from the exotic material and to afford a combination of combustion temperature and isotopic composition.

The study aims to assess the distribution of ^{13}C-rich carbon in fractions burning above 600°C. In essence, we hope to establish whether different meteorites possess different distributions of carbonaceous components with diagnostic isotopic compositions, or whether they contain varying amounts of a few common components, each of which can be characterised by a distinct isotopic composition. Although not a primary goal of this study, it is considered that recognition of different characteristics for CI1 and CM2 samples might serve as a useful taxonomic aid.

2. Experimental

All samples were treated with 12M HCl (24 hours at 18°C) to remove carbonate species, which are known to decrepitate and thus produce CO_2 at temperatures similar to those at which the refractory carbon starts to combust. Since meteoritic carbonate minerals are known to contain small ^{13}C-enrichments (CLAYTON, 1963), carbonate decomposition products could interfere with the interpretation of refractory carbon data. The acid treatment partially disaggregated some silicates, causing a *ca.* 50 to 70% weight loss (see Table 1) which assists in concentrating the rare components. Two samples of the HCl-resistant residues were further treated with HF (60 hours at 18°C in HF followed by 18 hours at 18°C in HCl) in order to demineralise the samples more effectively.

To remove macromolecular organic material which forms the bulk of the carbonaceous matter in C1 and C2 meteorites, each HCl-resistant residue was repeatedly combusted at low temperatures until the yield of carbon dioxide was minimal. This pre-combustion routine was carried out in one of two ways: either (1) at 600°C in the extraction vessel under around 500 mb pure O_2 gas, replenished every 30 min after removal of CO_2; or, (2) by raising the temperature of the sample from 200 to 550°C in one hour in a muffle furnace, with the highest temperature being maintained for five hours. Experiments carried out on the same samples using both techniques yield similar results.

Between 2 and 5 mg of acid-residues were used for the stepped combustion analyses. Full experimental details of the technique of stepped combustion using the current gas extraction and analysis system have been published elsewhere (CARR *et al.*, 1986). The magnitudes of the temperature increments used in the present study varied somewhat, but were generally between 25 and 50°C. For the most part the temperature interval for each experiment was maintained at a constant value. Samples were combusted over the temperature range 600 to 1300°C for approximately 20 to 30 min at each temperature step, after which non-condensible gases were pumped away. Condensible gases were trapped and purified, and sample CO_2 gas was admitted to the mass spectrometer, which has been described by CARR *et al.* (1986).

The small amounts of CO_2 obtained (usually less than 20 ng per step) meant that replicate analysis of the sample gas was not possible. Instead, each sample gas aliquot was compared with two separate aliquots of reference gas similar in size to the sam-

ple aliquot. This technique afforded $\delta^{13}C$ data for the sample and allowed assessment of the precision of this technique by comparing the reproducibility of the reference aliquots. The error in the isotopic measurement for a 10 ng sample gas CO_2 aliquot was $\pm 5‰$, whereas for a 3 ng specimen the error was $\pm 10‰$.

Another source of error in the experiment is in measurement of the carbon yield, which is measured using a capacitance manometer after cryogenic separation of CO_2 from other condensible gases. On the most sensitive range, one unit on the visual display corresponds to 0.19 ng. This device was found to be sensitive to temperature fluctuations. A realistic error for yield measurements would be *ca.* ± 0.5 ng (corresponding to about ± 0.1 ppm).

3. Results

Full carbon yield and isotopic data are given in the Appendix, whilst Table 1 summarises details of the 14 samples analysed, weights used, weight-losses incurred during the treatment, and integrated isotope and yield data. The data set comprises 14 experiments: 2 non-Antarctic CI1 meteorites; 5 non-Antarctic CM2 meteorites; 4 Antarctic C2 meteorites (probably of CM2 affinity); 1 unusual Antarctic carbonaceous chondrite (Yamato-82042); and 2 HF-resistant meteoritic residues (Orgueil (CI1) and Murchison (CM2)).

3.1. Non-Antarctic C1 meteorites

For Orgueil and Alais (Fig. 1) there is a general reduction in the amount of carbon

Table 1. Processed data for each experiment is presented in Appendix 1a–1d.

Meteorite	Type	Sample weight (mg)	Weight loss (%)	Max $\delta^{13}C$ (‰)	ppm C >800°C	ppm C >1000°C	$\delta^{13}C$ >800°C (‰)	$\delta^{13}C$ >1000°C (‰)
Orgueil	CI1	2.116	64.3	+493	24.9	8.8	+219	+359
Alais	CI1	4.087	63.7	+478	66.2	13.6	+183	+282
Y-82042	C1?	3.870	67.5	+33	229.2	155.4	+11	+12
Murray	CM2	3.536	62.7	+307	28.0	6.9	+122	+177
Murchison	CM2	4.104	57.6	+377	11.1	7.2	+149	+239
Mighei	CM2	4*	61.2	+335	9.6	3.2	+112	+178
Kivesvaara	CM2	2*	60.9	+370	51.1	14.3	+103	+174
"Cold Bokk"	CM2	4*	62.5	+237	—	—	—	—
Y-793321	C2	4.950	57.8	+279	40.9	35.1	+119	+164
Y-791824 (m)	C2	4.775	64.3	+281	104.6	36.6	+87	+140
Y-791198 (m)	C2	4*	66.0	+235	55.0	27.3	+74	+117
Belgica-7904 (m)	C2	5.137	57.5	+277	165.4	36.4	+67	+108
Orgueil (HF)	CI1	1.105	97.1	+645	382.4	231.8	+335	+447
Murchison (HF)	CM2	1.708	96.3	+928	58.5	38.7	+601	+736

Meteorite names, classes, sample weights, weight losses during acid dissolution, and a variety of maximum and aggregate $\delta^{13}C$ and concentration values are shown. The ppm values shown are the summed amounts between the given temperature and 1300°C, whilst the $\delta^{13}C$ values are the mean values between the temperature given and 1300°C. Note that 'm' refers to samples pre-combusted in a muffle furnace (see text for details), * refers to samples for which weights are estimated (minor sample loss during handling), and that "Cold Bokk" was only a partial analysis of the Cold Bokkeveld CM2 meteorite.

combusting with increasing temperature. However, there are peaks in the release profile over the temperature range 800 to 1300°C. This suggests the presence of some discrete carbonaceous components that are operationally distinguishable by their discrete combustion temperatures (McGARVIE *et al.*, 1985; WRIGHT *et al.*, 1986). It is further apparent from Fig. 1 that these components are themselves decreasing in magnitude with increasing temperature. It is interesting to note that the releases of carbon occur at similar temperatures in both samples.

