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LINE BLANKETING IN VEGA AND SIRIUS

Grant NSG 5030

Final Report

Principal Investigator
Dr. Robert L. Kurucz

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
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ABSTRACT

Our theoretical model and spectrum calculation for Vega seem to be realistic once we have corrected a few errors in the Kurucz and Peytremann line list. The abundance of carbon is approximately -3.8, which is 0.3 lower than the old solar value and supports Mount and Linsky's newer value. The oxygen abundance is approximately -3.5. Assuming that Vega has solar abundances, the solar oxygen abundance appears to have been overestimated by 0.3 in the log. Other abundances appear to be solar.

For Sirius the calculations do not agree with the observed spectrum. Line opacity is considerably underestimated, notably in third-spectrum iron group lines. Carbon is underabundant relative to Vega by 0.2 in the log. Nitrogen is unchanged. Oxygen is enhanced by 0.3. Heavier elements are enhanced by 1.0 in the log.

Our tentative calibration yields 1.3E-10 ergs/cm^2/s/nm for each U1 Copernicus count at 130 nm.

LINE BLANKETING IN VEGA AND SIRIUS

Final Report

1. INTRODUCTION

Vega and Sirius are two of the brightest, best observed stars. Vega is the archetypical "normal" star that we would expect to have solar or, because it was formed more recently than the sun, slightly enhanced solar abundances. Its angular diameter and distance are known and it does not suffer from theoretical problems such as convection, so one should be able to calculate realistic theoretical models and spectra. For any model atmosphere program or spectral calculation program to be considered accurate and realistic it must reproduce, at least in a general way, the spectrum and energy distribution of Vega. Furthermore, because photometric systems ultimately are defined relative to Vega, theoretical interpretation of photometry depends on the calculation of a model for Vega.

Once theoretical programs are available to treat normal stars, simple parameter changes should allow the prediction of models for evolved stars and stars of different populations. Sirius is a moderately metallic line star, a binary with a white dwarf companion that presumably transferred matter enriched in heavy elements to Sirius A. The mass, diameter, and distance are known for Sirius, and, because it is easily observed at high resolution, it makes a good test case for checking the effects of abundance changes.

With theoretical programs for computing models and spectra, we are investigating Vega and Sirius over the whole spectral range both to determine the properties of the stars themselves and to test the programs. Copernicus provides a unique opportunity to obtain spectra that show strong resonance lines of many elements and many other lines formed through a range of levels in the atmosphere. Such spectra present a strong test of the stellar atmosphere theory.

2. COPERNICUS OBSERVATIONS

Copernicus U1 scans of Vega and Sirius were made during September and November 1974 covering the region 130 to 135 nm with a resolution of approximately 0.0037 nm. We went to Princeton in December 1974 to collect the data.

In Figure 1 we show the scans for both stars normalized as discussed in Section 10. The individual data points for Vega are visible in Figure 8 and for Sirius in Figure 9. Since full scale at 130 nm corresponds to 2400 counts for Sirius and only 575 for Vega, the Vega scan is considerably noisier. The scans were made in small overlapping sections but one piece at 132.9 was not observed in Sirius. The Sirius wavelengths have been incremented by 0.003 nm to align the two spectra approximately, but no other effort has been made to process the data. Wavelengths should be considered uncertain by at least this amount. Although the noise causes some uncertainty, it appears that the same features appear in both spectra, that the stronger features are of similar strength in both stars (e.g., O I at 130.2 and C I at 132.9), but that many features weak in Vega are tremendously increased in Sirius.

3. MODEL ATMOSPHERE FOR VEGA

Observations are available for Vega in the visible that allow a reasonably accurate determination of model parameters. A good fit in the visible is important to this analysis because the far ultraviolet falls on the exponential side of the Planck maximum and, thus, is sensitive to small temperature changes. Conversely, the far ultraviolet continuum and line spectrum provide strong tests of the models because they are so sensitive.

We have computed a grid of model atmospheres that include line opacity in the form of statistical distribution functions (Kurucz, in preparation). By comparing these models to the energy distribution determined by Hayes and Latham (1975) we determined parameters $T_{eff} = 9400 \pm 200$ K and log g= 4.0 ± 0.5. Then, with Deane Peterson at Stony Brook, we programed the Vidal, Cooper, Smith theory (Vidal, Cooper, and Smith, 1973) for hydrogen line profiles. By comparing to Peterson's (1969) Balmer line profiles we determined log g= 3.95 ± 0.05. These parameters are consistent with Code's (1975) empirical values, 9660 ± 130, and 3.94 ± 0.08. Figures 2 and 3 show the comparisons between the observations and a 9400, 3.95 model. There is a small discrepancy in that the Balmer line cores are narrower than those observed. As discussed in Section 7, Vega has a projected rotational velocity of approximately 25 km/s. Rotationally broadening the theoretical profile would widen the core to match but would leave the central residual intensity too high. Non-LTE effects, which have not been included, presumably would lower the central intensity (Peterson, 1969).

This model was computed assuming solar abundances from Withbroe's compilation (1971). Thus we assumed -3.48 for the log carbon abundance relative to the total. However, as discussed in Section 9, the actual carbon abundance is nearer -3.8. Since the carbon continua are important features in the far ultraviolet, the abundance change reduces the total ultraviolet opacity and decreases the backwarming. This may mean that a slightly hotter model with the new abundances may be more correct. We have not yet determined the magnitude of such a correction.

4. MODEL ATMOSPHERE FOR SIRIUS

In the grid calculation described above, it is a simple matter to compute models at scaled solar abundances, but it is expensive to make changes that require recomputing line opacity. As a moderately metallic line star, Sirius has decidedly nonscaled abundances, with light elements near solar and with metals overabundant by a factor of 10 or so (Kohl, 1964; Latham, 1970). As a first step we tried the approximation of a 10,000,4.3 model with all abundances increased by 0.5 in the log. These parameters are approximately Code's (1975), 9975 ± 150 and 4.31 ± 0.04. This model agrees fairly well with Peterson's (1969) Balmer line profiles and with the energy distribution given by Latham (1970), corrected to the new calibration of Vega by Hayes and Latham (1975). It would be useful to have new, improved observations of the energy distribution of Sirius.

The initial spectrum calculation with abundances increased by 0.5 in the log was grossly inconsistent with the observations. We were able to improve the fit by changing abundances of various elements. Then we computed a model with abundances C -4.00, N -4.00, O -3.22, and heavier elements 10 times solar, but with line opacity tables computed for abundances 10 times solar. Thus the model is not consistent. We are currently using this model in the spectrum calculations; but, as discussed in Section 9, there remain inconsistencies in the spectrum indicating that the model may need improvement.

5. SPECTRUM SYNTHESIS PROGRAM

We have continually improved our spectrum synthesis program during the course of this research. The basic program works as follows. For a given model atmosphere tabulated at 40 depths, we compute number densities and partition functions for all atoms and ions. Then we read the magnetic tape that lists the gf values calculated by Kurucz and Peytremann (1975, hereinafter called KP) and compute a line opacity spectrum at each depth. The expressions for radiative, Stark, and van der Waals broadening are

$$\Gamma_R = \Gamma_{\text{classical}} = 2.223\text{E}13/\lambda^2 \quad , \qquad \lambda \text{ wavelength in nm} \quad ;$$

$$\Gamma_S = 1.0\text{E-}8\ n_{\text{eff}}^{\ 5}\ N_e \quad ;$$

$$\Gamma_W = 4.5\text{E-}9\,\langle r^2\rangle^{4/10}\ [N_H + 0.42\ N_{He} + 0.85\ N_{H_2}]\ (T/10,000)^{3/10} \quad ;$$

where

$$\langle r^2\rangle = 2.5\ n_{\text{eff}}^{\ 2}/Z_{\text{eff}}^{\ 2} \quad ,$$

$$n_{\text{eff}}^{\ 2} = R\ Z_{\text{eff}}^{\ 2}/E_{\text{up}} \quad ,$$

Z_{eff} is the charge plus 1, E_{up} is the upper level energy, and R is the Rydberg energy. Next, continuum quantities, opacities, source functions, and fluxes, are evaluated at several points in the wavelength interval. Then, the continuum quantities are interpolated to each point in the spectrum, the line opacity added, the source function approximated by

$$[(\kappa + \sigma)S_{\text{cont}} + \ell\ S_{\text{line}}]/(\kappa + \sigma + \ell) \quad ,$$

and the surface flux or intensity computed. Here κ and σ are the continuous absorption and scattering coefficients, ℓ is the line absorption coefficient, S_{cont} is the continuum source function, and S_{line} is the line source function, which is assumed to be the Planck function.

The following improvements have been made. We have computed mean square radii for the 4p orbitals of the iron group atoms and ions, and produced an interpolation formula

$$\langle r^2 \rangle = (45 - A + Z)/(Z + 1) \quad ,$$

where A is the atomic number and Z is the charge. This expression is used for van der Waals broadening of all iron group atoms, assuming that the strong lines are all resonance lines with a 4p upper state.

There is now provision for additions, deletions, and corrections to the table of gf values and for use of individual "real" radiative, Stark, and van der Waals damping constants for each line.

To resolve the contribution of individual lines to blends, we now compute, in addition to the spectrum, the central intensity for each line in isolation.

We automatically produce spectrum plots with identifications.

6. ROTATIONAL BROADENING OF THE THEORETICAL SPECTRUM

In practice, most spectra must be rotationally broadened to compare with observations. We have developed a broadening procedure of direct numerical integration over the stellar disk. This procedure is simple and easily generalized to treat gravity darkening, nonuniform rotation, nonspherical stars, and binaries. In the simple case of uniform rotation, no gravity darkening, and circular projection, we can use symmetry to reduce the evaluation to one quadrant.

The integration is performed by laying a grid of any fineness over the stellar disk and simply adding the intensity at each point. For the calculations reported here we used a spacing of 0.02 times the radius. At each point on the grid we compute the doppler shift and the cosine of the angle of projection. The doppler shift is converted to an integral number of steps in the spectrum (multiples of the point spacing) and the cosine is converted to an integral multiple of 0.01. In general there will be grid points on the disk that have the same values of these integers. All the values are sorted and the multiplicity of each is noted. The multiplicities are added and a normalization factor is determined such that integration of I_ν produces H_ν. This set of numbers is the rotation operator.

For the work described here we computed the spectrum with a spacing of 0.5 pm at 17 angles and interpolated to 100 cosines from 0.005 to 0.995. These spacings were chosen arbitrarily. Smaller spacings might improve the accuracy of the final spectrum. Fewer angles than 17 are possible. We should point out that computation time is not proportional to the number of angles since the opacity spectrum need be computed only once for any number of angles.

To broaden the spectrum rotationally, we read the intensities $I_{j\mu}$ one wavelength at a time and distribute each intensity into a flux spectrum H using the rotation operator. For example, if part of the operator is an 11-step doppler shift for a cosine index μ of 37 with a multiplicity of 4, we would add $4I_{j37}$ to H_{j+11} and, by symmetry, to H_{j-11}. Thus we go through every term of the operator for every wavelength in the spectrum. Once the totals are completed we normalize. If the doppler width of the operator includes many steps, N, the accuracy is improved by filtering with a $(1 + N/5)$-step straight mean. The accuracy of this procedure is better than 1 percent for computing flux from intensity at zero rotation velocity, for the parameters quoted. The accuracy can be improved to any desired limit by increasing the resolution.

7. ROTATION OF VEGA AND SIRIUS

These stars have quite significant projected rotational velocities that blend the lines and greatly complicate the analysis. We have been collaborating with Ingemar Furenlid at Kitt Peak and with John Lester at SAO to obtain high-resolution, low-noise spectra in the visible. Through visual examination of 1 A/nm plates taken by Furenlid, we estimate velocities of 15 to 20 km/s for Sirius and 25 to 30 km/s for Vega. These spectra have not yet been reduced so we have assumed velocities of 15 and 25 km/s in our calculations thus far. The zero velocity and rotationally broadened spectrum for Vega is shown in Figure 4 and for Sirius in Figure 5. The observed Copernicus spectra suggest a velocity somewhat larger than 15 km/s for Sirius and seem consistent with 25 km/s for Vega.

We have also undertaken a project with Wesley Traub, Nathaniel Carleton, and John Lester of SAO to measure a Ba II line profile in Sirius with a high-resolution interferometer. Since the project was begun before we found that Sirius has a high rotation velocity, we had hoped to determine both a rotation velocity and a maximum turbulent velocity. The reductions have not yet been completed, but we provisionally find a rotation velocity of 17 km/s.

8. THEORETICAL LINE LIST

One of the aims of this research is to check the available line data for accuracy and completeness and to identify areas where further work is required. Our basic source of these data is the KP line list, which was computed, for sequences up through nickel, by using scaled Thomas-Fermi-Dirac wavefunctions and eigenvectors found through least-squares fits of eigenvalues to observed levels (Kurucz, 1973). Heavier elements and the lightest elements were taken from the literature. The data published by KP represent only a fraction of the lines calculated, those between known levels. There are many lines between predicted levels that cannot be used for spectrum synthesis because the wavelengths are uncertain, but which can be used in computing the statistical distribution functions for the model atmosphere calculations.

We emphasize that spectroscopic analyses of many elements leave considerable room for improvement. There are levels that have not been classified, and so cannot be included in a gf calculation, and there are levels that are misclassified. Most important, many analyses are highly incomplete. Several of the iron group second spectra have not even been observed in the vacuum ultraviolet. We expect such lines account for a number of unidentified features in the Copernicus spectra.

Through examination of Kelly and Palumbo's (1973) line list and the ultraviolet multiplet table (Moore, 1962) we have found one prominent example of the incompleteness of KP. Multiplet 56 of Mn II is not in the list because the upper term has not been classified and so could not be computed. Kelly and Palumbo list a number of weak lines that have not been classified and do not appear in KP.

Thus far we have identified two sorts of errors in the KP line list through the presence of identifiable observed lines where the line list predicts none, and through the presence of a prominent predicted feature where none is observed. Several C II, N III, and Si II transitions involving sp^2, and several O I, Si II, and S I transitions involving an excited parent, are missing, presumably through programing mistakes. These errors may also occur in other elements that have not yet been checked.

Fortunately, these strong lines appear in the NBS compilations (Wiese, Smith, and Glennon, 1966; Wiese, Smith, and Miles, 1969; Wiese and Glennon, 1972). We have also found a few excited, LS forbidden, C I and N I lines that are computed too strong. Apparently the eigenvector mixing was overestimated.

In general, we assume that laboratory gf values based upon lifetime measurements are more reliable than KP. We are undertaking to replace KP data with such data, especially from the NBS compilations. However, we expect KP to be more accurate than NBS coulomb approximation f values and to give better relative strengths within multiplets than NBS LS multiplets.

We are also undertaking to include radiative and Stark damping constants for the stronger lines. At the present time we are filling in transition arrays and summing A's by hand to get the radiative damping constants. Programs are under development that will produce the radiative damping constants for every transition of an element. The sources used thus far for Stark broadening are Sahal-Brechot and Segre (1971) and Griem (1974). To use Griem's widths we compute

$$\Gamma_s/N_e = 3767\ W/\lambda^2$$

with width W at 10,000 or 20,000 K and wavelength λ in A. We have not yet included all Griem's data.

We expect to publish, either as part of this work, or as a separate publication, tables of these revisions.

9. COMPARISON OF THE SPECTRA

Figures 6 and 7 show the current theoretical and observed spectra for Vega and Sirius normalized as discussed in Section 10. Figures 8 and 9 are the same plots with identifications for all theoretical lines with zero rotation residual fluxes less than 0.99 in Vega and 0.98 in Sirius. In calculating the spectra the 9400, 3.95 and 10,000,4.3 models described in Sections 3 and 4 were used. In Vega the carbon abundance with reduced from -3.48 to -3.8. A microturbulent velocity of 2 km/s was assumed for the time being.

Since improvements and corrections to the program and line data are an ongoing process, the current plots are the result of a long series of iterations. Except for the abundance changes described in Sections 3 and 4 and below, no attempts have been made to adjust individual lines for a match. The fit is remarkably good for Vega. For Sirius a number of lines match very well but the majority of the lines are grossly underestimated in the calculations. No fourth spectrum or higher lines appear in either the calculations or the observations. In the discussion of individual elements below we assume that the gf values and damping constants are correct. (We use the terms weak and strong to refer to the comparison, calculation relative to observation, not to the strengths of the lines.)

Hydrogen. There is background Lyman α wing but the Vega data are too noisy and the match in Sirius is not good enough to draw any conclusions at this time.

Helium, Lithium, Beryllium, Boron. There are no lines in this spectral region.

Carbon. The C I resonance lines at 132.9 are computed too strong in Vega but match well in Sirius. The lines around 131.1 from the ^1D lower level are blended in features that are calculated too weak. The continuum in this region arises from the ^1S level. The C II resonance lines at 133.5 are computed with approximately correct cores. The wings are not right in Vega but there may be lines present in the noise. A C III line at 130.870 does not appear in the spectra. Since C is mainly C II we would expect the C II lines to be more reliable abundance indicators, and the C I lines to be much more sensitive to atmospheric variations. For abundances other than -3.8 in Vega and -4.0 in Sirius the C II lines are discrepant.

Through personal conversations with M. A. J. Snijders of Goddard, we found that his non-LTE calculations predict increased ionization of C I in Vega and LTE in Sirius. Thus the C I lines would become weaker in Vega without significantly changing the C II lines. The strength of the continuum would also be reduced.

Since we expect Vega to have solar abundances, the solar abundance of C may be overestimated by a factor of 2. Such a result has been found by Mount and Linsky (1975) through analysis of solar molecular features. Sirius is depleted in C by 0.2 in the log relative to Vega.

Nitrogen. There is an isolated N I doublet at 131.967 that is a good match. The blended features at 131.89 and 130.00 are difficult to interpret. N II lines at 134.3, 134.5, and 134.6 do not appear in the predicted spectra, but there are features in the observed spectra. N III lines do not appear. The N abundance is equal and approximately solar in both stars.

Oxygen. The O I resonance lines at 130.2, 130.4, and 130.6 are predicted too strong in Vega and approximately correct in Sirius. We have not yet determined the O abundance in Vega but we guess -3.5. Since we expect Vega to have solar abundances, we suggest that the solar abundance should be -3.5 instead of -3.22, which is currently assumed. In Sirius the abundance is approximately -3.22, a factor of 2 enhanced over Vega.

Fluorine. There are no F I lines in this region. The high excitation F II lines at 132.7, 132.8, 133.2, 133.3, 134.3, and 134.4 do not appear in the calculations, however, in some cases, observed features do correspond. The same situation applies to F III. We can say nothing about the F abundance.

Neon. There are no Ne lines in this region.

Sodium. There are no Na I lines in this region. Na II and III lines do not appear in either spectrum.

Magnesium. There are no Mg I lines in this region. In Vega, the Mg II lines match at 130.67 and 130.82, are too strong at 130.78, and are blended at 130.94. In Sirius, 130.67 matches while 130.78 and 130.82 are slightly strong. Mg III lines do not appear. The Mg abundance is approximately solar in Vega and +1.0 in Sirius.

Aluminum. There are no Al lines in this region.

Silicon. There are no Si I lines in this region.

Si II:	130.08	weak
	130.43	blend, strong
	130.56	blend, good
	130.9	blend, good
	134.68	Vega, slightly strong; Sirius, strong
	134,85	Vega, slightly strong; Sirius, strong
	135.0	strong
Si III:	130.11	slightly strong
	130.33	blend, strong
	131.25	weak?
	134.24	blend
	134.33	blend

The Si abundance in Vega is approximately solar and in Sirius at least +1.0. The models predict the correct ionization.

Phosphorus. The P I line at 130.447 is blended. P II lines at 130.18, 130.46, 130.54, 130.98, and 131.07 are blended in such a way that one can tell the lines are approximately the right strength. Of the P III lines, 133.48 is blended and, in Sirius, blended and strong, 134.43 is blended and strong, 134.49 possibly matches. The wavelengths are discrepant. Other lines do not appear in either star. The P abundance is approximately solar in Vega and +1.0 in Sirius. The models predict the correct ionization.

Sulfur.

S I:	130.23 blend	131.32 blend, good
	130.28 blend, slightly strong	131.65 slightly strong
	130.31 blend, slightly strong	132.35 slightly strong
	130.34 blend, slightly strong	132.66 blend, slightly strong
	130.58 blend, good	133.37 blend, strong
	131.01 blend, good	

There are no S II lines in this region. S III lines do not appear in the spectra. The sulfur abundance is approximately solar in Vega and +1.0 in Sirius.

Chlorine. The Cl I line at 133.57 is blended. The line at 134.72 is slightly weak. There are no Cl II or III lines in this region. The Cl abundance is approximately solar in Vega and +1.0 in Sirius.

Argon. There are no Ar I lines in this region. There is an Ar II line at 134.72 that does not appear in the predicted spectrum for Vega but does weakly in the predicted spectrum for Sirius. There is an observed feature in both stars at this wavelength that is stronger in Sirius. These lines are highly excited and would be very sensitive to temperature changes. There are no Ar III lines in this region. We can draw no conclusions about the abundance of Ar.

Potassium. There are no K lines in this region.

Calcium. There are no Ca I lines in this region.