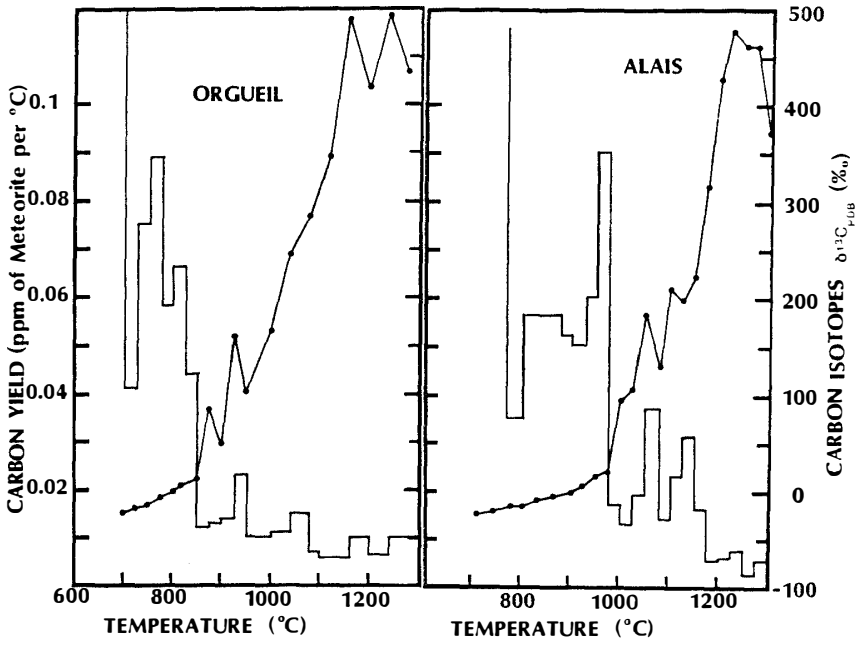

Fig. 1. Stepped combustion plots of Orgueil and Alais. The yields are plotted as histograms with the scale on the left vertical axis, whilst the isotopes are the joined dots (scale on the right vertical axis). Note that each isotope point has been drawn directly above the yield for that particular step. The yield at each step is plotted as the total amount of carbon combusting between the temperature of the step at which the yield was measured and the previous temperature step. This convention will be adopted for all further plots of this type.

The isotope profile rises steeply from 850°C in Orgueil to reach a double maximum $\delta^{13}C$ value of *ca.* +490‰ between 1160 and 1240°C. In Alais the sharp change in slope occurs at a somewhat higher temperature, 1000°C, but $\delta^{13}C$ reaches a similar maximum value *ca.* +475‰ between 1225 and 1275°C. The difference between Orgueil and Alais may be explained by the presence of the smaller amounts of carbon combusting from 600 to 950°C in the latter sample.

For both meteorites distinct deviations in the isotope profile produce a "sawtooth" pattern. In Orgueil, peaks occur across two temperature ranges: between 850 and 1000°C, and between 1160 and 1300°C. In Alais the deviations are between 1025 and 1150°C, and between 1225 and 1300°C. Such excursions may result from either sudden combustion of a ^{13}C-rich component, leading to positive deviations from an otherwise smooth rise in $\delta^{13}C$ with temperature, or combustion of a ^{12}C-rich component, which would result in a correspondingly negative deviation.

In Orgueil, it can be seen that minima in $\delta^{13}C$ at 950°C and above 1200°C correlate with increases in the carbon yield. At no point where there is a rise in the $\delta^{13}C$ value is there a corresponding increase in the yield of carbon. These observations jointly suggest that it is the combustion of isotopically light, or normal components (*i.e.*, relatively ^{12}C-rich by comparison to the overall isotope trend) which largely produces the sawtooth nature of the Orgueil isotope profile.

In Alais, three peak releases of carbon correspond with minima in $\delta^{13}C$: 1075, 1150 and 1250°C. Thus, as for Orgueil, the combustion of isotopically light carbon components in Alais seems to be the main factor producing the sawtooth structure to the $\delta^{13}C$ profile. Clearly, ^{13}C-rich and ^{12}C-rich carbon components are intimately associated with one another, in a variety of different sites. Presumably since the light carbon is subject to sudden combustion it must have a different physico-chemical structure (McGARVIE *et al.*, 1985).

3.2. Non-Antarctic CM2 meteorites

The results for Cold Bokkeveld, Kivesvaara, Mighei, Murchison and Murray are presented in Figs. 2 and 3. Note that the Cold Bokkeveld experiment is only a partial analysis (600 to 1125°C) because of equipment failure. As with the CI1 meteorites, there is a general decrease in the amount of carbon released with increasing temperature, and rise in $\delta^{13}C$ with increasing temperature. Maximum $\delta^{13}C$ values attained in the four completed analyses are at least 100‰ lower than for CI1 meteorites and lie between +307 and +377‰, in the temperature interval between 1125 and 1260°C. Three of the four maxima are even more tightly confined between 1125 and 1150°C, a substantially lower temperature than observed for the CI1's. Only Murchison, which exhibits the maximum $\delta^{13}C$ of +377‰, for a CM2, is at a higher temperature. Thus there seems to be important differences between the CI1 and the CM2 meteorites with respect to the nature or location of their refractory carbon fraction. Overall, the five non-Antarctic CM2 meteorites analysed show very similar carbon release patterns and isotopic characteristics that are consistent with their identification as a discrete chemical group and petrologic type.

A careful examination of the yield data again reveals several discrete releases of carbon in the temperature interval 800 to 1300°C (McGARVIE *et al.*, 1985). In contrast to the CI1's, the carbon yield does not always decrease steadily with increasing temperature. In common with the CI1 meteorites however, $\delta^{13}C$ varies with temperature in a way which suggests the presence of several components. In a few cases the peaks in the isotope trace correspond to peaks in carbon yield suggesting that isotopically heavy carbon components were combusting, which is the opposite to what was observed for the CI1's.

Both ^{13}C- and ^{12}C-rich refractory carbon components may co-exist in a number of sites in CM2 meteorites (McGARVIE *et al.*, 1985). Either the sites are different from those in CI1 meteorites, or different carbonaceous components are involved.

3.3. HF-resistant residues of Murchison and Orgueil

HCl-resistant residues from CI1 meteorites attained higher $\delta^{13}C$ values than corresponding residues from CM2 meteorites, by more than 100‰. More processed

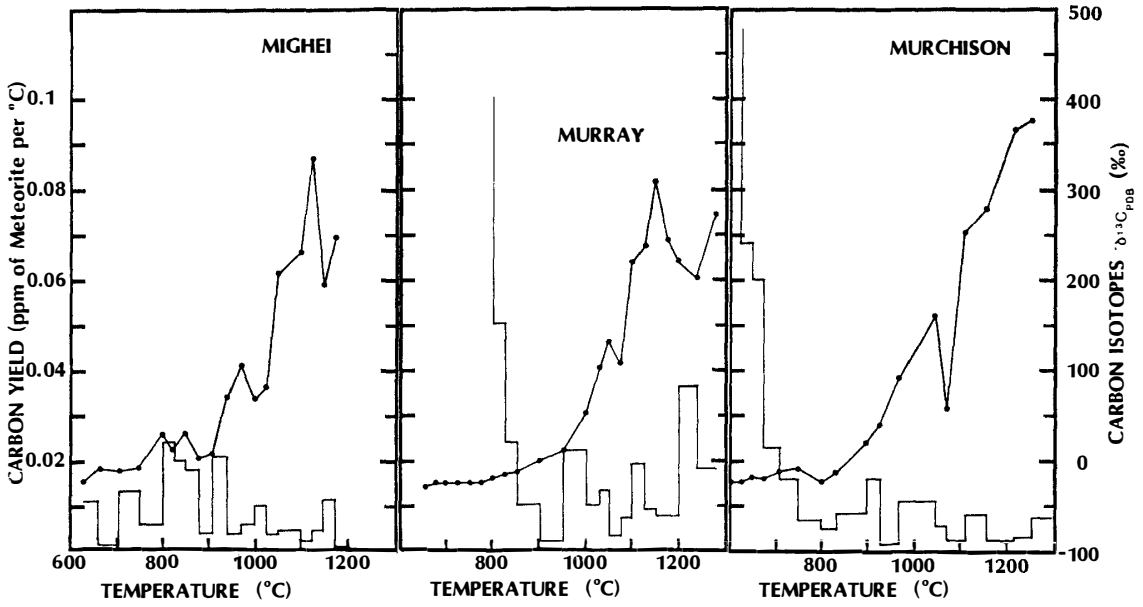

Fig. 2. Stepped combustion plots of three non-Antarctic C2 meteorites: Mighei, Murray and Murchison.

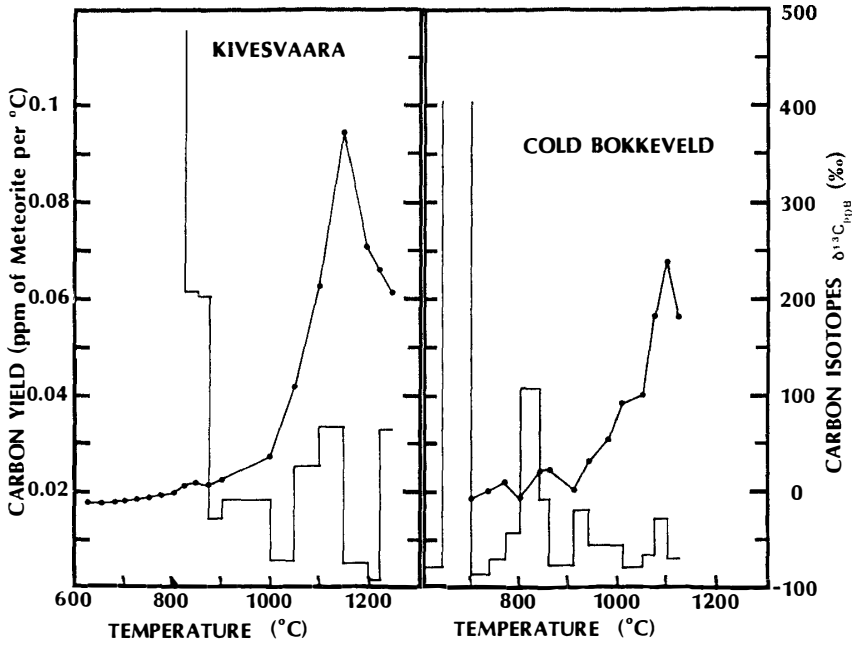

Fig. 3. Stepped combustion plots of two non-Antarctic C2 meteorites: Kivesvaara and Cold Bokkeveld.

(HF-resistant) residues from Orgueil and Murchison were investigated to determine whether this trend was maintained.