Ca II:	130.56 masked
	132.98 blended, strong in both stars
	133.09 match in both
	134.18 slightly weak in both
	134.25 blend, slightly weak in Vega, matches in Sirius

Ca III lines do not appear in the predicted spectra. There is an unidentified feature at 133.74, which is the wavelength of one of the lines. The Ca abundance is approximately solar in Vega and +1.0 in Sirius.

Scandium. There are no Sc I or III lines in this region. Sc II lines have not yet been observed in this region.

Titanium. There are no Ti I lines in this region. Ti II lines have not yet been observed in this region. Ti III 132.75 matches in both stars, 132.98 is blended, and 133.96 is noisy in Vega and matches in Sirius. The Ti abundance is approximately solar in Vega and +1.0 in Sirius.

Vanadium. There are no V I lines in this region. There are six V II lines that are masked, blended, or insignificant. A feature is observed in Sirius at 131.38, but the calculated feature is much weaker. There are a dozen V III lines but they are all masked, blended, or insignificant. We can say nothing about the V abundance.

Chromium. There is no Cr I in this region. Cr II has not yet been observed. The relative strengths of Cr III lines are the same in both stars but many of the lines are very noisy in Vega.

Cr III:	131.15 blended, masked	132.16 blend, weak
	131.40 very weak	132.28 weak
	131.54 masked	132.84 very weak
	131.64 blend, slightly strong	133.15 blend, weak
	132.00 very weak	133.77 weak

Either Cr has a greatly enhanced abundance or there is some error in the models that produces the wrong ionization for Cr III.

Manganese. There are no Mn I lines in this region.

Mn II:	130.10 blend, strong in both stars
	130.67 blend
	133.15 blend, weak
	134.43 blend, strong
	134.56 weak

The gf values for multiplet 56 could not be computed by KP but the lines are present in the observed spectra,

130.56 masked
131.34 masked
131.37 present in both stars, stronger in Sirius
131.73 may be present in blend
131.77 present in Sirius, not apparent in Vega
131.80 present in both stars, stronger in Sirius.

The Mn III line at 134.76 is very weak. We can draw no conclusions about the Mn abundance.

Iron. There are no Fe I lines in this region. There are numerous Fe II and Fe III lines. We get the impression that many features observed in Sirius correspond to Fe III lines that are weak in the calculated spectrum. It is possible that this is a coincidence because there are so many lines. In Vega, the noisiness and questions about the normalization level make the comparison difficult for many of the weaker features. In Vega there are a number of Fe II lines that seem to match so we guess that the abundance is approximately solar. In Sirius those lines are predicted slightly weak which may indicate an Fe abundance increase greater than 1.0. There seem to be problems with ionization and Boltzman factors.

Cobalt. There are no Co I lines in this region. The Co II lines at 130.69, 131.18, and 131.81 are weak in both stars. Other lines are masked or blended. The Co III line 132.68 is not seen in Vega and is predicted to be insignificant in Sirius. The Co abundance is greater than solar in Vega and greater than +1.0 in Sirius. The solar Co abundance may be underestimated.

Nickel. There are no Ni I lines in this region. There are numerous Ni II lines. The resonance lines at 130.88, 131.72, 133.52, and 134.58 match. Higher excitation lines are weak but correspond to many features. The Ni III lines are weak. There seems to be some ionization problem. If some way could be found to increase the strength of the weak Ni II and III lines the calculated spectra would fit much better.

Copper. There are no Cu I lines in this region. Cu II lines do not appear in Vega. Two lines, 130.39 and 133.18, are predicted as small in Sirius. No Cu III lines appear in any of the spectra.

Zinc. Zn I lines have not been observed in this region. The Zn II line at 130.6741 was not computed by KP but may be present in the observed spectra. All Zn III lines are insignificant or masked.

Elements heavier than the nickel sequence. Heavier elements were not computed by KP and gf values for lines in this region were not available from the literature so the line list does not predict any heavy lines in this region. An examination of Kelly and Palumbo (1973) and Moore (1962) does not produce any obvious identifications. Detailed searches will be made in the future.

Our overall impression is that there is a temperature problem with the models because resonance lines of lighter elements seem to match in all stages of ionization, while highly excited iron group lines are predicted too weak. Further work is required to determine whether temperature increases will resolve the discrepancy. Temperature changes in Vega cannot be very large because of the good fits with the strong lines and in the visible.

10. CALIBRATION OF COPERNICUS IN THE REGION 130 TO 135 nm

We have assumed that the wavelength dependence of the Copernicus sensitivity did not vary in the time between the observations of the two stars so the same relative shape applies to both Sirius and Vega. In plotting the spectra we overlaid the observations on the calculations and determined a relative shape and the number of counts at full scale required to force a match. Currently, the counts are 2400 for Sirius and 575 for Vega at 130 nm. The shape factor that converts from counts to energy is given in this table:

Wavelength	130 nm	131	132	133	134	135
Factor	1	1.0	1.0	1.1	1.1	1.2

The noisiness of the Vega spectrum and the large number of lines in the Sirius spectrum that do not match leave considerable room for subjective fitting. Since there are several places in Vega where the observed spectrum rises above the calculated spectrum, these numbers will probably be revised.

To determine the absolute calibration in ergs/cm^2/s/nm per count in U1, we use the angular diameters measured by Hanbury Brown, Davis, and Allen (1974). The flux at the earth is inversely proportional to the square of the distance,

$$\text{flux} = (R_*/D)^2\, 4\pi H_\lambda = (\theta/2/206265)^2\, 4\pi H_\lambda \quad ,$$

where θ is the angular diameter of the star in arc seconds. At 130 nm we find

	Sirius	Vega
θ	0.00589 ± 16	0.00324 ± 7 arc sec
H_λ, full scale	1.320E8	8.842E7 ergs/cm^2/s/ster/nm
U1 counts, full scale	2400	575
flux/count	1.41E-10	1.20E-10 ergs/cm^2/s/nm/count

11. FURTHER WORK

We expect to compute one or two more iterations of the Vega spectrum to determine the oxygen abundance and include additional damping constants. We also plan to check for non-LTE effects in C I using b's computed by Snijders and another spectrum synthesis program that we have developed to do non-LTE spectra. We need to make another iteration on Sirius with the additional damping constants and we will attempt to identify additional features. This additional research and this final report will be submitted to the Astrophysical Journal Supplement.

We will apply for additional observing time on Copernicus to obtain as much of the spectra of the two stars as possible, hopefully with lower noise in Vega. In fact, we believe that observations of Sirius and Vega are so important that Copernicus should be used to produce atlases for the two stars.

Since we are undertaking a detailed analysis of both stars in the visible as well as the ultraviolet, we think that detailed discussion of f values and individual abundances should wait until complementing observations from all spectral regions can be considered together.

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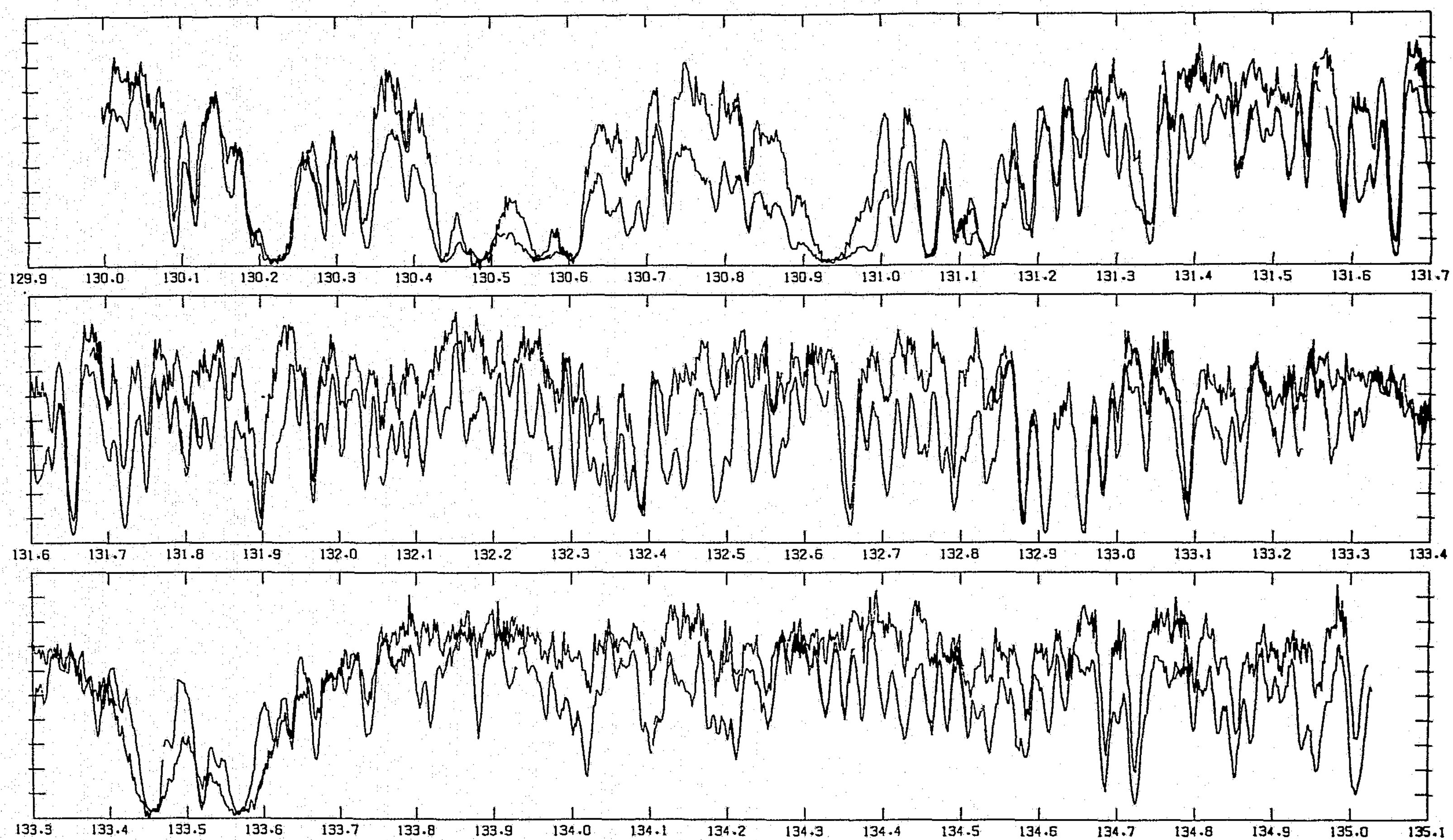


Figure 1. Copernicus Ul spectra of Vega and Sirius for the interval 130 to 135 nm. Sirius is the less noisy, generally lower curve. Full scale at 130 nm corresponds to 2400 counts for Sirius and 575 for Vega. Figures 8 and 9 show the individual data points.

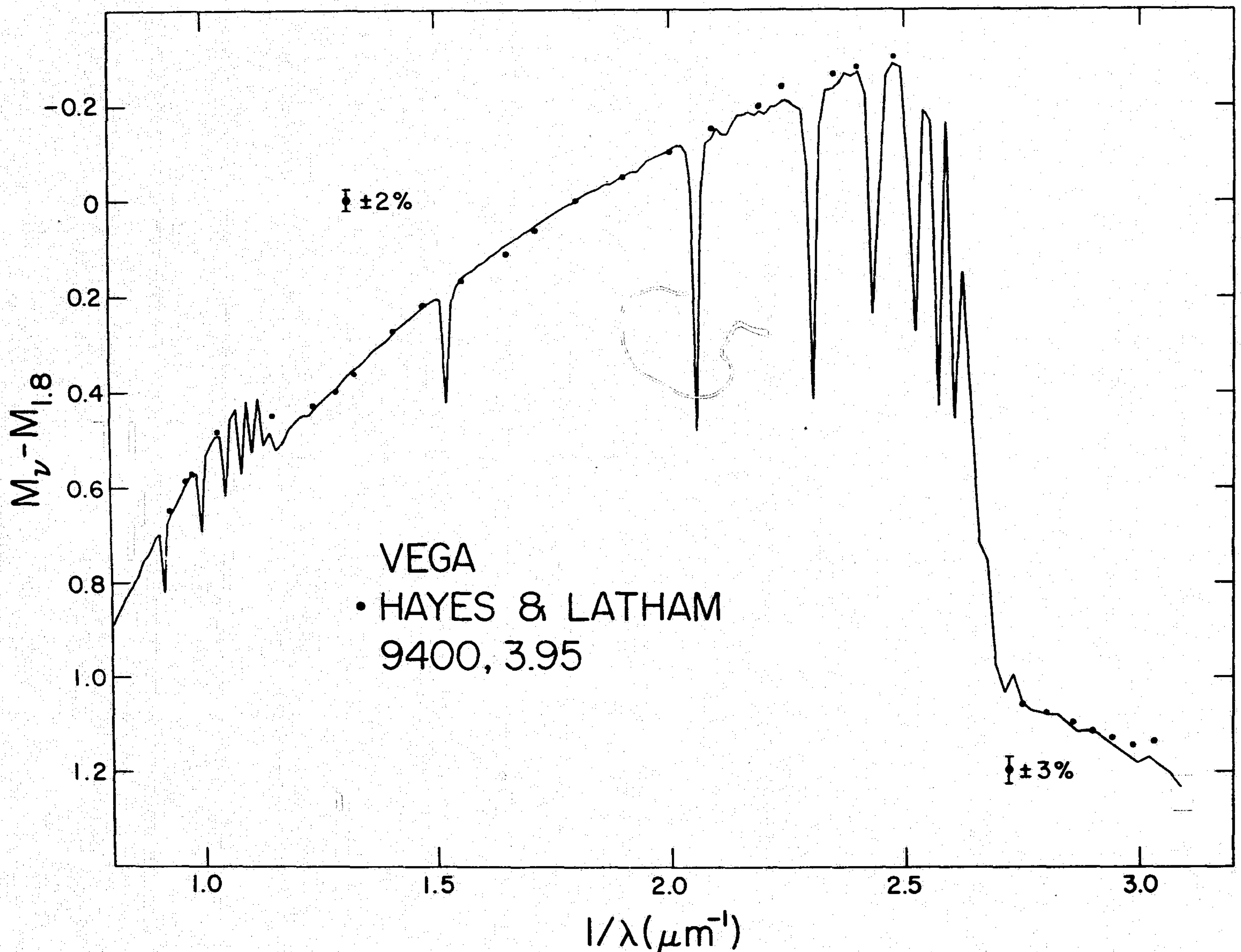


Figure 2. Comparison of the colors of the theoretical model with $T_{eff} = 9400$, $\log g = 3.95$ with the new Vega observations of Hayes and Latham (1975). Error bars for the observations are indicated.

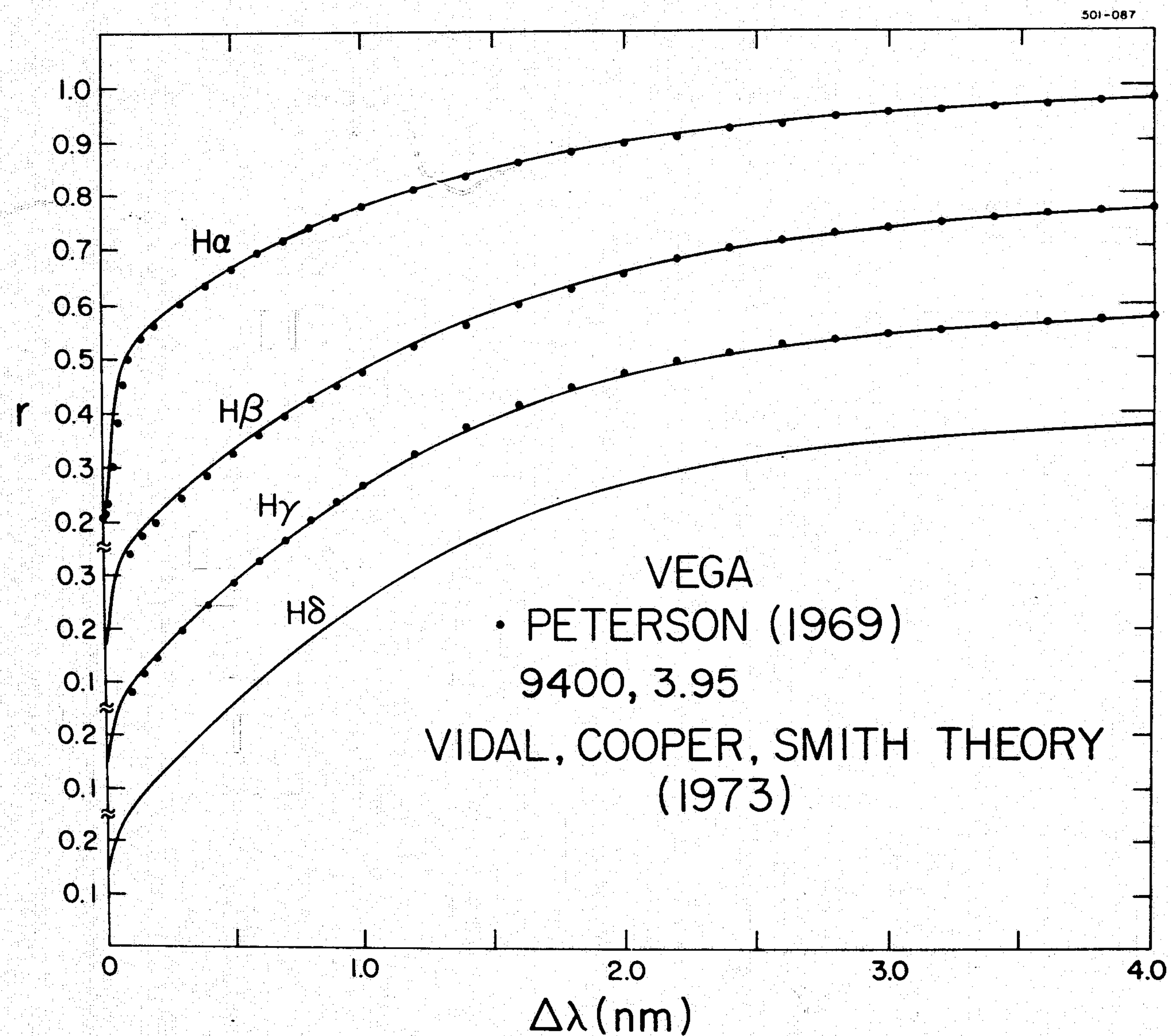


Figure 3. Theoretical Balmer line profiles for the same model compared with the observations of Peterson (1969).

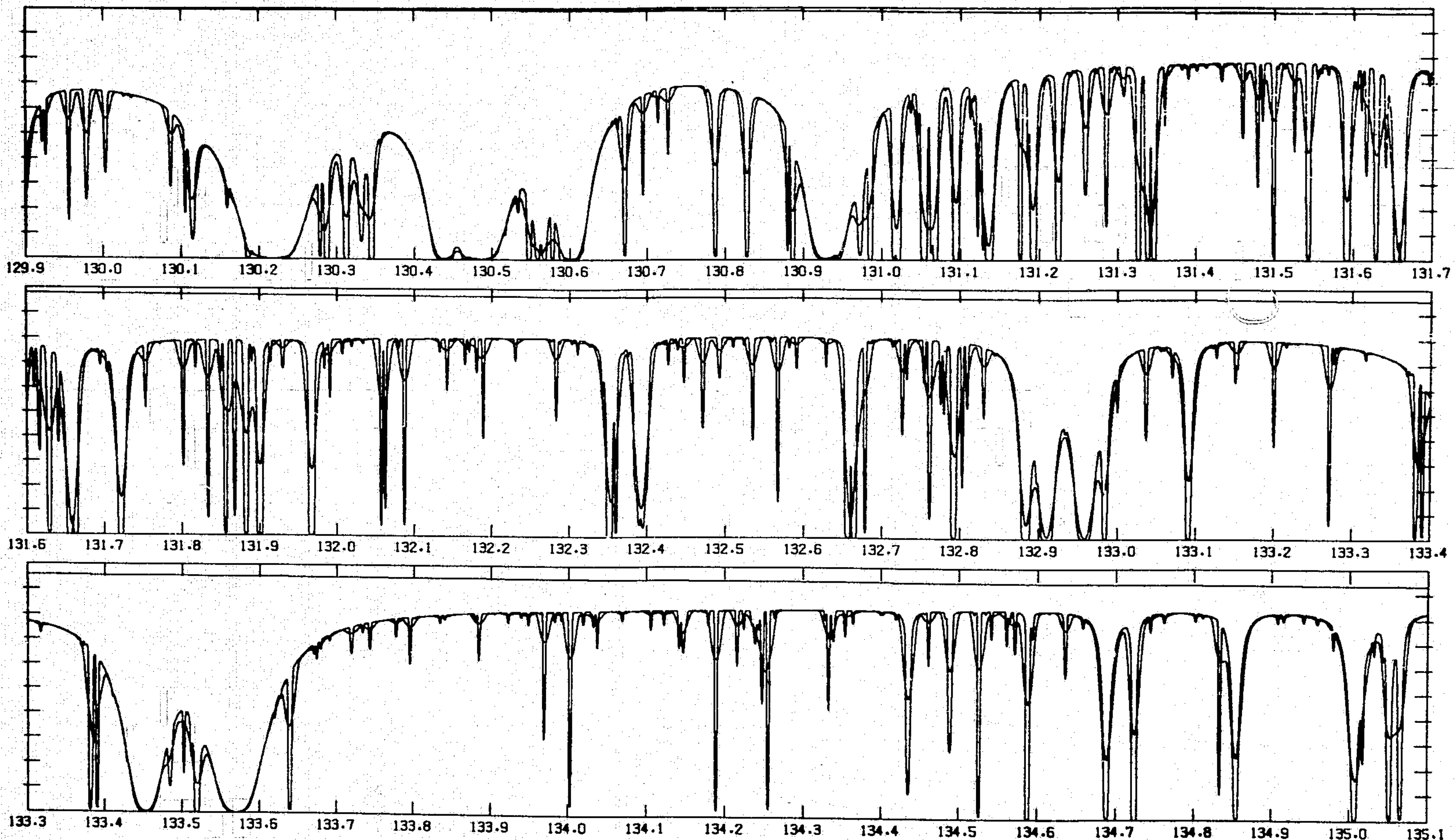


Figure 4. Calculated spectrum for Vega at 0 km/s and rotationally broadened to 25 km/s. The continuum is also shown. Full scale is 8.842E7 ergs/cm^2/s/ster/nm.