The results are presented in Fig. 4. For HCl-resistant residues, Orgueil (CI1) exhibited the higher $\delta^{13}C$ value (+493 *vs.* +377‰) whereas in the HF-resistant residues the position is reversed (+648 *vs.* +928‰). The peak isotopic values for the two meteorites are within about 25 of 1100°C. The overall carbon release of

Orgueil shows a discernible pattern, with increasing amounts of carbon released up to *ca.* 1100°C, thereafter yields begin to decrease; Murchison does not show such a well resolved pattern. Also, the isotopic variation with temperature is more apparent in the case of Orgueil. For Orgueil, the minima in the isotopic profile correspond for the most part with maxima in the carbon release. This verifies that combustion of normal or ^{12}C-rich carbon is the controlling factor.

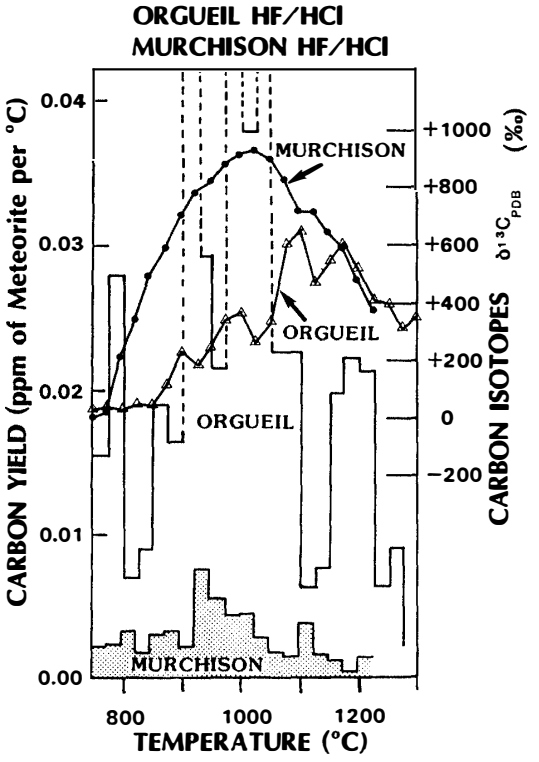

Fig. 4. Stepped combustion plots of two HF+HCl-resistant residues: the Murchison C2 meteorite and the Orgueil C1 meteorite. The yield pattern for Murchison has a dotted ornament. Note that Orgueil has vastly greater amounts of carbon combusting at any given temperature.

It is paradoxical that the pattern of $\delta^{13}C$ variation in Murchison is extremely smooth and regular, which strongly hints at the combustion of one major ^{13}C-rich component, and yet the $\delta^{13}C$ pattern appears to bear no clear relation to the highly complex yield profile. In this respect it is noteworthy that the maxima in the isotope trace does not correlate directly with a single, well-defined carbon release.

3.4. Japanese Antarctic C2 meteorites

Four Antarctic C2 meteorites were analysed: Belgica-7904, Yamato-791198, -791824 and -793321. The aim of the exercise was to determine whether the stable carbon isotopic compositions of Antarctic samples were similar to those of non-Antarctic CM2 meteorites in the light of current theories which speculate that Antarctic and non-Antarctic meteorites sample different source populations (DENNISON *et al.*, 1986a, b).

The relevant stepped combustion plots are presented in Fig. 5. Three of the samples show a general reduction in yield with increasing temperature but Y-793321, on the other hand, shows a very pronounced increase. The bulk of this carbon must be mostly indigenous as its isotopic composition ($\delta^{13}C > +220‰$) clearly demonstrates an exotic signature. The long carbon release tail in Y-791824 (Fig. 5) is the result of

incomplete combustion of low temperature organic contaminant material. However, above *ca.* 900°C, the amounts of carbon released are comparable to the other three Antarctic C2's.

All four samples show a more steady rise in $\delta^{13}C$ than non-Antarctic CM2's with increasing temperature. The maximum values lie between +235 and +280‰ at 1265 to 1300°C and are all lower than non-Antarctic CM2's. There are a number of maxima and minima in $\delta^{13}C$, although these do not seem to correlate with any of the peaks in carbon releases. This observation is in accord with the previous discussion on non-Antarctic CM2 meteorites.

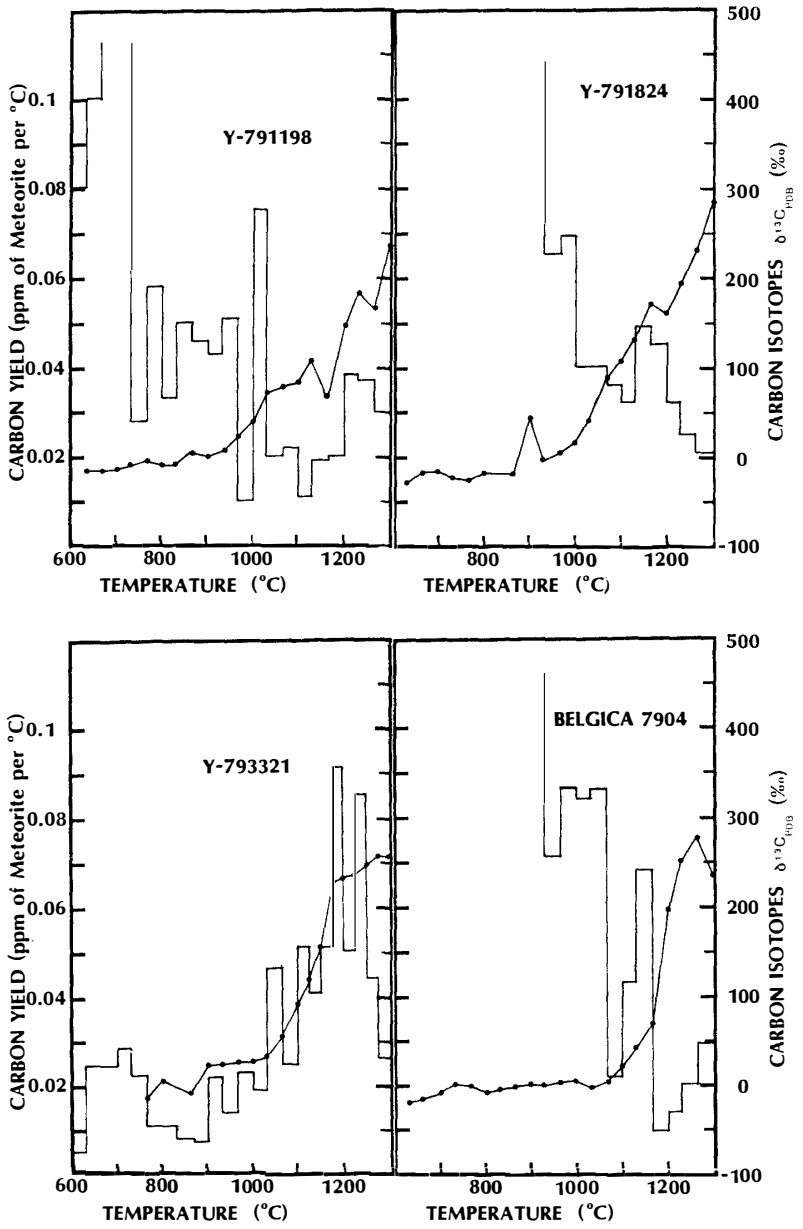

Fig. 5. Stepped combustion plot of four Antarctic C2 meteorites: Y-791198, -791824, -793321 and Belgica-7904.

3.5. *The Y-82042 meteorite*

This unusual meteorite has characteristics distinctive of both C1 and C2 meteorites (see GRADY *et al.* this volume), and may possibly be an important link between the two groups. Since the bulk carbon content of 1.05 wt% is low for both CI1 and CM2 meteorites, and since the abundance of carbonate minerals is greater, the meteorite must have an unusually low organic matter content. On the basis of petrologic and chemical data, GRADY *et al.* (1986) suggested that Y-82042 might be the first CM1 meteorite to be recorded. However, the low volatile content would seem to argue against this interpretation.

Figure 6 shows the stepped combustion plot of an HCl-resistant residue of Y-82042 over the temperature range 600 to 1300°C. Two features are immediately apparent which mark this meteorite as different from any of the samples discussed previously. Firstly, there is a rise in the amount of carbon released with increasing temperature, a feature only seen before for Y-793321. Secondly, the maximum $\delta^{13}C$ value attained during the experiment was only +33‰, which is a considerably lower ^{13}C-enrichment than any other sample studied herein, and quite different from Y-793321. Nevertheless, in common with all other meteorites so far discussed, there is a general trend of increasing $\delta^{13}C$ with increasing temperature.

Examining Fig. 6 in more detail, it can be seen that above 600°C there are four distinct temperature regions where carbon shows a peak release: *ca.* 700, 800, 900–1000 and 1100–1200°C. Overall, the amount of carbon combusting within each of these four releases increases with increasing temperature, with the largest carbon release occurring at the highest temperature regime. Although there is a general increase in the $\delta^{13}C$ value of carbon combusting with increasing temperature, in detail the variation of $\delta^{13}C$ with temperature is very irregular, shifting in excess of 20‰ between adjacent

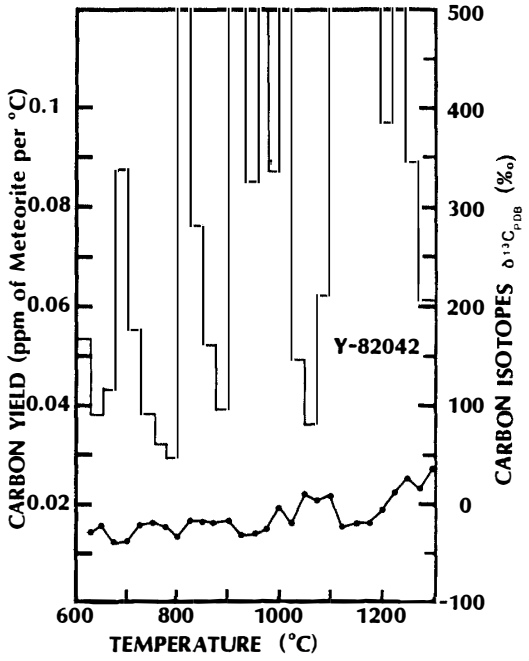

Fig. 6. Stepped combustion plot of Y-82042.

steps. It is noteworthy that the four major releases of carbon correspond to distinct $\delta^{13}C$ minima. Only one rise in $\delta^{13}C$ occurs that correlates with a release of carbon–that of a component at 1250°C.

Thus, Y-82042 presents the best evidence so far for isotopically normal or ^{12}C-rich refractory carbon components. However, whether this refractory material is simply shielded, ^{12}C-rich, low-temperature organic materials surrounded by mineral grains, or whether this material is indeed indigenous ^{12}C-rich refractory carbon, is unclear.

4. Discussion

4.1. The isotopic signatures of C1 and C2 chondrites

The results presented in the previous sections indicate that whilst ^{13}C-rich carbon is present in both CI1 and CM2 chondrites, these meteorite groups behave differently during stepped combustion. Figure 7 shows a summary diagram of $\delta^{13}C$ *vs.* temperature for all the specimens studied herein (the unusual meteorite Y-82042 excepted). It can be seen that the different categories of sample analysed fall into fairly restricted domains. At the very least, this suggests that genetic relationships do exist which may be an additional aid to sub-classification of meteorite groups. A possible explanation for the differences observed between groups is the presence of different ^{13}C-rich carbon components which have variable $\delta^{13}C$ values and exist in different proportions in C1 and C2 chondrites (McGARVIE *et al.*, 1986). Thus a CI1 meteorite would contain larger amounts of a mildly ^{13}C-rich component than a C2 meteorite, whereas a C2 meteorite would contain a greater proportion of a more ^{13}C-rich carbon component.