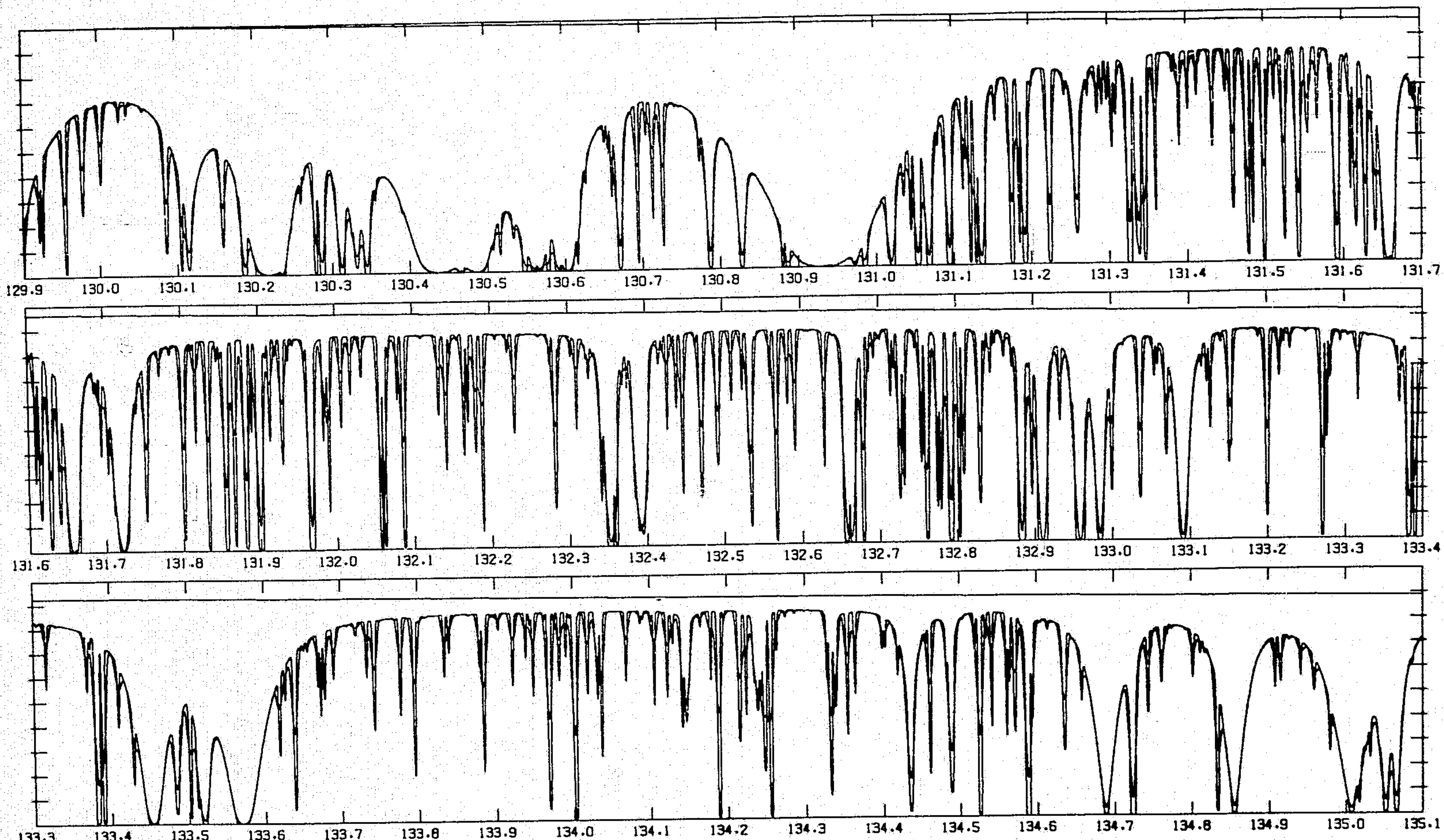


Figure 5. Calculated spectrum for Sirius at 0 km/s and rotationally broadened to 15 km/s. The continuum is also shown. Full scale is 1.320E8 ergs/cm^2/s/ster/nm.

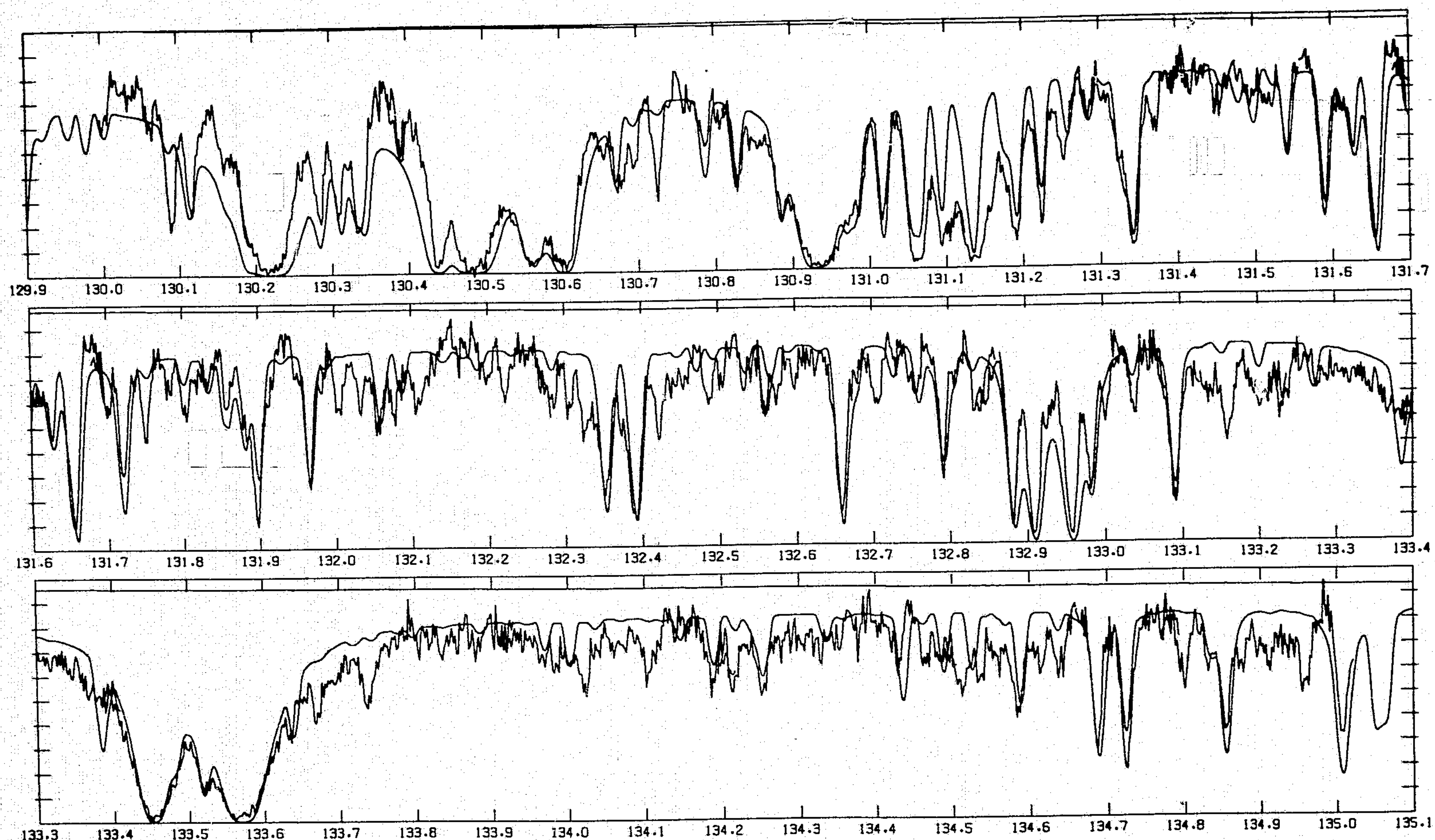


Figure 6. Calculated spectrum for Vega compared to the observations.

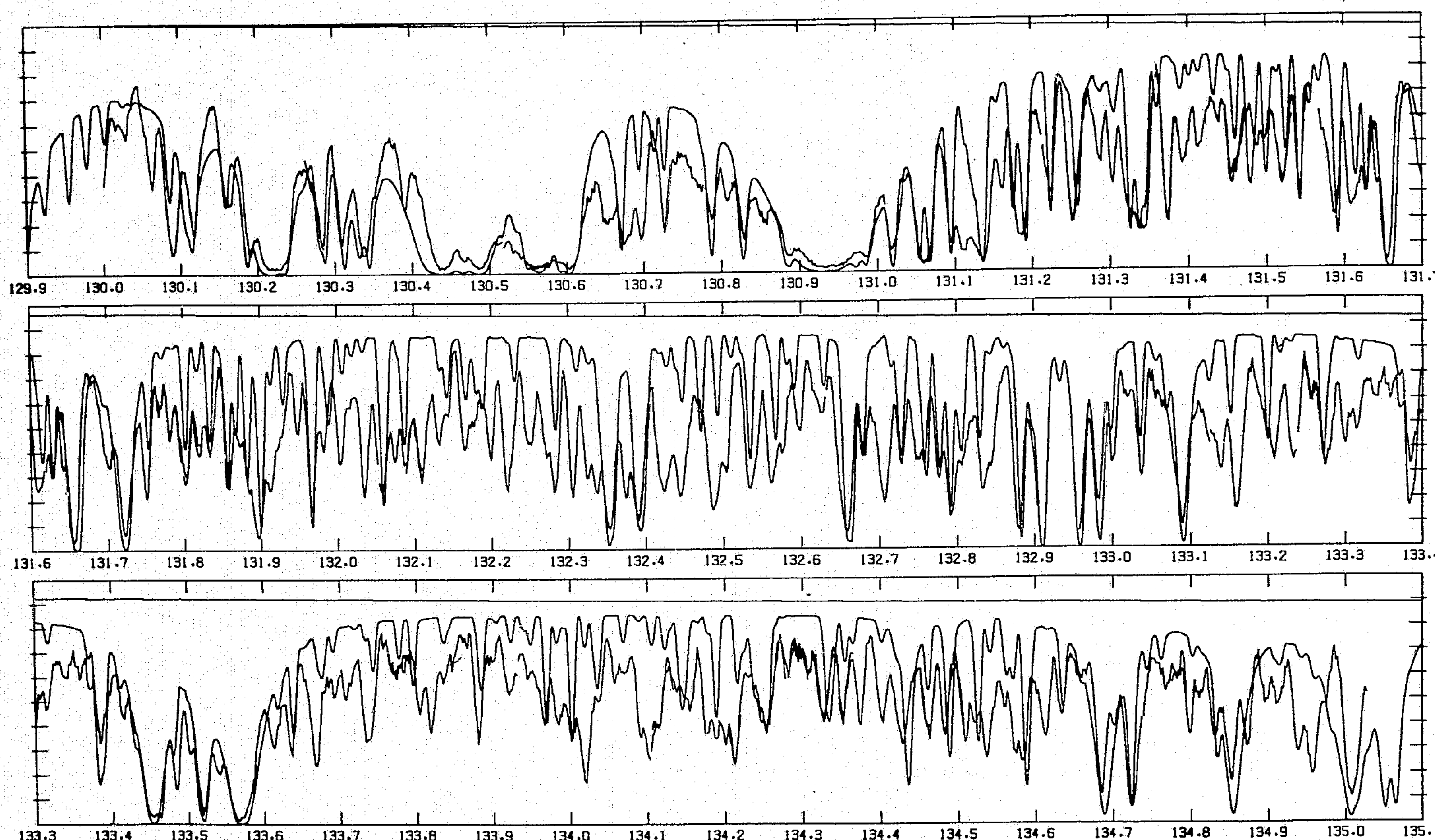
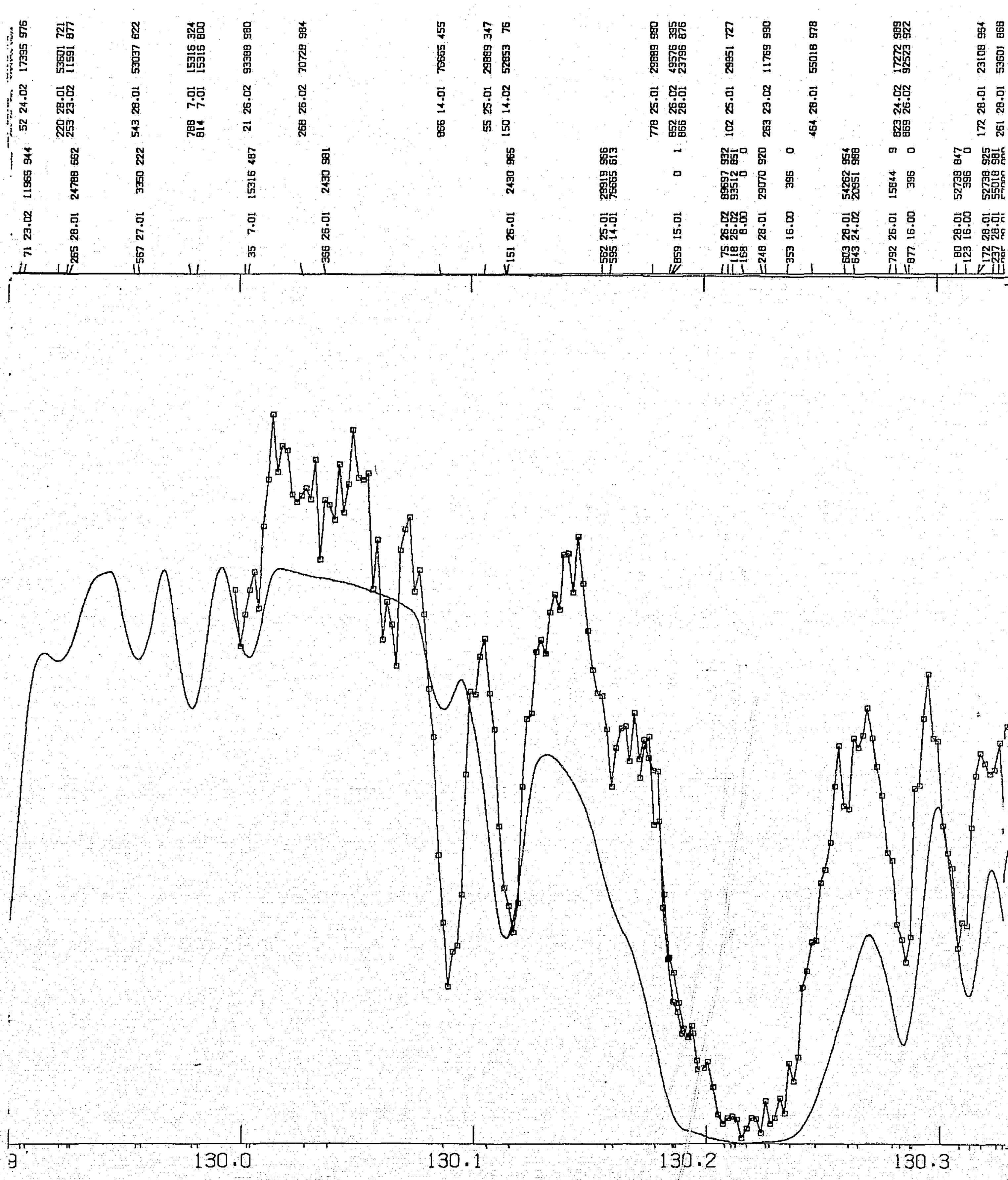


Figure 7. Calculated spectrum for Sirius compared to the observations.

Figure 8. Calculated spectrum for Vega compared to the observations with identifications. The labels consist of the last three digits of the wavelength, the symbol for the ion – atomic number plus charge, lower energy level in cm^{-1}, and the residual flux in per mil at line center in the unrotated spectrum.

Figure 8 (Continued)



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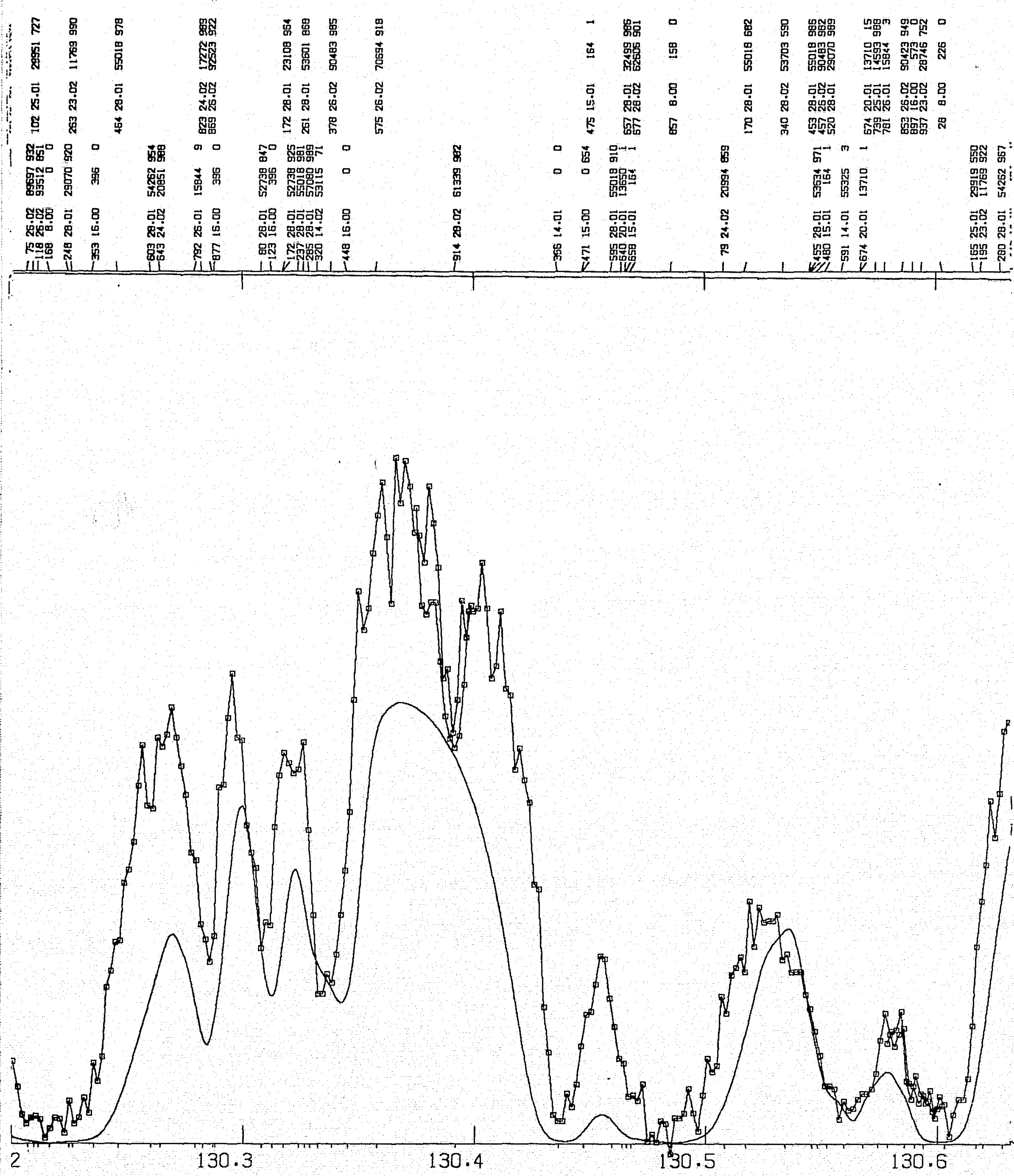