The variation of $\delta^{13}C$ with temperature in Alais and Orgueil residues may be controlled by the combustion of refractory, isotopically normal or light, carbon components. The existence of such material surviving to high temperatures is most aptly demonstrated by analysis of the unique meteorite Y-82042. The variation of $\delta^{13}C$ in C2 samples does not seem to be quite so influenced by light, or normal, carbon.

Two possible explanations can be tendered for the increase in $\delta^{13}C$ following HF treatment: (1) some isotopically light carbon components are preferentially removed or released to burn at lower temperatures during demineralisation with HF. The fact that the sawtoothed isotope pattern still exists in the HF/HCl-resistant residue of Orgueil argues against a hypothesis that the light carbon in the HCl-resistant residues is simple macromolecular carbon trapped in the mineral matrix. However the dramatic 650‰ rise in the $\delta^{13}C$ maximum for Murchison could mean that such an effect is possible in CM2's; and (2) isotopically heavy carbon is contained within mineral grains or other sites which are not completely removed by dissolution in HCl (only 50 to 60% sample weight loss) and are stable to temperatures up to 1300°C. These coating materials are dissolved in HF (96 to 97% sample weight loss), thus freeing entrapped isotopically heavy carbonaceous matter which can combust at lower temperatures. This hypothesis needs to be examined by combusting HCl-resistant residues at temperatures in excess of 1300°C.

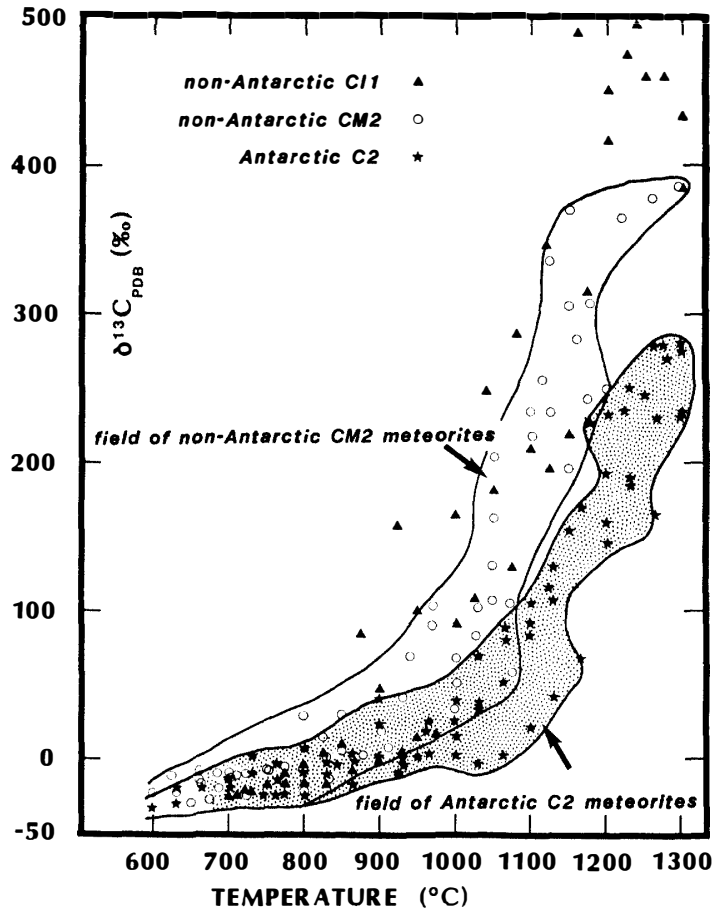

Fig. 7. Isotope profiles from all meteorites analysed during this study are synthesised in this temperature vs. isotopic composition diagram. Each group of meteorites is given a different symbol to enable differences between them to be distinguished. The field of Antarctic C2 meteorites has an ornament and a boundary envelope drawn around it, whilst only a boundary envelope has been drawn around the non-Antarctic CM2 meteorites. For clarity an envelope has not been drawn around the CI1 data points (solid triangles).

4.2. Differences between Antarctic and non-Antarctic meteorites

Although similarities exist between the Antarctic and non-Antarctic C2 meteorites, the main difference between these two groups are as follows: (i) maximum $\delta^{13}C$ values attained are between +235 and +280‰ for the former, and between +307 and +377‰ for the latter; (ii) the temperatures at which the maximum $\delta^{13}C$ values are reached are also different, being 1265 to 1300°C and 1150 to 1260°C respectively; and, (iii) there are much greater amounts of carbon above 800°C in the Antarctic C2 meteorites. It appears that there are genuine differences between the stable carbon isotopic systematics of the Antarctic and non-Antarctic CM2 meteorites.

Recently, DENNISON *et al.* (1986a, b) have suggested that compositional differences in elemental abundances exist between Antarctic and non-Antarctic meteorites. This conclusion was reached after a study applied to the H5 group of chondrites. Implicit in this chemical analysis of H5 chondrites was the suggestion that Antarctic meteorites either differ in genetic history, or sample different extraterrestrial parent popula-

tions, or both (Dennison *et al.*, 1986a, b).

The comparisons made earlier in this paper suggest that these differences also extend to C2 carbonaceous chondrites. The Antarctic C2 meteorites were found to be grossly similar to the non-Antarctic meteorites in their carbon release characteristics, but to be significantly different in their $\delta^{13}C$ values. Figure 7 summarises these differences, and emphasises the overall lower $\delta^{13}C$ values attained at any given step for the Antarctic C2 meteorites. From Table 1 it is further apparent that the Antarctic C2 meteorites have much greater quantities of carbon combusting above 1000°C. Four possible explanations are: (i) that either the Antarctic meteorites contain lower proportions of ^{13}C-rich carbon; or, (ii) that they contain larger quantities of ^{12}C-rich carbon components (*c.f.*, Y-82042); or, (iii) that they contain a ^{13}C-rich component which is less enriched in ^{13}C than the comparable components which exist in non-Antarctic C2 meteorites; or, (iv) the isotopically heavy carbon is somehow leached out in the Antarctic environment (the most spectacular example of which could be Y-82042). At present we are unable to say which of these, or which combination of these, is most likely to produce the observed variations.

Acknowledgements

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Appendix 1

The data tabulated here are the raw data which were acquired in this study. It comprises the temperature steps, carbon isotopic measurements and carbon yield data (nanograms and ppm) for each step of each experiment.

Appendix 1a.

ORGUEIL				ALAIS				Y-82042			
T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm
700	125.7	-24.7	59.4	710	56.5	-25.0	13.8	625	15.7	-31.8	4.1
725	6.1	-19.0	2.9	730	51.8	-22.5	12.7	650	11.3	-22.1	2.9
750	11.1	-17.1	5.2	775	21.8	-18.1	5.3	675	12.8	-41.1	3.3
775	13.2	-9.9	6.2	800	97.0	-18.2	23.7	700	26.0	-39.5	6.7
800	8.6	-2.5	4.1	830	18.9	-11.5	4.6	725	16.4	-22.3	4.2
825	9.7	5.7	4.6	865	22.0	-7.7	5.4	750	11.3	-20.6	2.9
850	6.5	11.1	3.1	900	20.4	-3.3	5.0	775	9.6	-24.6	2.5
875	1.7	84.5	0.8	925	14.1	4.4	3.5	800	86.3	-34.6	22.3
900	1.9	48.3	0.9	950	17.0	14.3	4.2	825	41.6	-17.8	10.7
925	2.1	157.7	1.0	975	25.6	16.7	6.3	850	22.5	-18.4	5.8
950	3.4	100.8	1.6	1000	4.8	91.9	1.2	875	15.5	-20.3	4.0
1000	2.9	164.3	1.4	1025	3.6	106.9	0.9	900	11.7	-18.9	3.0
1040	2.7	246.3	1.3	1050	5.3	180.9	1.3	925	41.4	-32.1	10.7
1080	3.6	284.3	1.7	1075	10.5	128.4	2.6	950	25.4	-30.6	6.6
1120	1.7	344.9	0.8	1100	4.0	208.4	1.0	975	40.7	-27.1	10.5
1160	1.3	489.1	0.6	1125	6.5	194.6	1.6	1000	25.8	-4.8	6.7
1200	2.5	417.4	1.2	1150	8.6	218.5	2.1	1025	48.5	-20.1	12.5
1240	1.5	492.6	0.7	1175	4.6	313.9	1.1	1050	14.5	9.4	3.7
1280	2.5	435.1	1.2	1200	1.5	449.3	0.4	1075	10.7	2.1	2.8
				1225	1.7	475.6	0.4	1100	18.3	8.4	4.7
				1250	2.1	460.0	0.5	1125	157.7	-25.3	40.7
				1275	0.8	460.0	0.2	1150	58.4	-20.7	15.1
				1300	1.5	371.9	0.4	1175	81.4	-19.0	21.0
								1200	67.3	-8.5	17.4
								1225	29.0	11.5	7.5
								1250	45.1	24.3	11.7
								1275	26.5	14.1	6.8
								1300	18.2	33.1	4.7

Appendix 1b.

MURRAY				MIGHEI				COLD BOKKEVELD				MURCHISON				KIVESVAARA			
T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm
650	2032.5	-29.3	574.8	630	315.6	-23.0	78.9	640	1.8	-27.9	0.5	600	768.8	-23.1	187.3	625	104.7	-12.0	52
675	423.9	-27.4	119.9	660	3.5	-8.4	0.9	700	101.3	-10.9	25.3	625	80.8	-23.2	19.7	650	189.2	-14.0	94
700	259.7	-26.0	73.4	705	0.4	-12.3	0.1	735	0.9	-	0.2	650	16.4	-18.5	4.0	675	119.0	-12.0	59
725	81.3	-26.1	23.0	750	6.1	-8.0	1.5	770	2.1	8.9	0.5	675	14.5	-21.2	3.5	700	44.1	-11.1	22
750	30.2	-27.0	8.5	800	3.1	29.5	0.8	800	3.6	-10.2	0.9	710	7.8	-11.0	1.9	725	46.6	-10.7	23
775	68.8	-25.1	19.4	825	6.1	13.2	1.5	840	17.4	21.7	4.3	750	6.3	-7.2	1.5	750	34.8	-8.5	17
800	25.0	-19.9	7.1	850	5.2	30.7	1.3	870	5.7	22.5	1.4	800	3.4	-23.2	0.8	775	28.1	-6.8	14
825	11.6	-17.3	3.3	880	5.5	3.0	1.4	910	1.9	1.6	0.5	835	1.7	-13.1	0.4	800	27.7	-3.7	13
850	5.7	-13.6	1.6	910	1.1	8.7	0.3	940	5.0	31.3	1.2	900	5.3	19.6	1.3	825	26.8	4.0	13
900	4.6	0.0	1.3	940	3.5	71.0	0.9	980	3.6	53.1	0.9	930	4.6	41.6	1.1	850	7.8	6.0	3
950	1.0	1.2	0.3	970	1.3	103.7	0.3	1010	2.7	89.9	0.7	970	0.8	90.1	0.2	875	7.6	4.7	3
1000	10.3	53.5	2.9	1000	1.9	67.8	0.5	1050	1.7	97.6	0.4	1050	8.6	161.5	2.1	925	3.6	9.3	1
1030	2.9	101.3	0.8	1025	2.7	82.8	0.7	1075	1.7	181.2	0.4	1075	1.3	57.0	0.3	1000	6.7	33.5	3
1050	2.5	131.8	0.7	1050	0.9	204.5	0.2	1100	3.8	236.6	1.0	1115	1.0	255.1	0.2	1050	1.1	107.1	0
1075	0.8	106.0	0.2	1075	0.0	-	-	1125	1.5	179.4	0.4	1160	3.4	281.8	0.8	1100	6.4	210.9	3
1100	1.5	217.1	0.4	1100	1.1	231.4	0.3					1220	1.5	366.2	0.4	1150	8.4	369.5	4
1125	4.4	234.5	1.2	1125	0.6	334.7	0.1					1260	11.3	376.9	2.7	1200	1.4	249.3	0
1150	2.1	307.0	0.6	1150	1.1	192.6	0.3					1295	2.5	175.4	0.6	1250	0.4	209.4	0
1175	0.4	242.0	0.1	1175	3.3	244.3	0.8									1275	4.2	41.0	2
1205	2.1	219.8	0.6	1210	0.2	61.7	0.0												
1240	11.8	201.9	3.3	1250	0.8	-	-												
1280	6.5	270.5	1.8	1280	0.0	-	-												

Appendix 1c.