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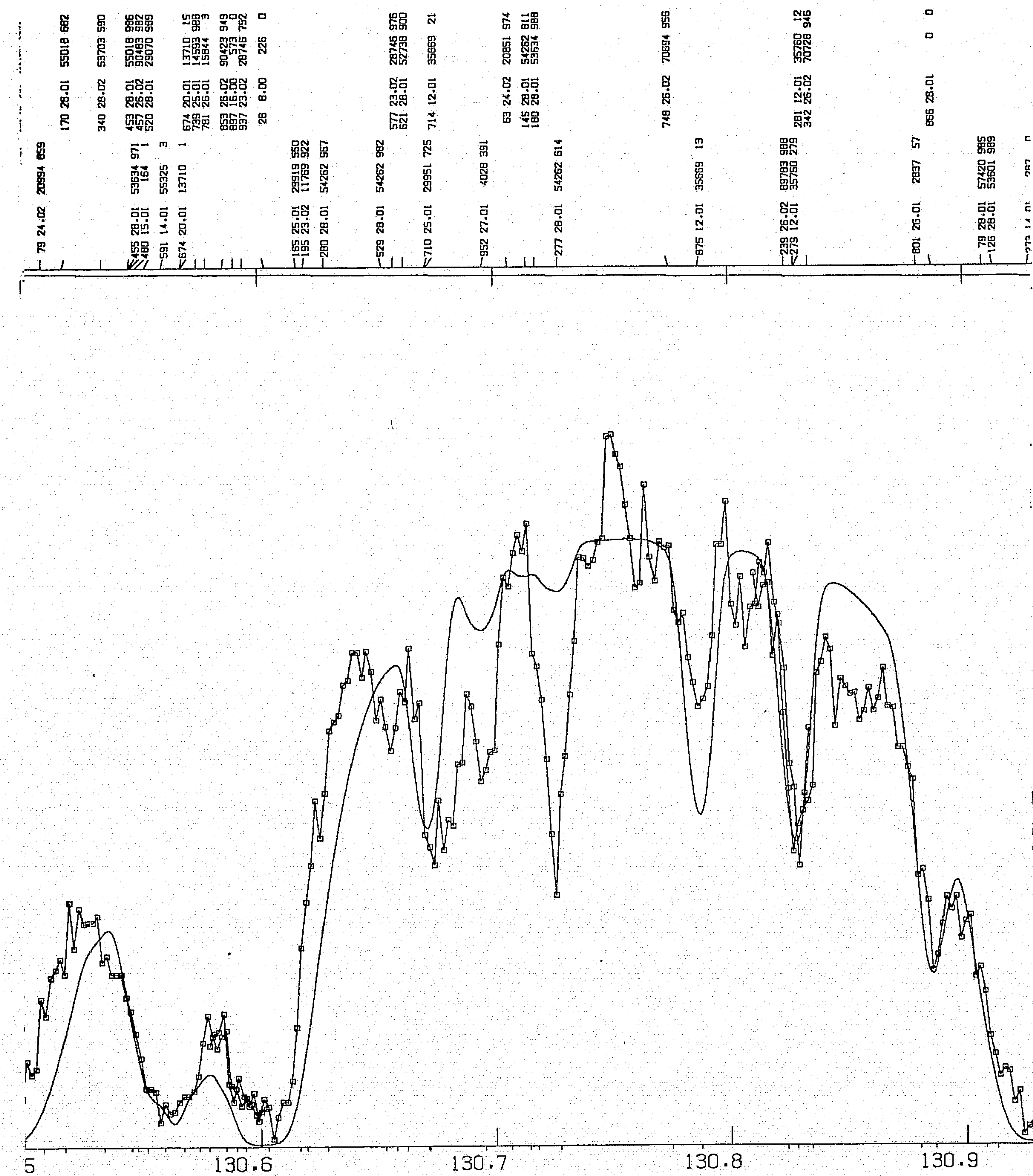

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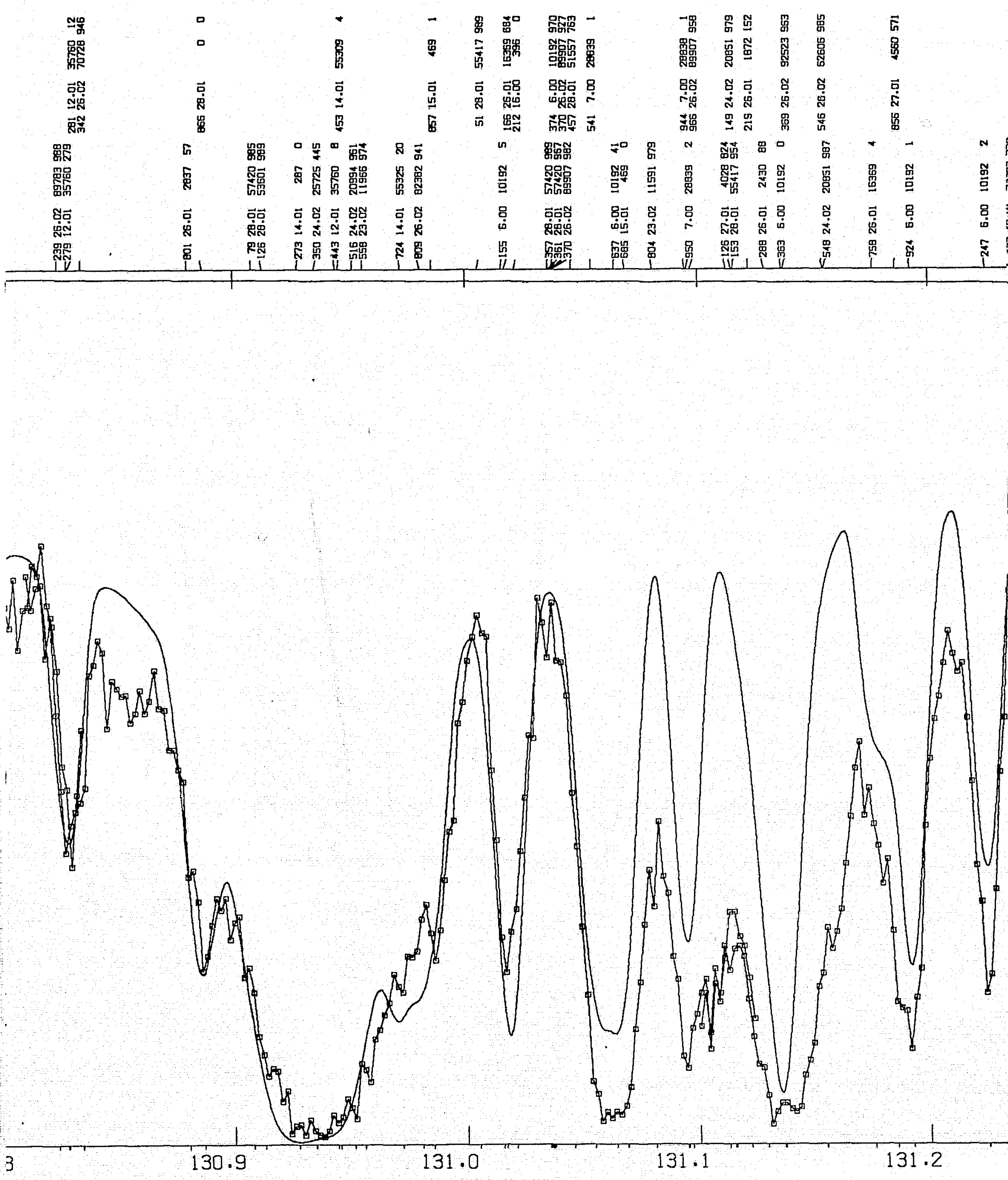

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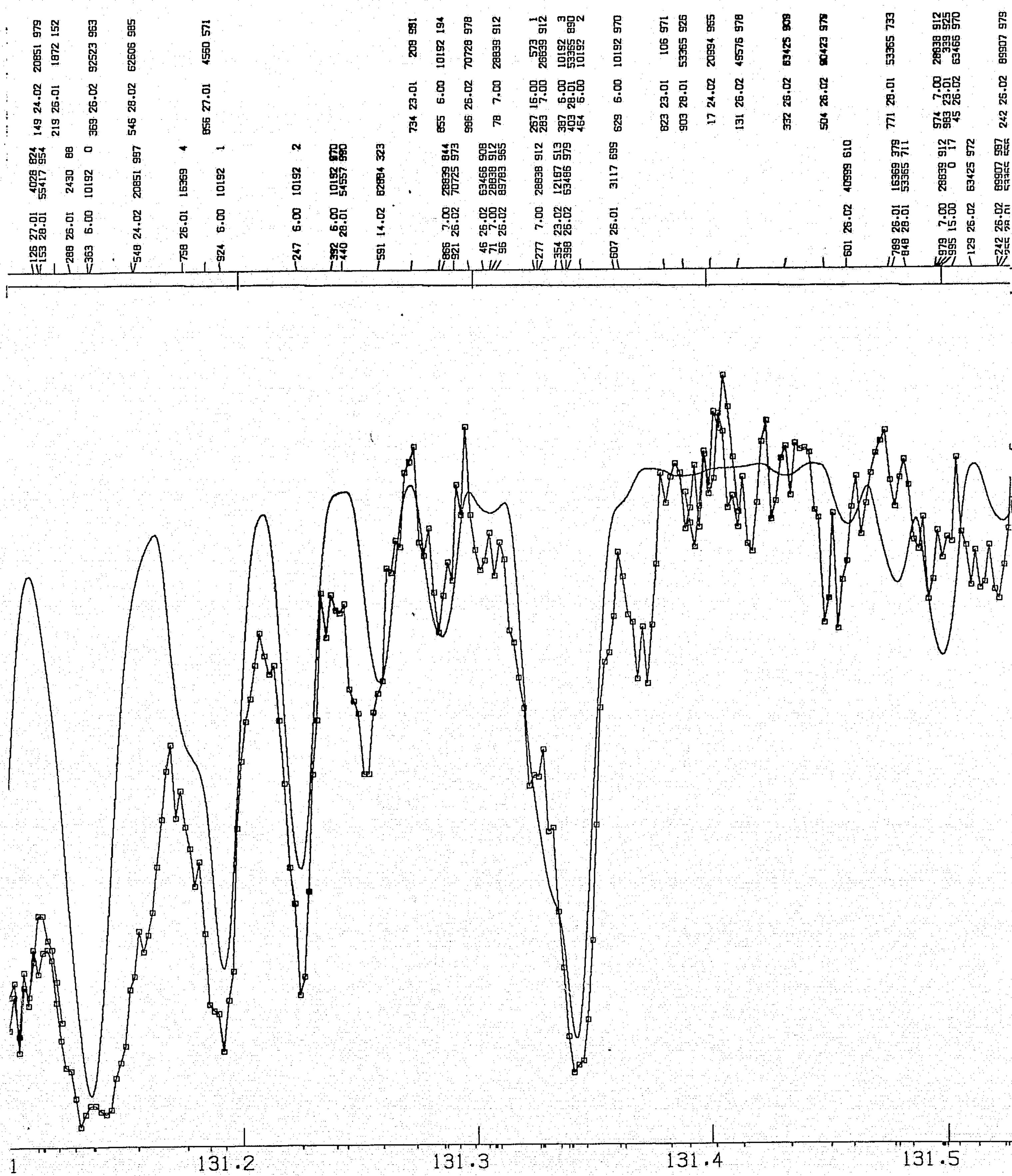

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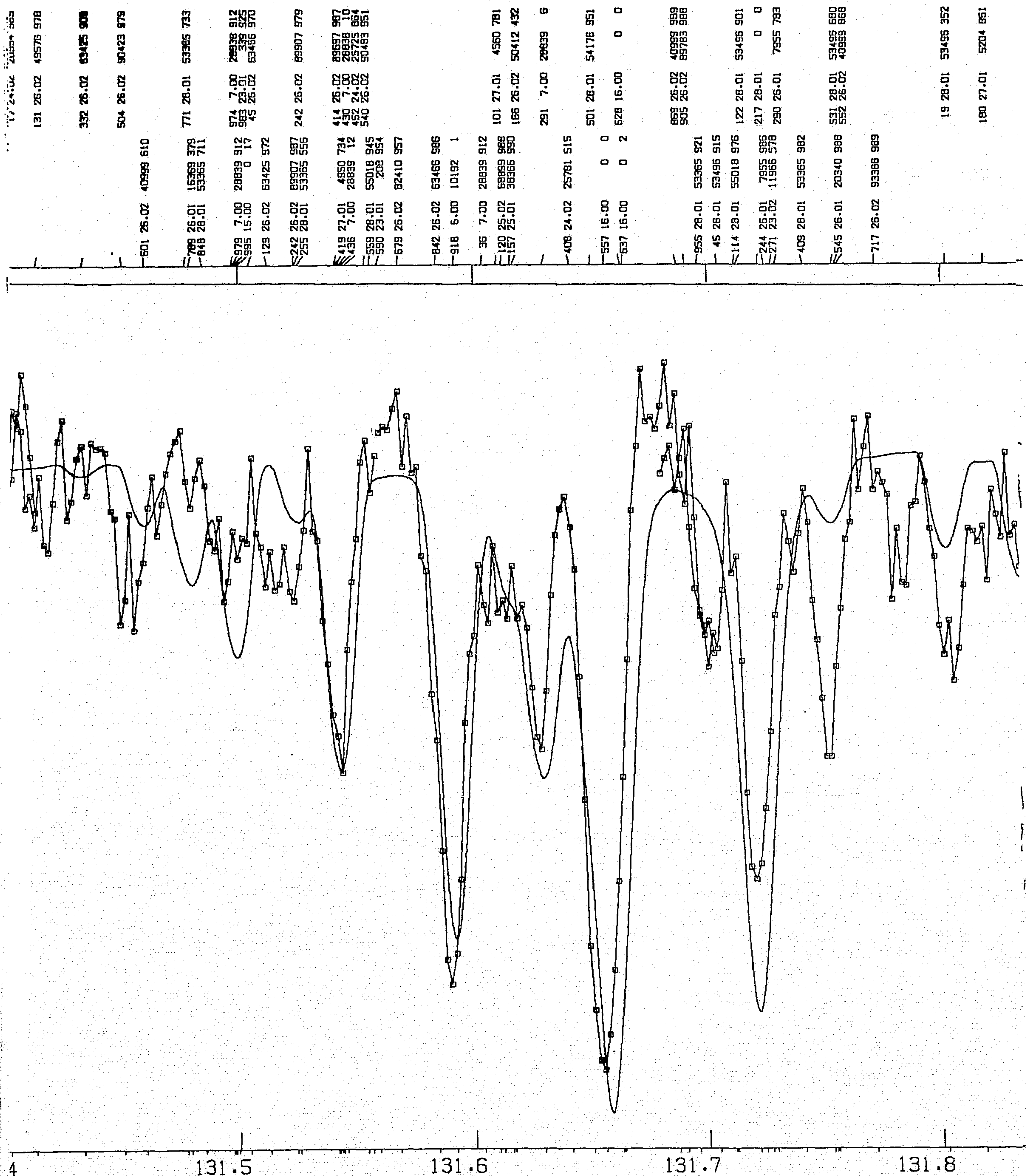

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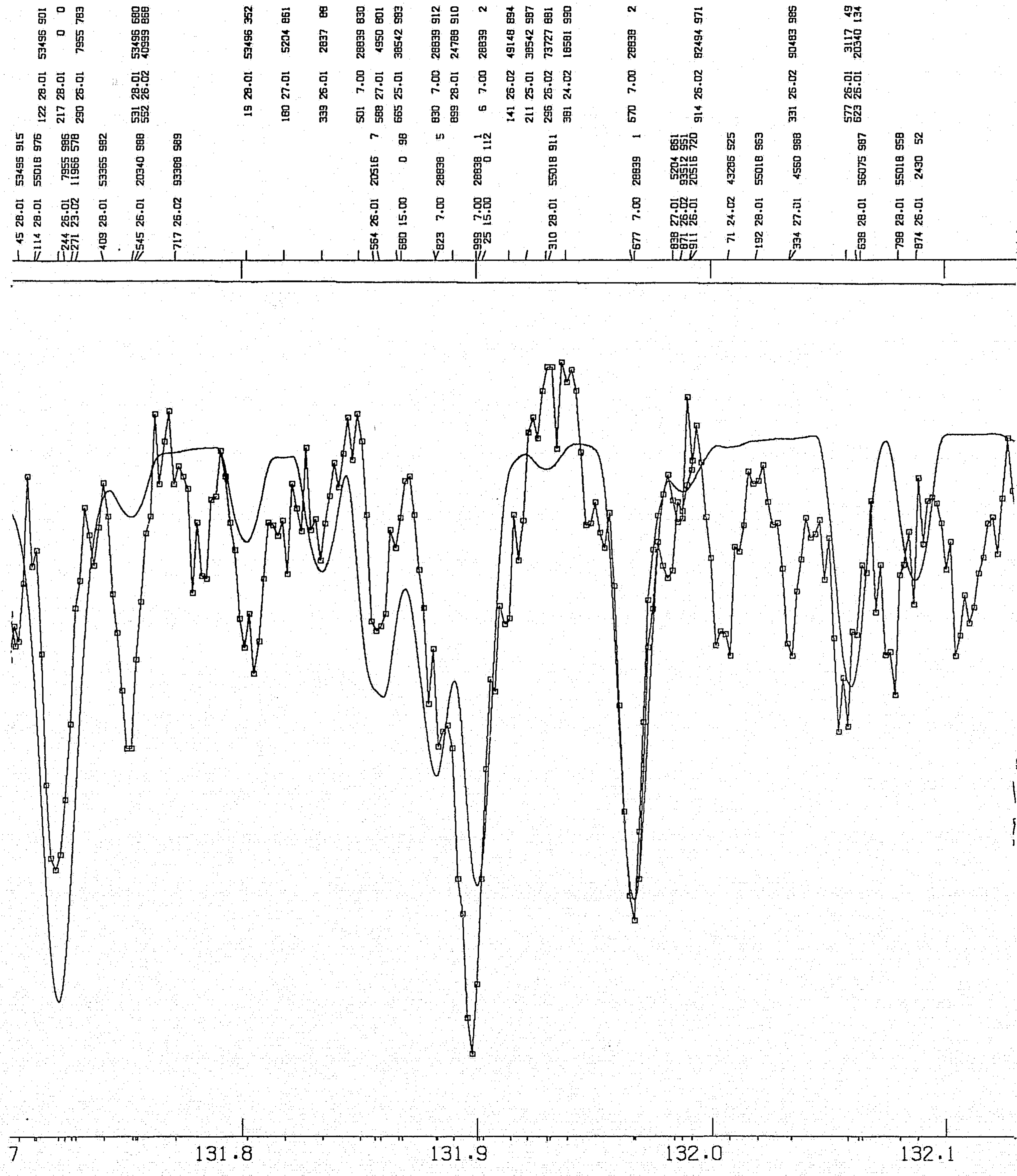

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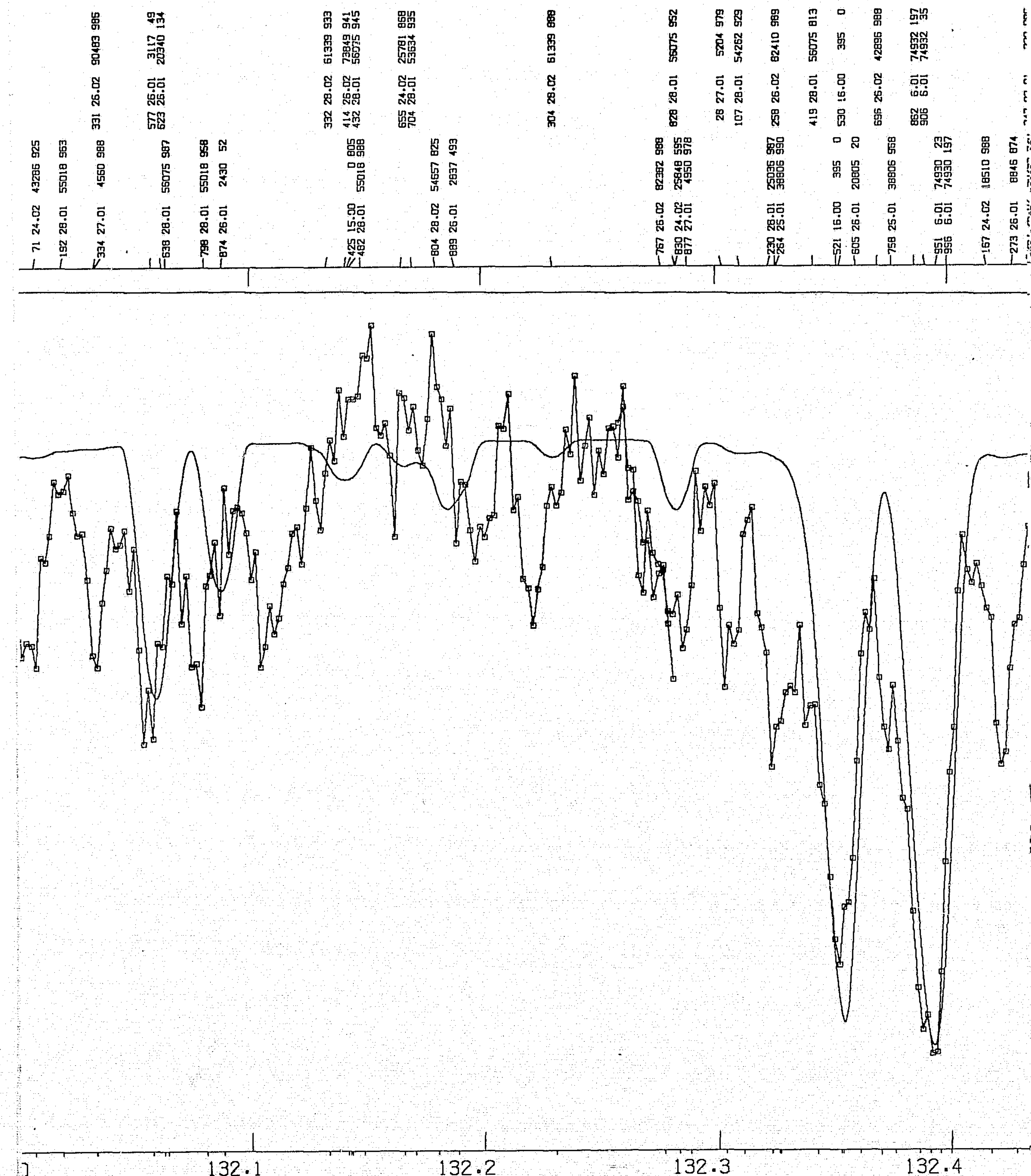

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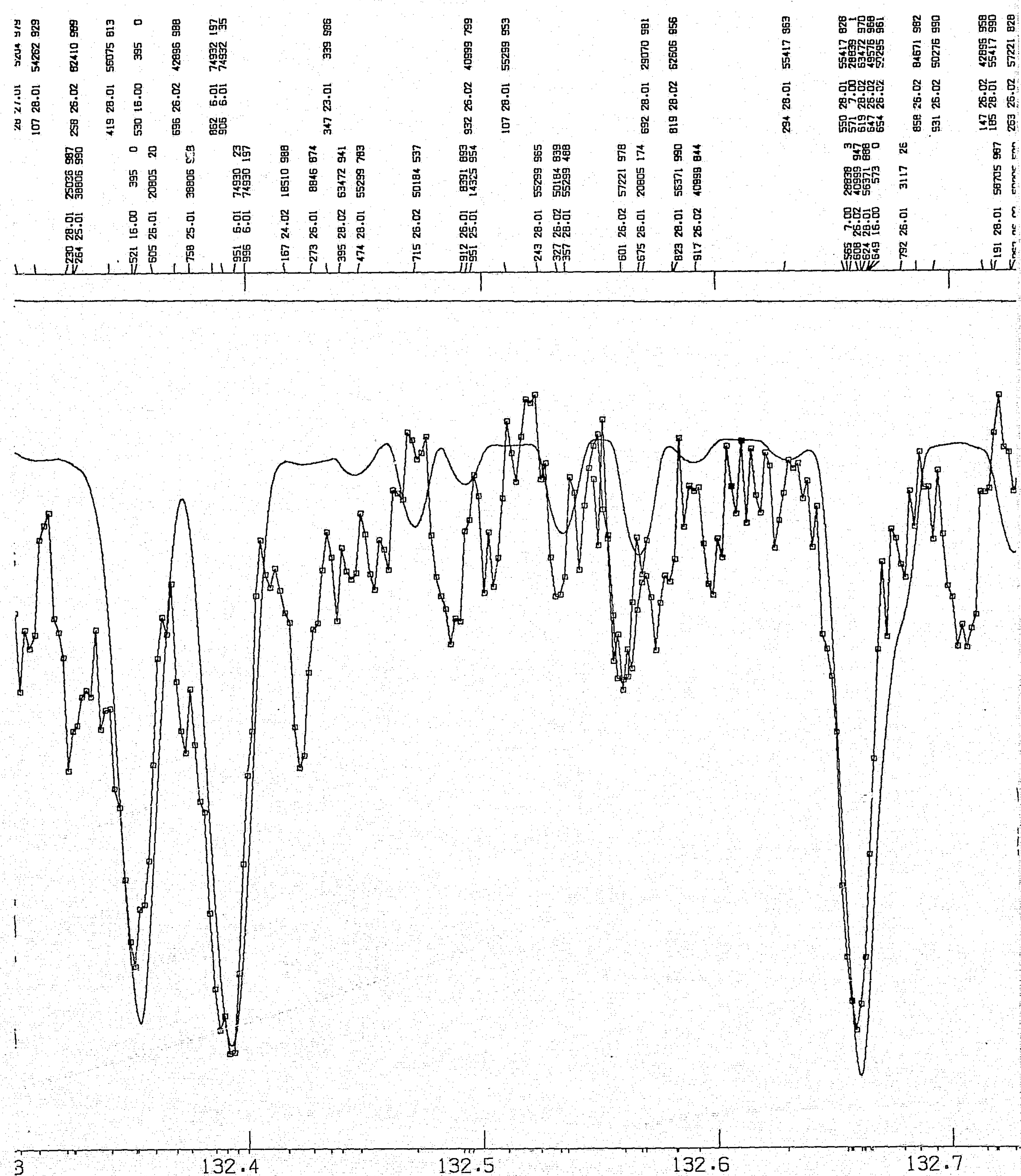

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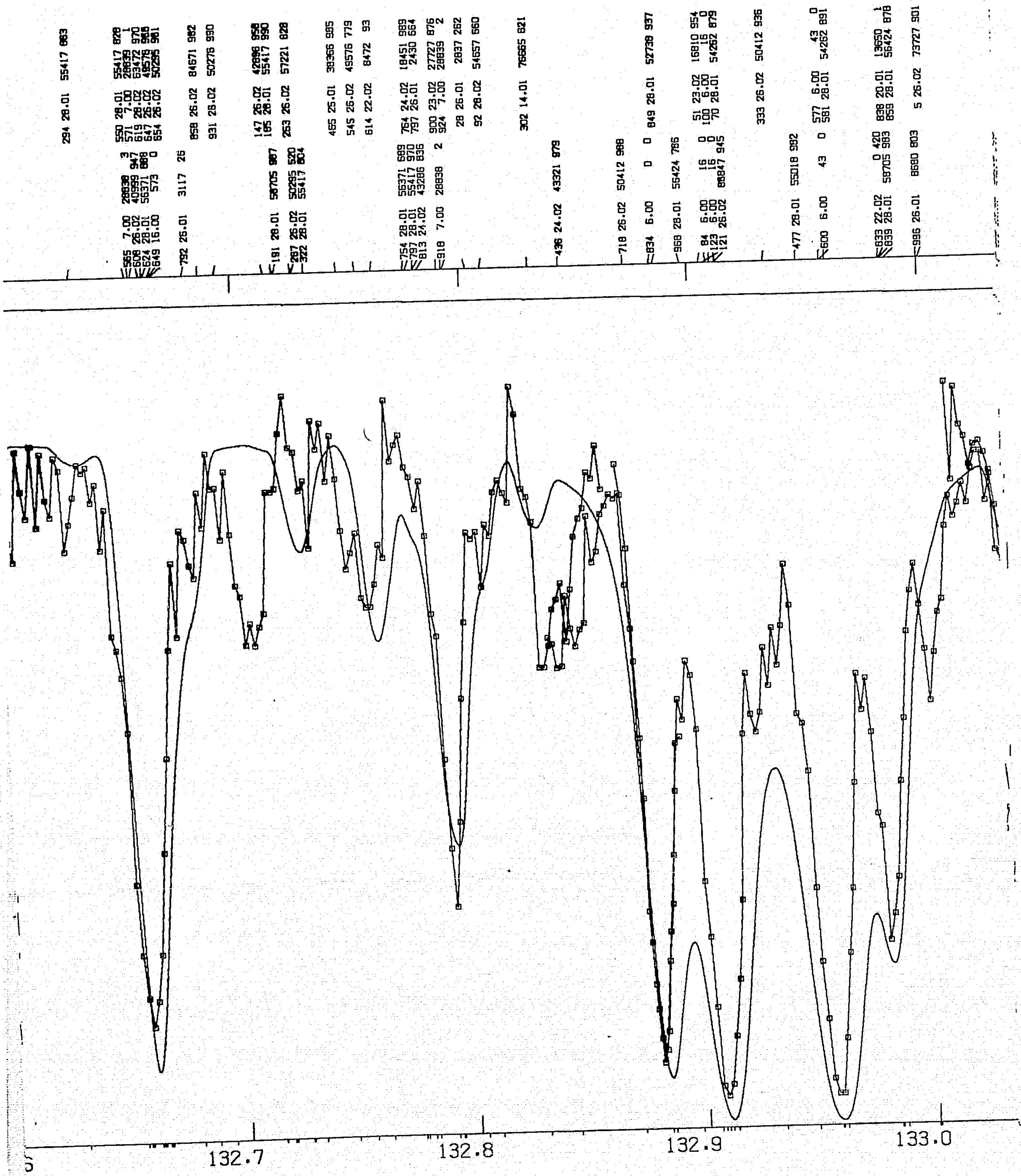

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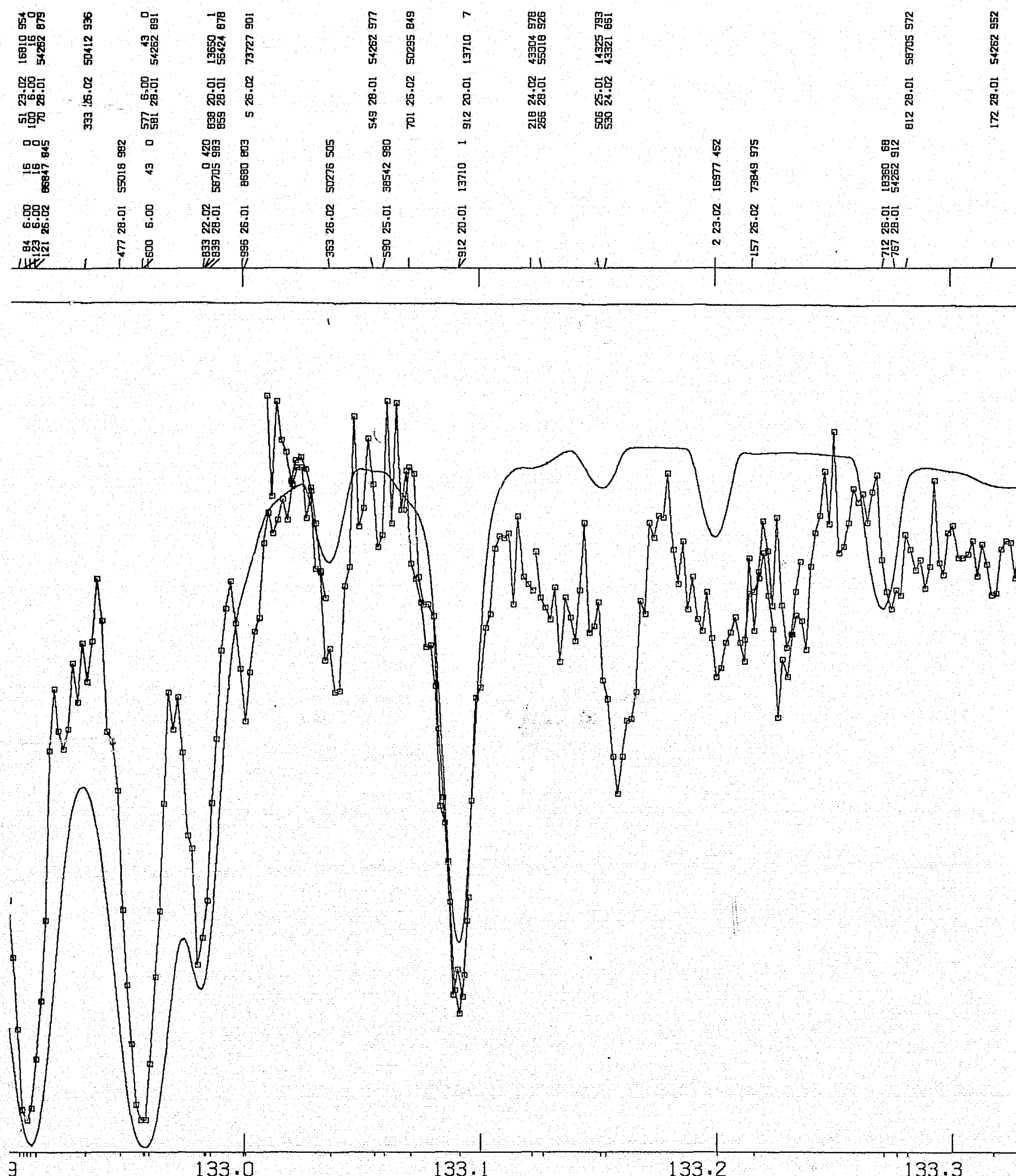

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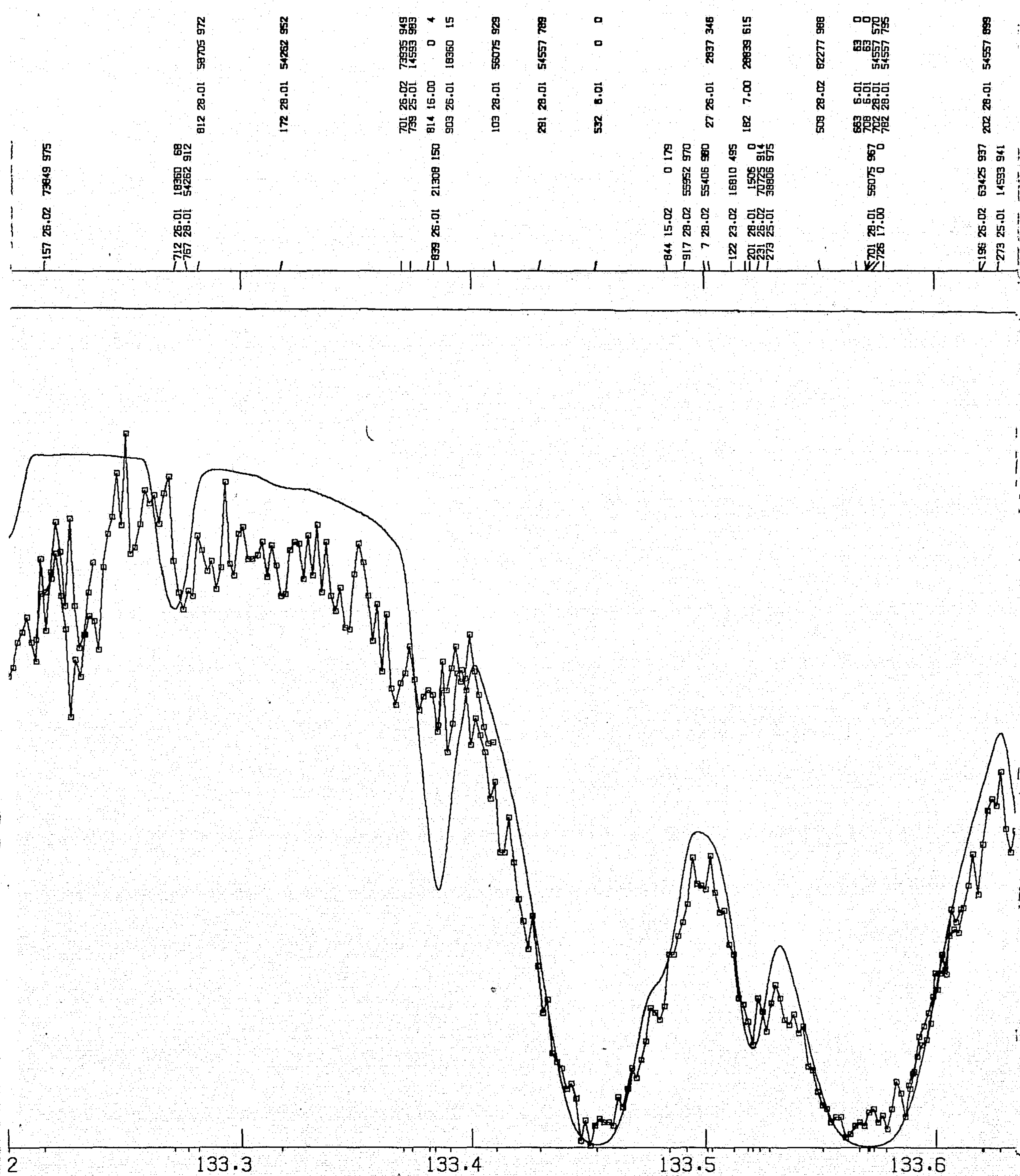

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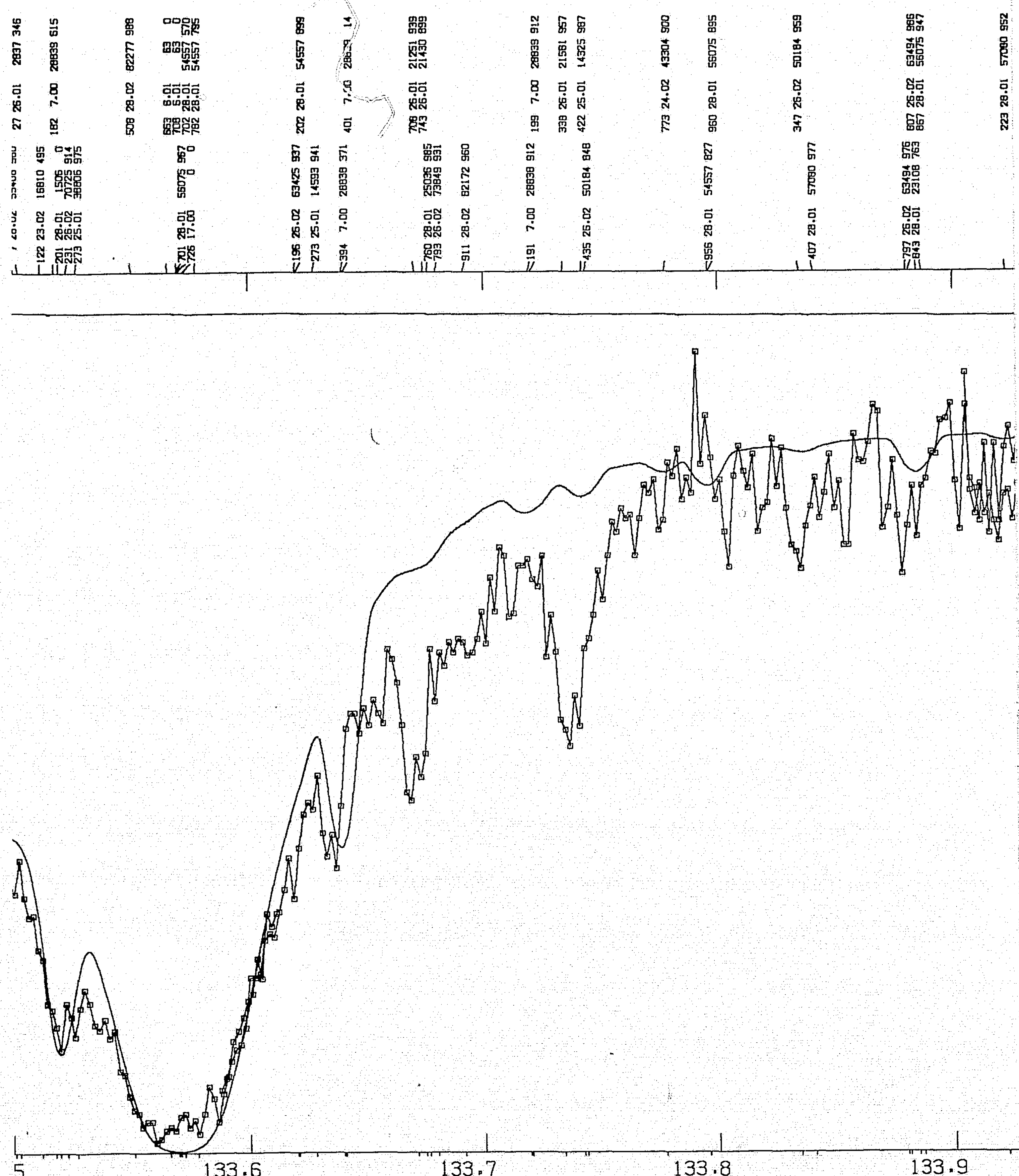