Y-791824				Y-791198				BELGICA-7904				Y-793321			
T°C	ngC	δ^{13}	ppm	T°C	ngC	δ^{13}	ppm	T°C	ngC	δ^{13}	ppm	T°C	ngC	δ^{13}	ppm
								600	133.70	-33.2	26.0	600	-	-	-
630	444.9	-29.1	93.2	630	28.6	-18.3	7.2	630	45.80	-25.7	8.9	630	1.70	-	0.3
665	179.5	-18.4	37.6	665	42.0	-17.0	10.5	665	161.40	-16.6	31.4	665	10.00	-	2.0
700	133.7	-18.8	28.0	700	84.0	-14.6	21.0	700	313.90	-10.5	61.1	700	10.00	-	2.0
730	105.0	-24.0	22.0	730	64.9	-11.3	16.2	730	443.00	1.8	86.2	730	10.00	-	2.0
765	106.9	-26.0	22.4	765	11.5	-4.7	2.9	765	229.70	-2.6	44.7	765	9.20	-16.60	1.9
800	93.6	-18.0	19.6	800	23.7	-9.7	5.9	800	324.60	-8.2	63.2	800	4.80	6.7	1.0
830	57.3	-18.6	12.0	830	11.5	-11.3	2.9	830	101.20	-3.3	19.7	830	4.00	-	0.8
865	61.1	-18.6	12.8	865	20.4	4.4	5.1	865	63.80	-4.1	12.4	865	3.80	-9.9	0.8
900	47.7	42.6	10.0	900	18.9	0.9	4.7	900	95.40	-1.6	18.6	900	3.10	22.8	0.6
930	34.4	-5.3	7.2	930	15.3	4.9	3.8	930	47.70	-1.7	9.3	930	7.80	-0.8	1.6
965	30.6	3.3	6.4	965	21.0	19.5	5.3	965	30.20	2.9	5.9	965	5.70	25.7	1.2
1000	32.5	14.8	6.8	1000	4.4	37.2	1.1	1000	36.30	2.6	7.1	1000	9.40	26.9	1.9
1030	15.9	38.3	3.3	1030	26.4	70.7	6.6	1030	30.60	-3.4	6.0	1030	6.50	32.6	1.3
1065	18.7	86.9	3.9	1065	8.2	78.4	2.0	1065	36.30	1.3	7.1	1065	19.10	51.8	3.9
1100	16.8	104.6	3.5	1100	9.0	83.8	2.3	1100	9.20	21.4	1.8	1100	10.10	90.8	2.0
1130	12.8	128.7	2.7	1130	4.0	108.4	1.0	1130	15.80	41.9	3.1	1125	14.90	116.7	3.0
1165	22.9	169.9	4.8	1165	8.0	67.4	2.0	1165	28.60	66.8	5.6	1150	12.00	151.7	2.4
1200	21.0	158.1	4.4	1200	8.2	144.2	2.0	1200	4.00	192.7	0.8	1175	14.90	226.6	3.0
1230	12.8	191.3	2.7	1230	13.4	182.7	3.3	1230	5.00	249.9	1.0	1200	26.70	232.6	5.4
1265	11.5	228.5	2.4	1265	15.3	164.1	3.8	1265	9.00	277.0	1.8	1225	14.50	238.8	2.9
1300	9.7	280.6	2.0	1300	12.4	235.3	3.1	1300	12.20	234.6	2.4	1250	24.80	246.1	5.0

Appendix 1d.

ORGUEIL HF				MURCHISON HF			
T°C	ngC	δ13	ppm	T°C	ngC	δ13	ppm
625	80.2	-17.6	72.6	750	-	-	
650	18.7	-8.5	16.9	775	6.11	-7.9	3.6
675	55.2	6.7	50.0	800	9.17	3.6	5.4
700	36.5	34.5	33.0	825	6.11	23.5	3.6
725	27.7	15.9	25.1	850	6.68	223.4	3.9
750	20.4	29.2	18.5	875	9.17	353.6	5.4
775	14.3	38.0	12.9	900	5.16	498.3	3.0
800	25.8	31.1	23.3	925	8.59	595.4	5.0
825	7.1	49.5	6.4	950	9.74	704.2	5.7
850	8.2	37.5	7.4	975	5.92	787.4	3.5
875	17.6	111.9	15.9	1000	21.01	823.9	12.3
900	15.1	236.8	13.7	1025	15.27	883.1	8.9
930	51.2	175.0	46.3	1050	12.03	919.5	7.0
950	21.6	239.0	19.5	1075	12.22	928.4	7.2
975	19.9	337.6	18.0	1100	7.83	901.5	4.6
1000	43.0	365.1	38.9	1125	5.16	826.2	3.0
1025	34.8	262.1	31.5	1150	4.58	719.0	2.7
1050	48.3	328.3	43.7	1175	10.69	719.7	6.3
1075	21.0	597.9	19.0	1200	4.58	648.7	2.7
1100	21.0	647.6	19.0	1225	3.44	596.4	2.0
1125	5.9	471.2	5.3	1250	1.53	482.3	0.9
1150	7.1	546.0	6.4	1280	4.01	383.0	2.3
1175	18.3	610.8	16.6				
1200	20.6	517.3	18.6				