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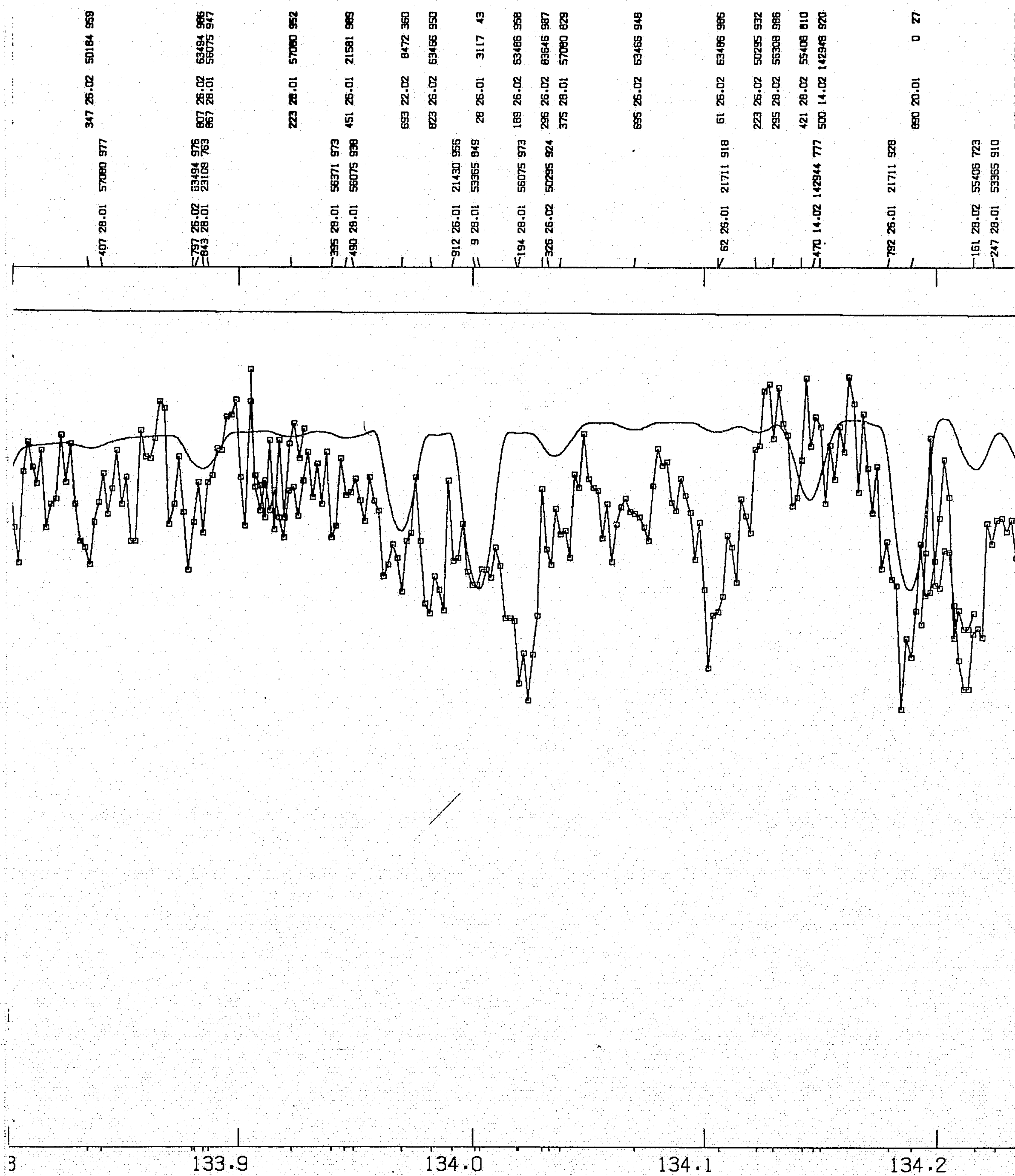

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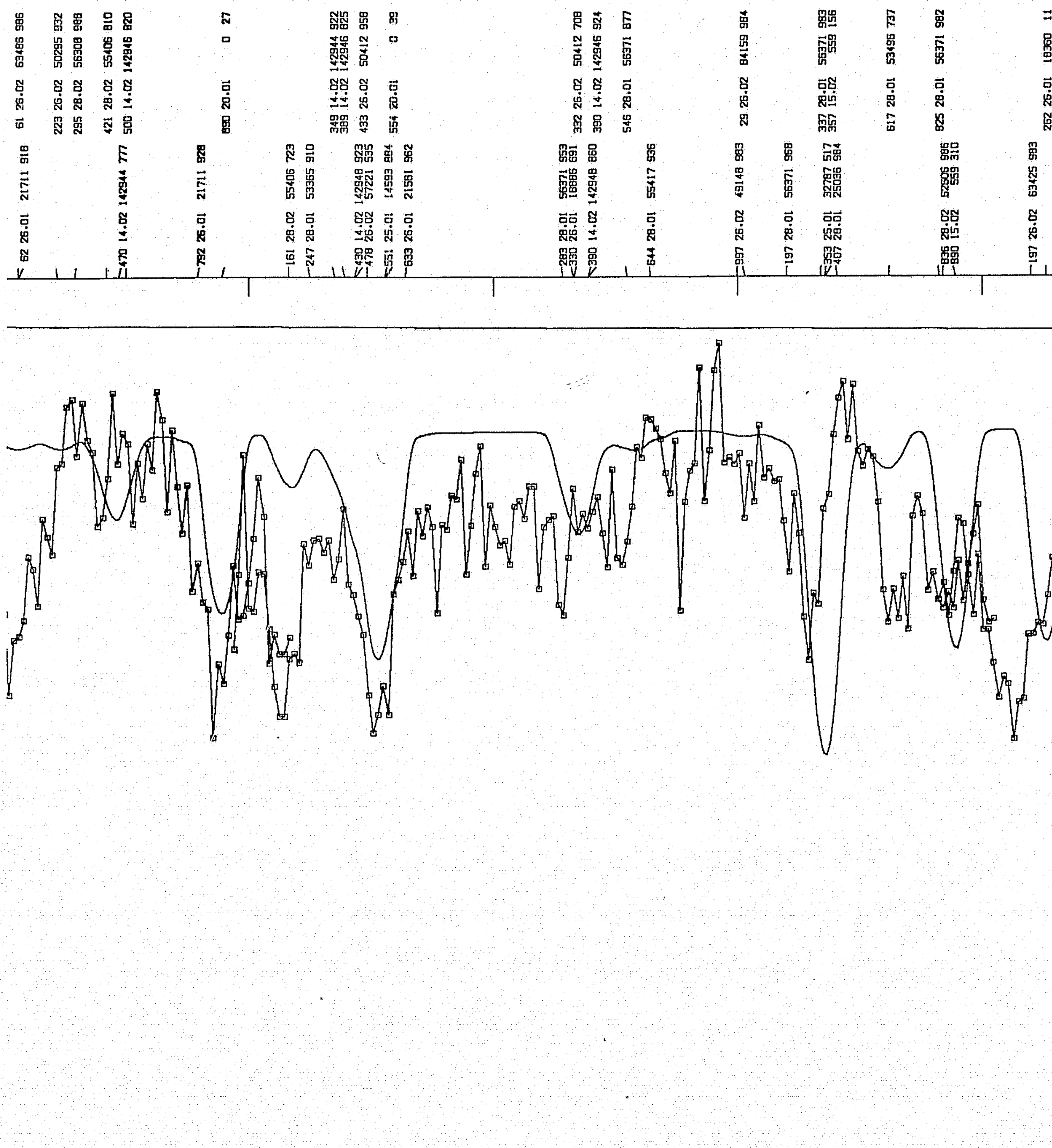

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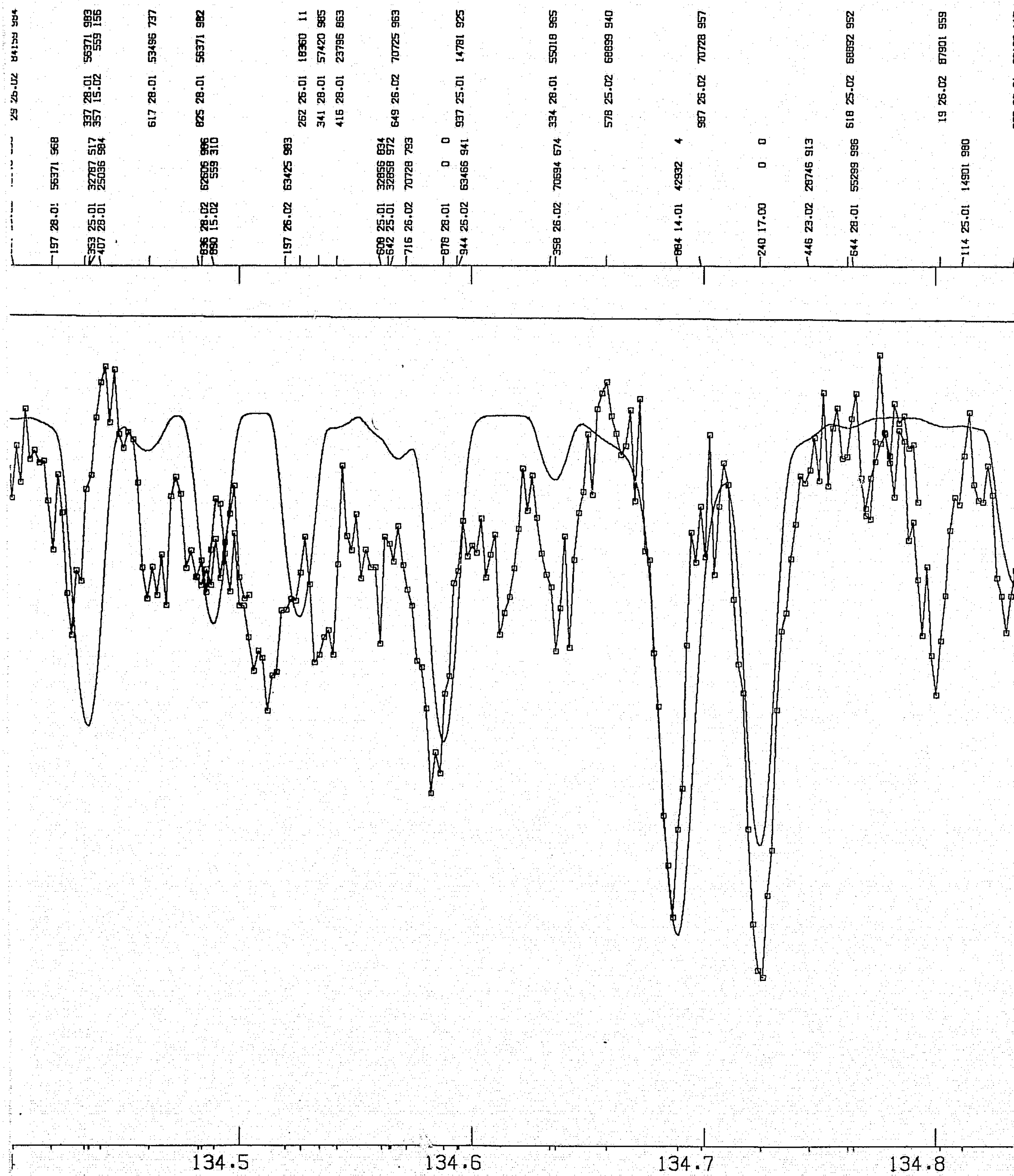

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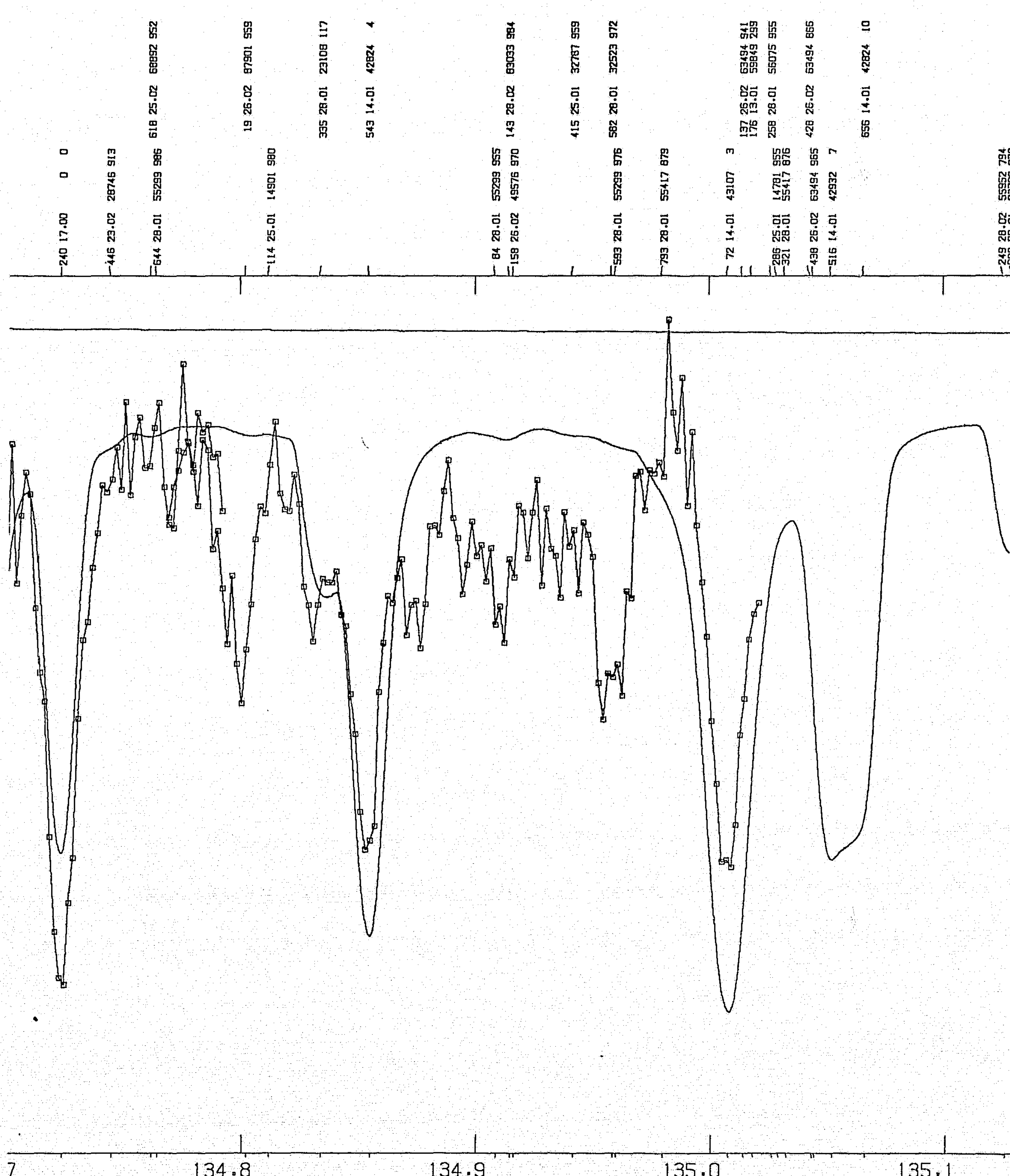
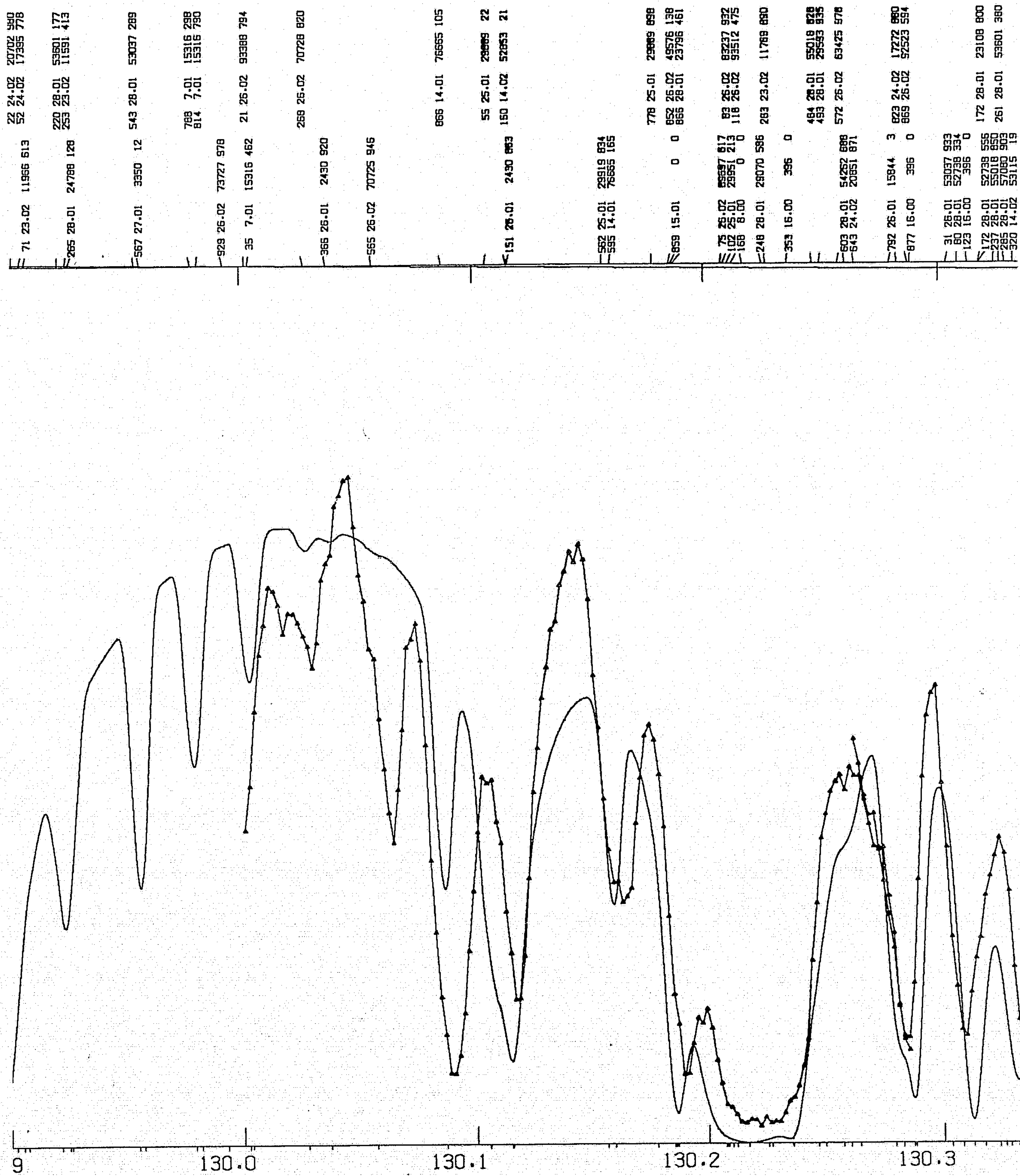


Figure 9. Calculated spectrum for Sirius compared to the observations with identifications. See Figure 8 for an explanation.

Figure 9 (Continued)



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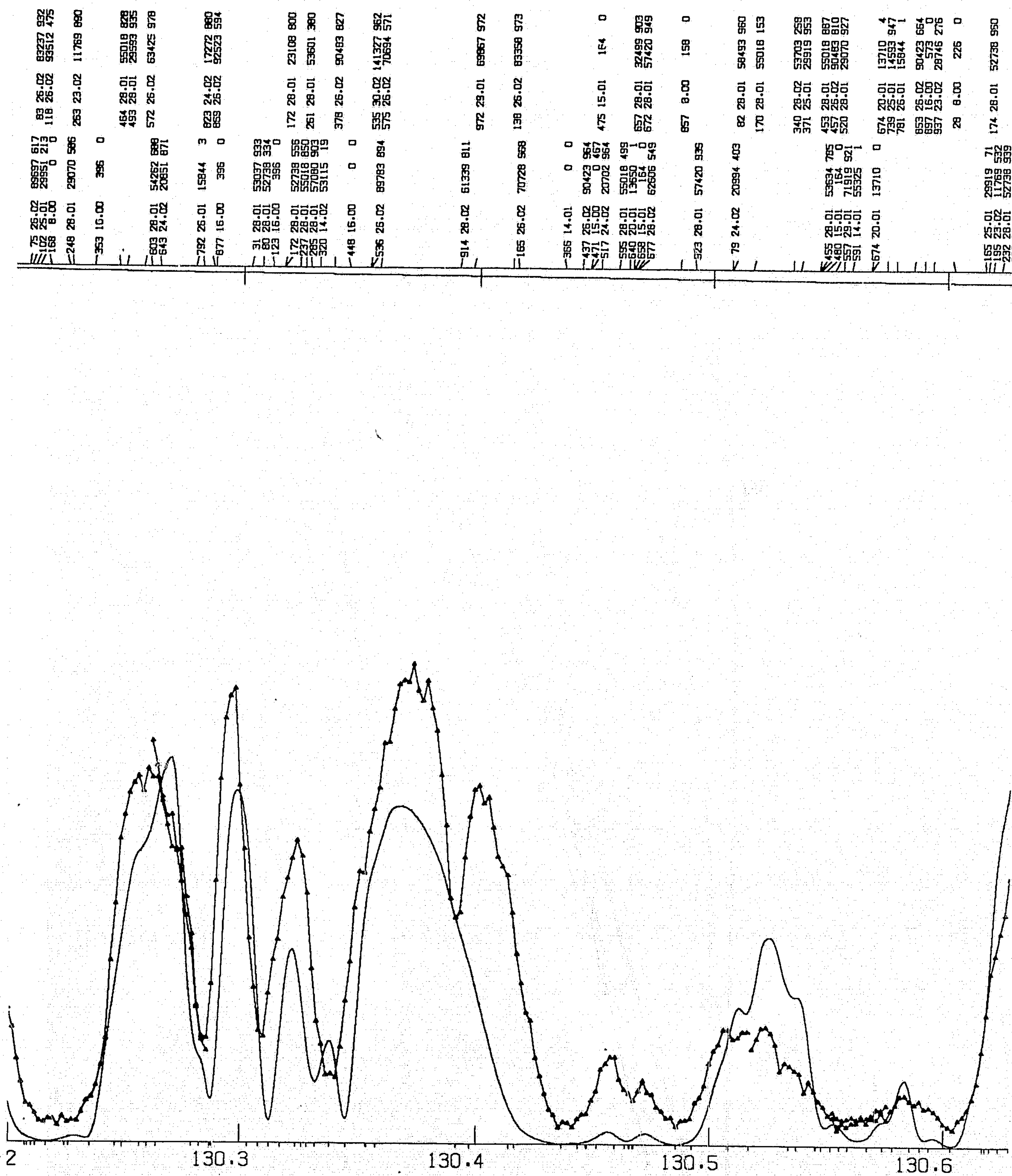

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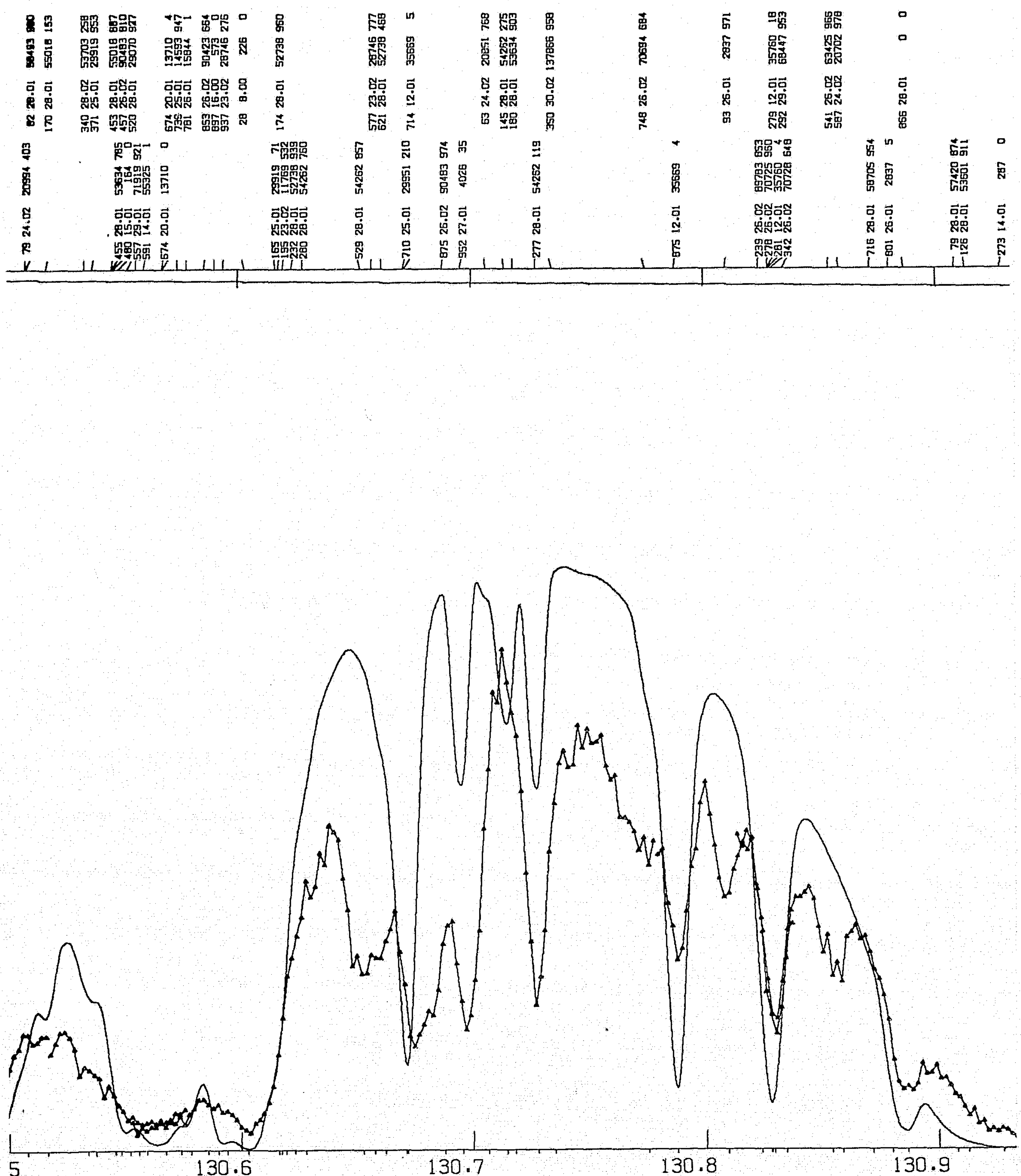

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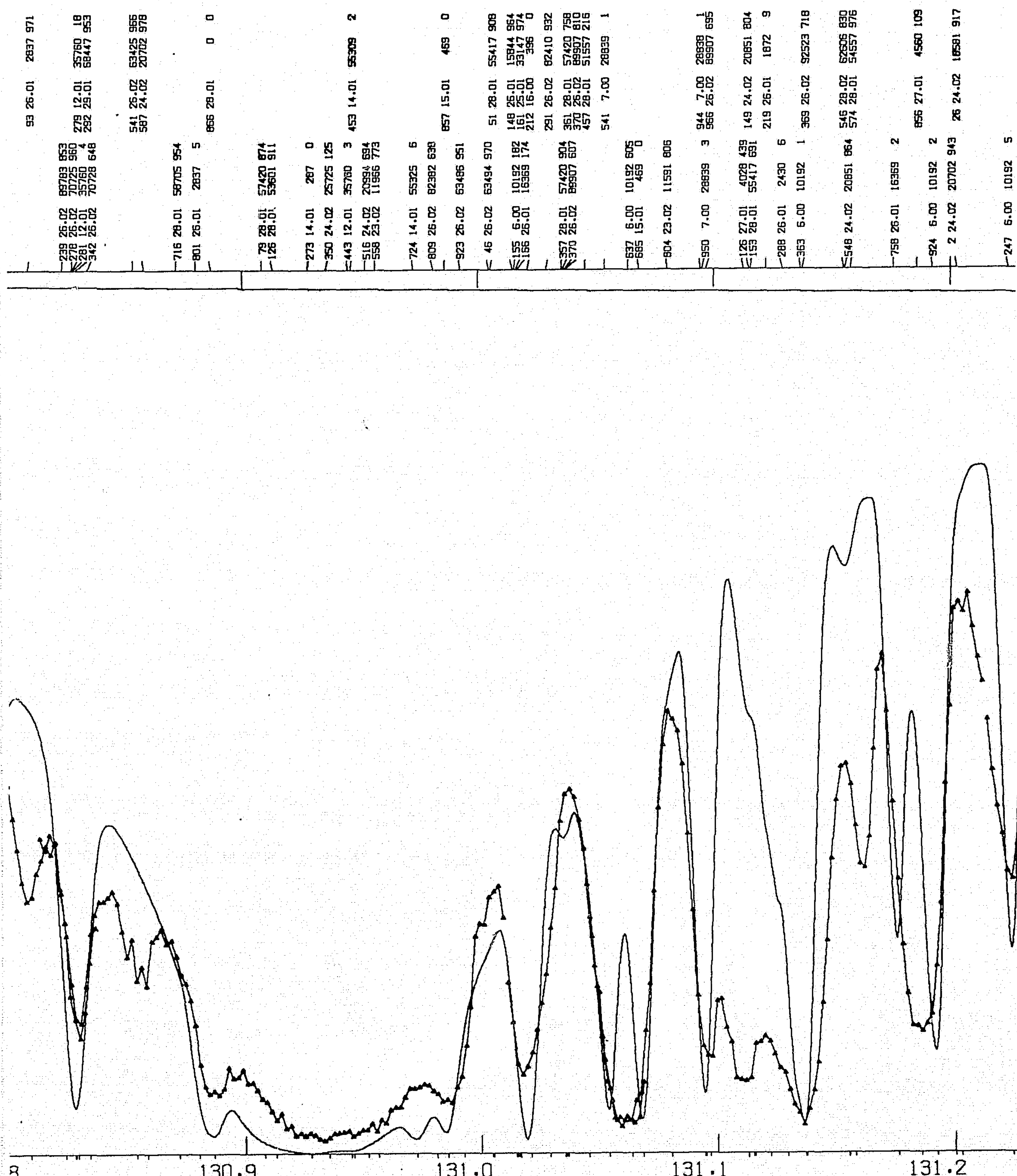

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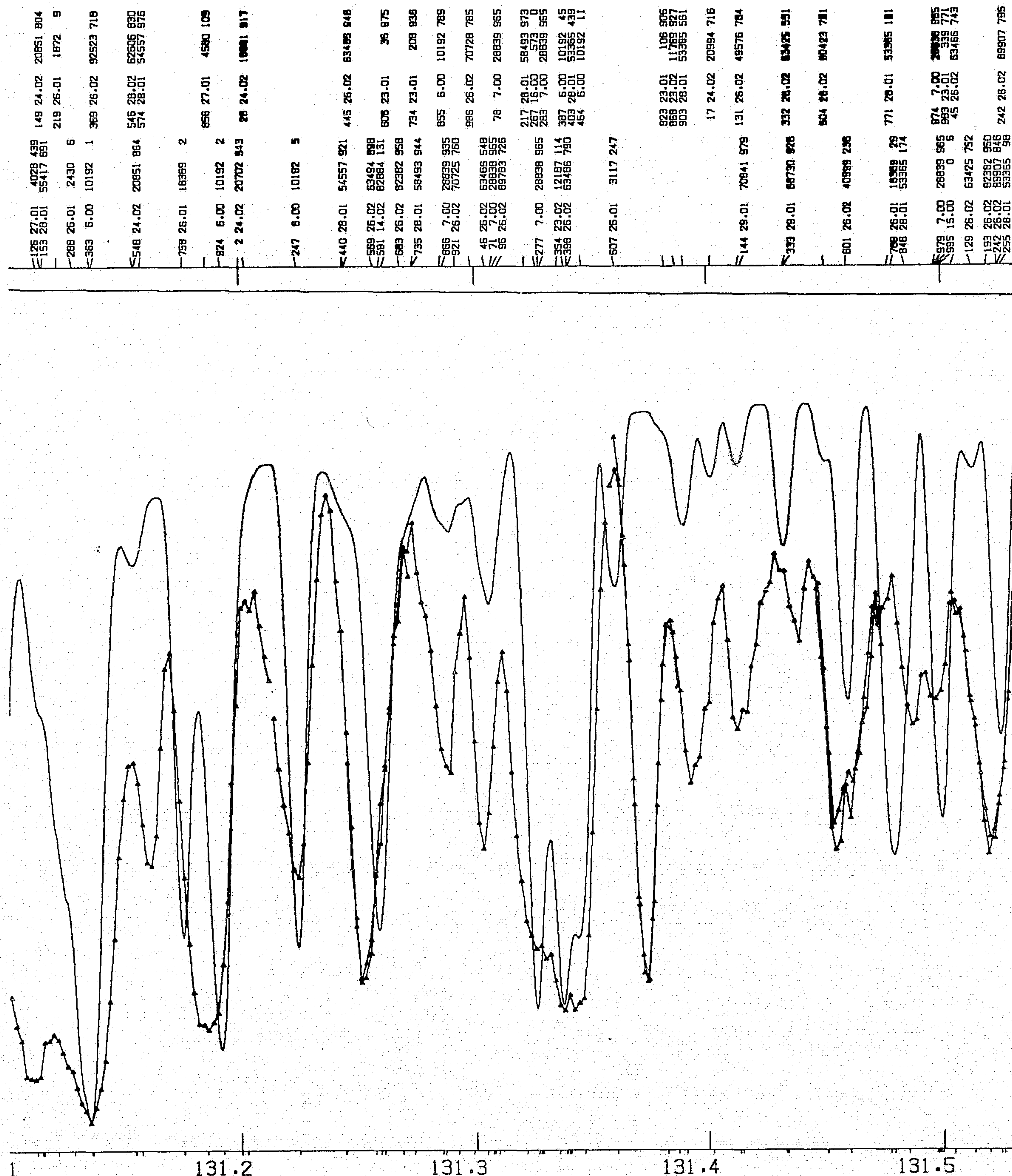

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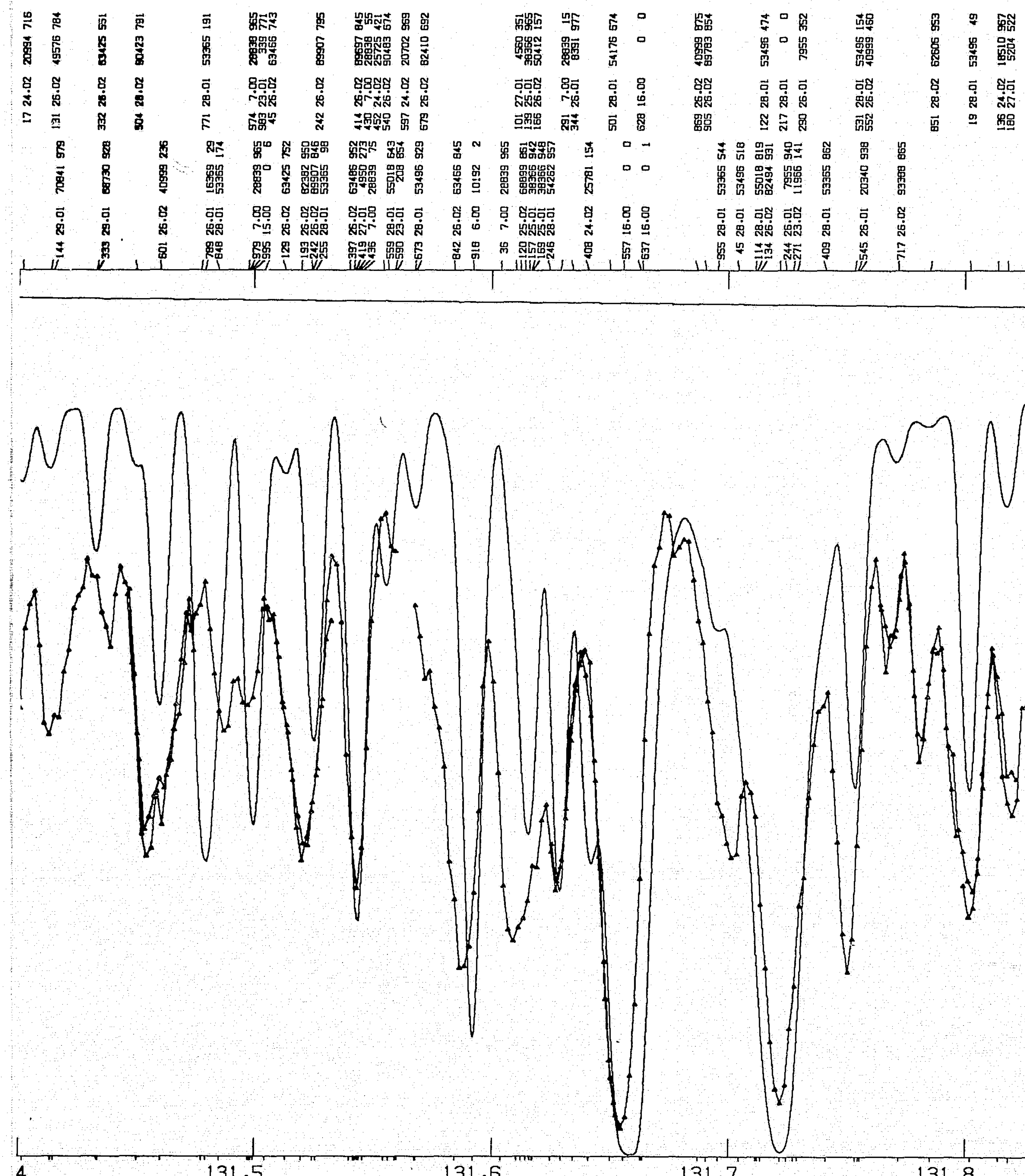

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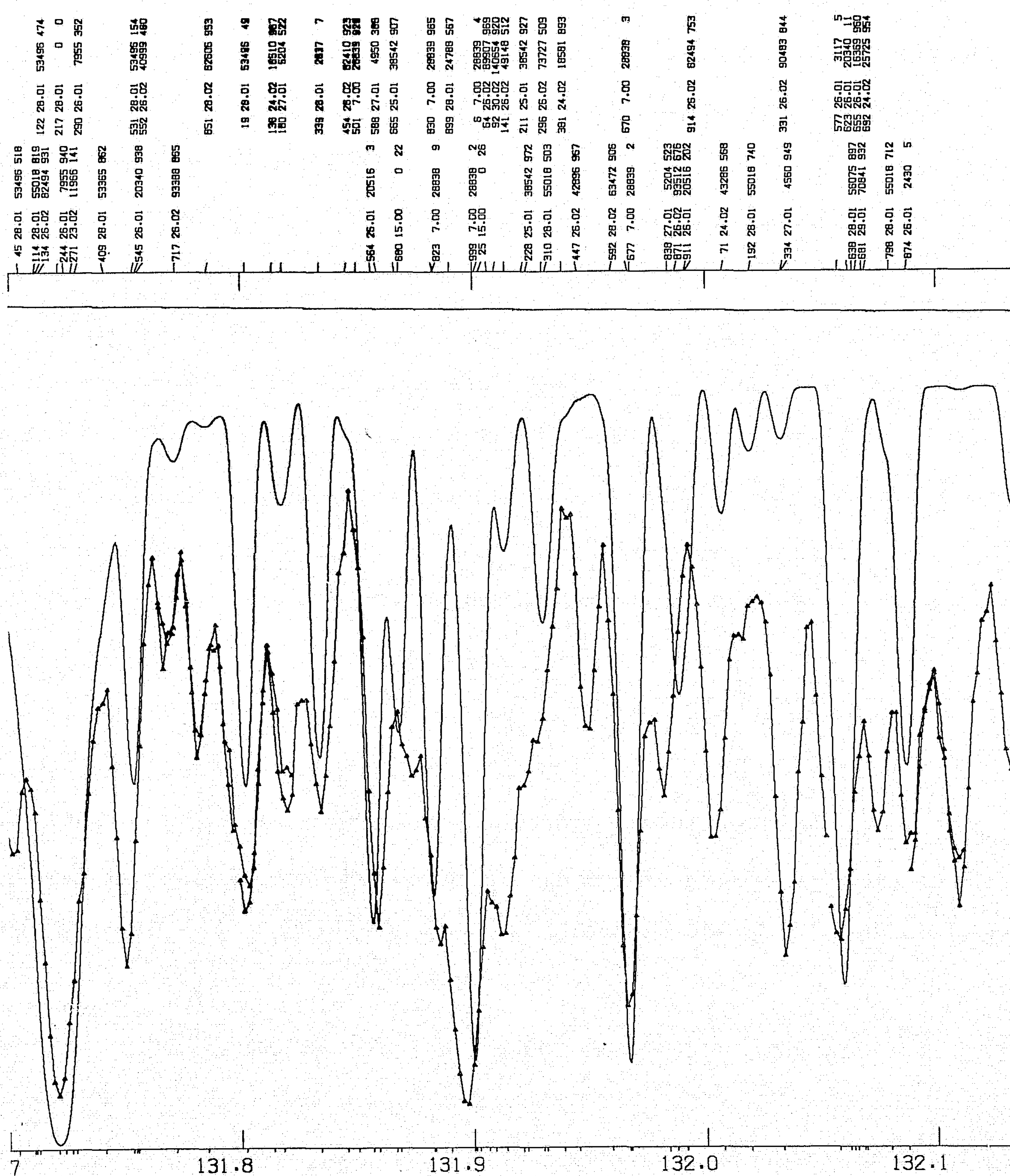

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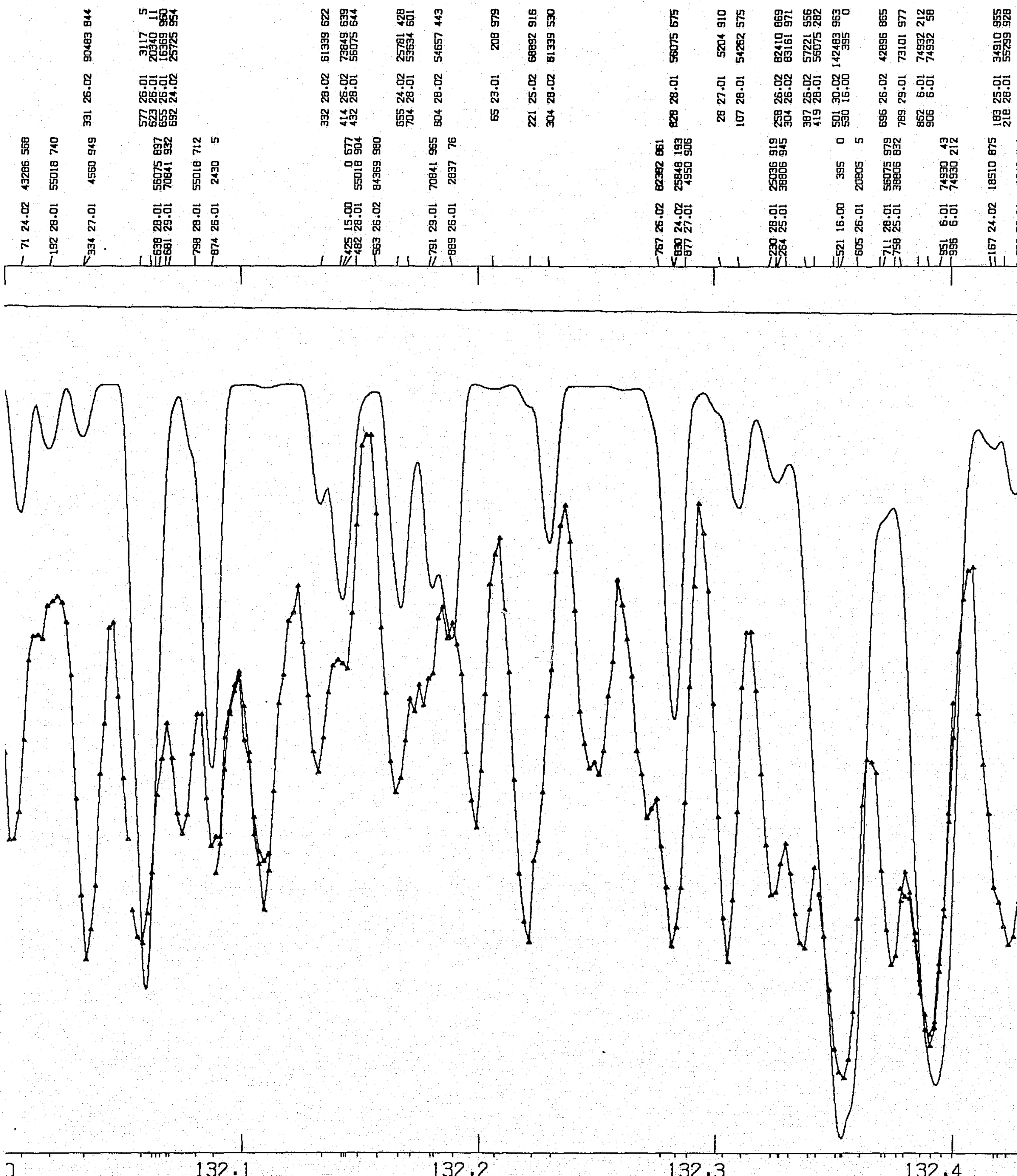

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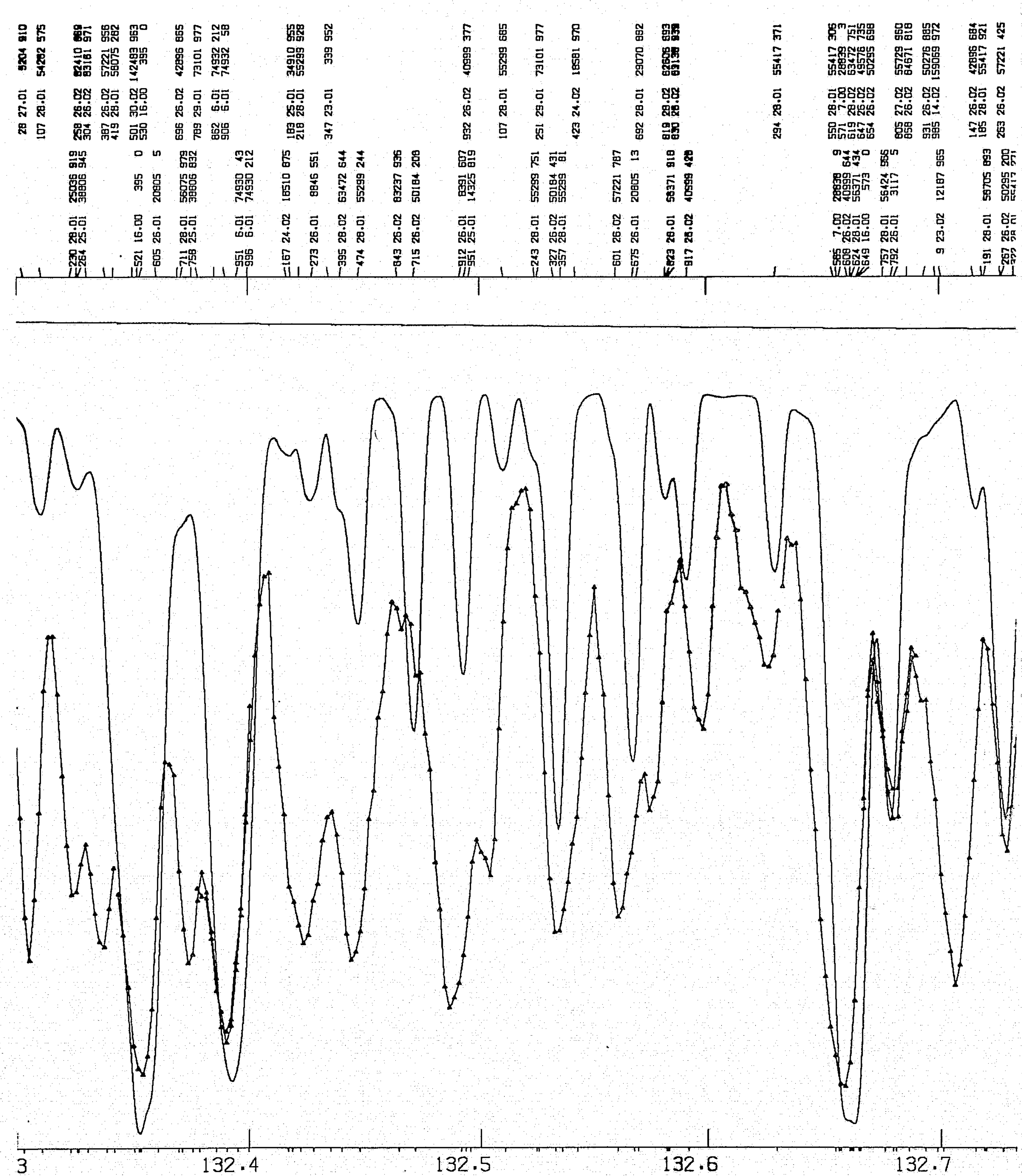

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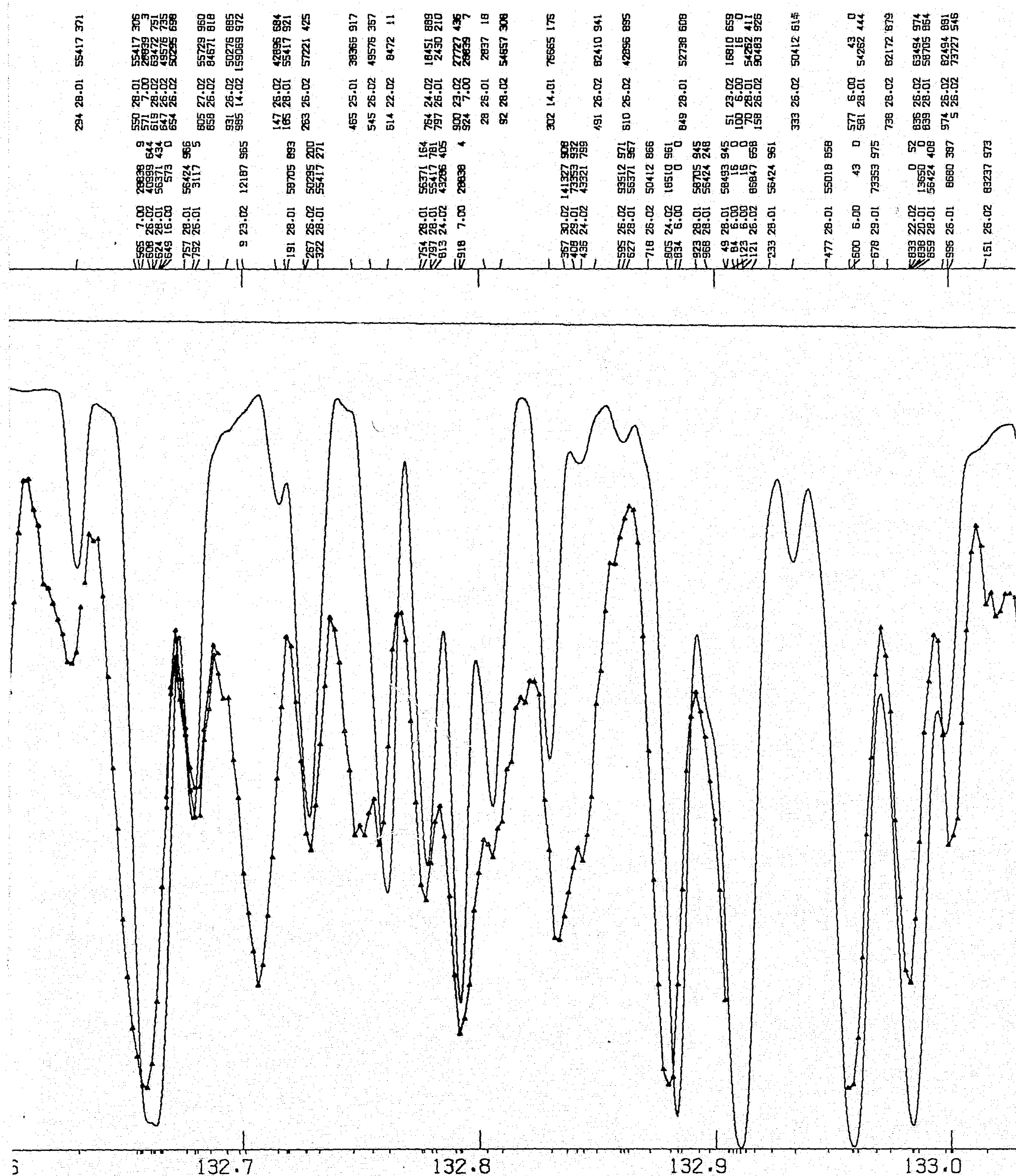

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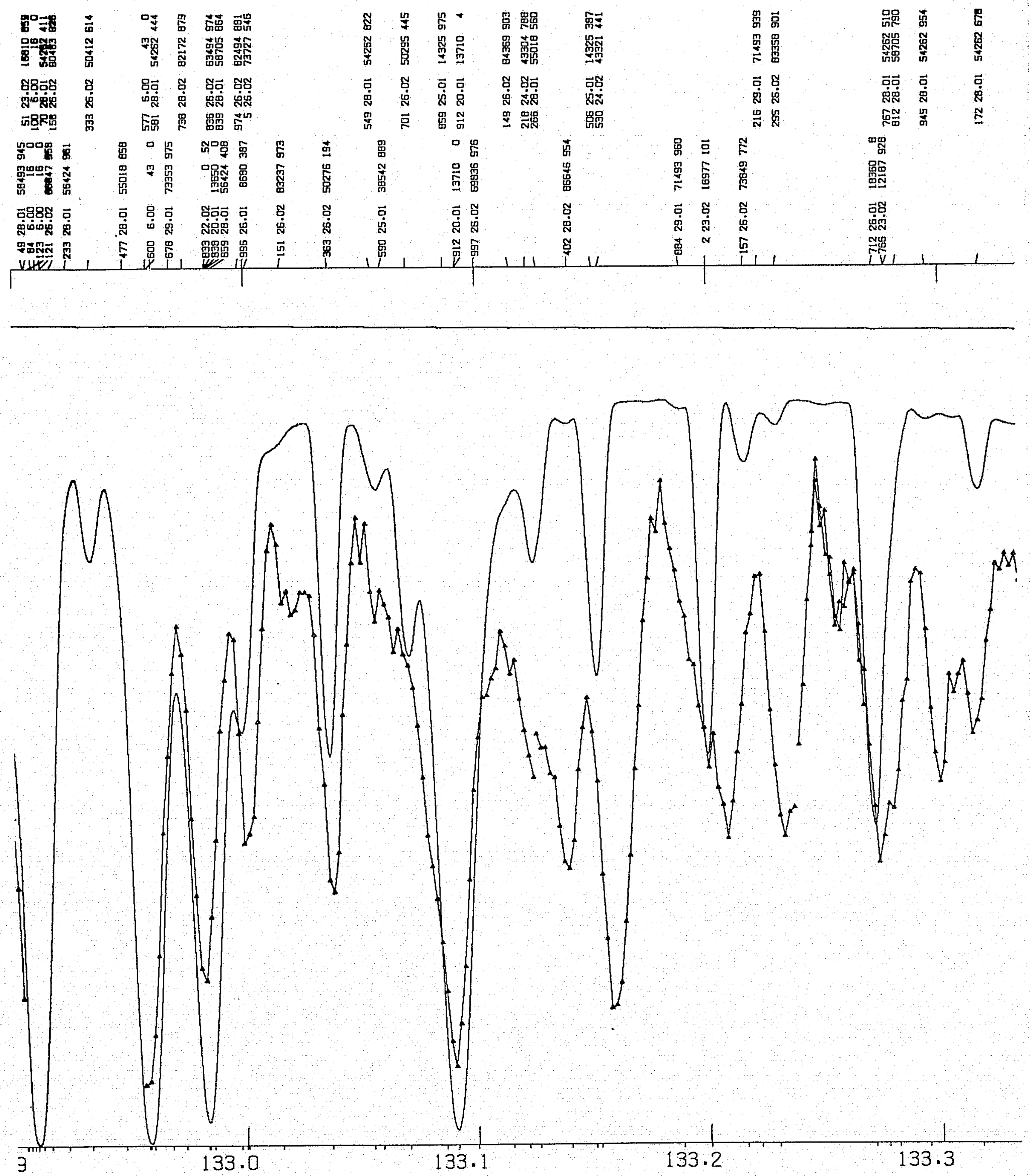

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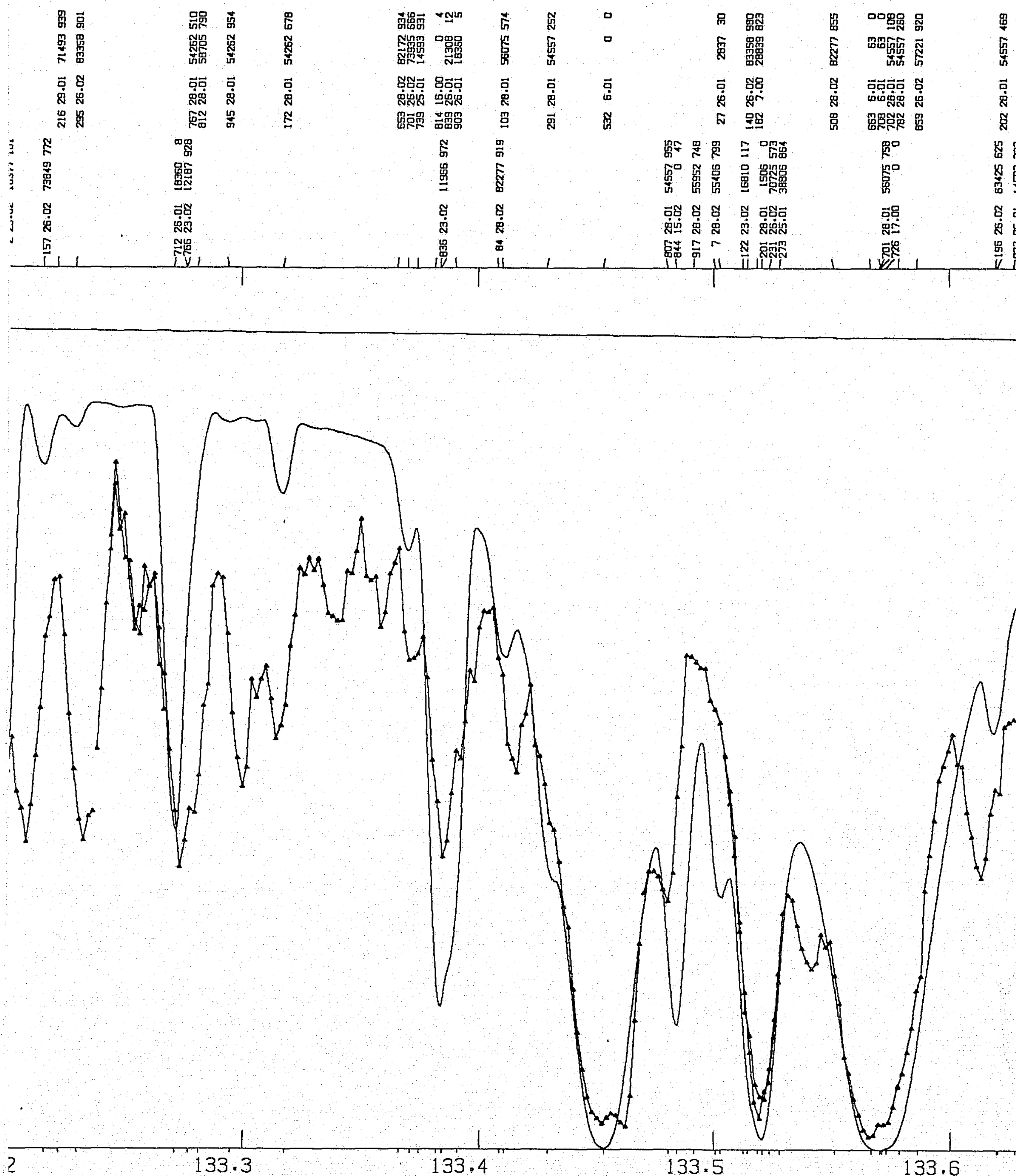

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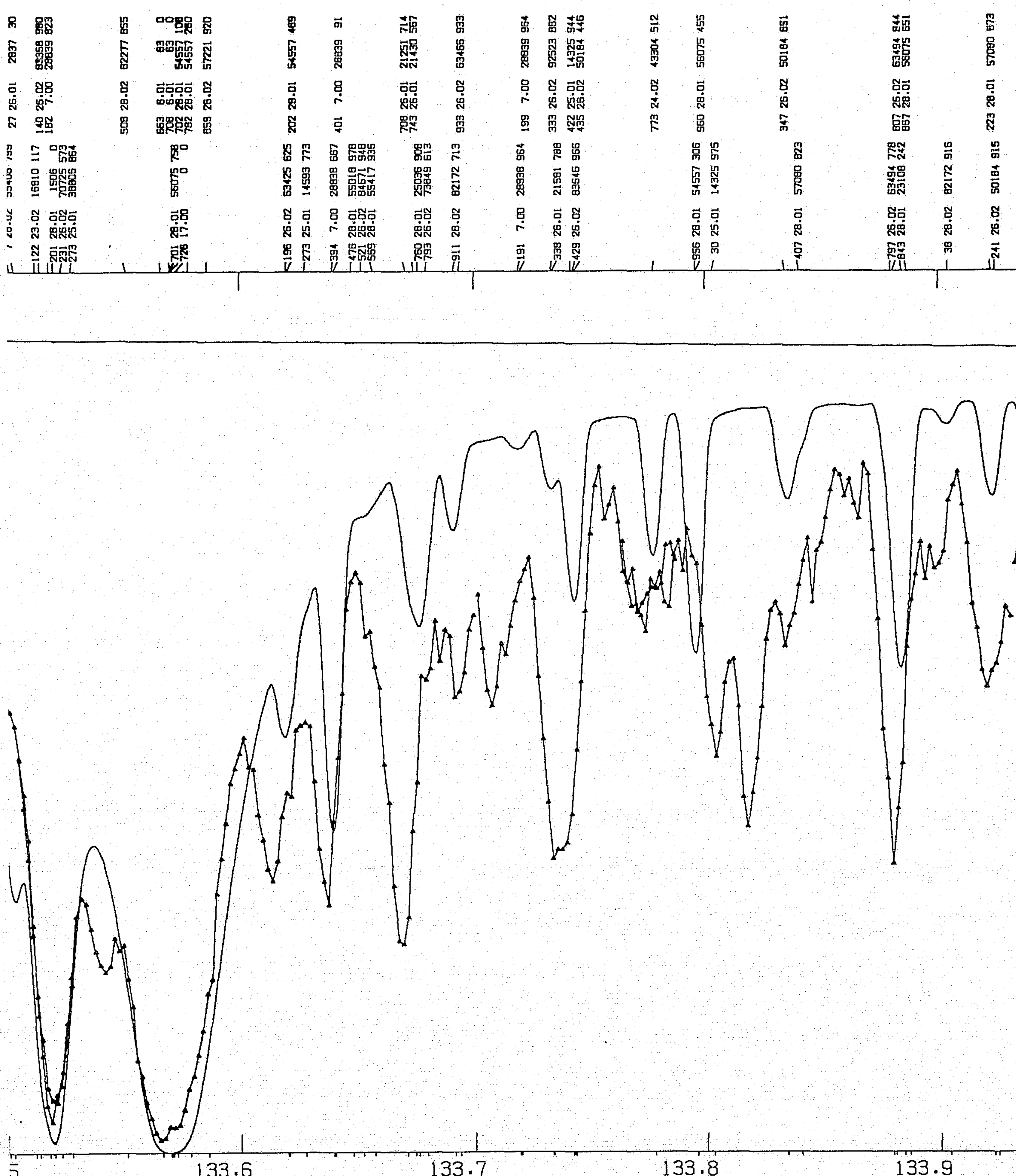

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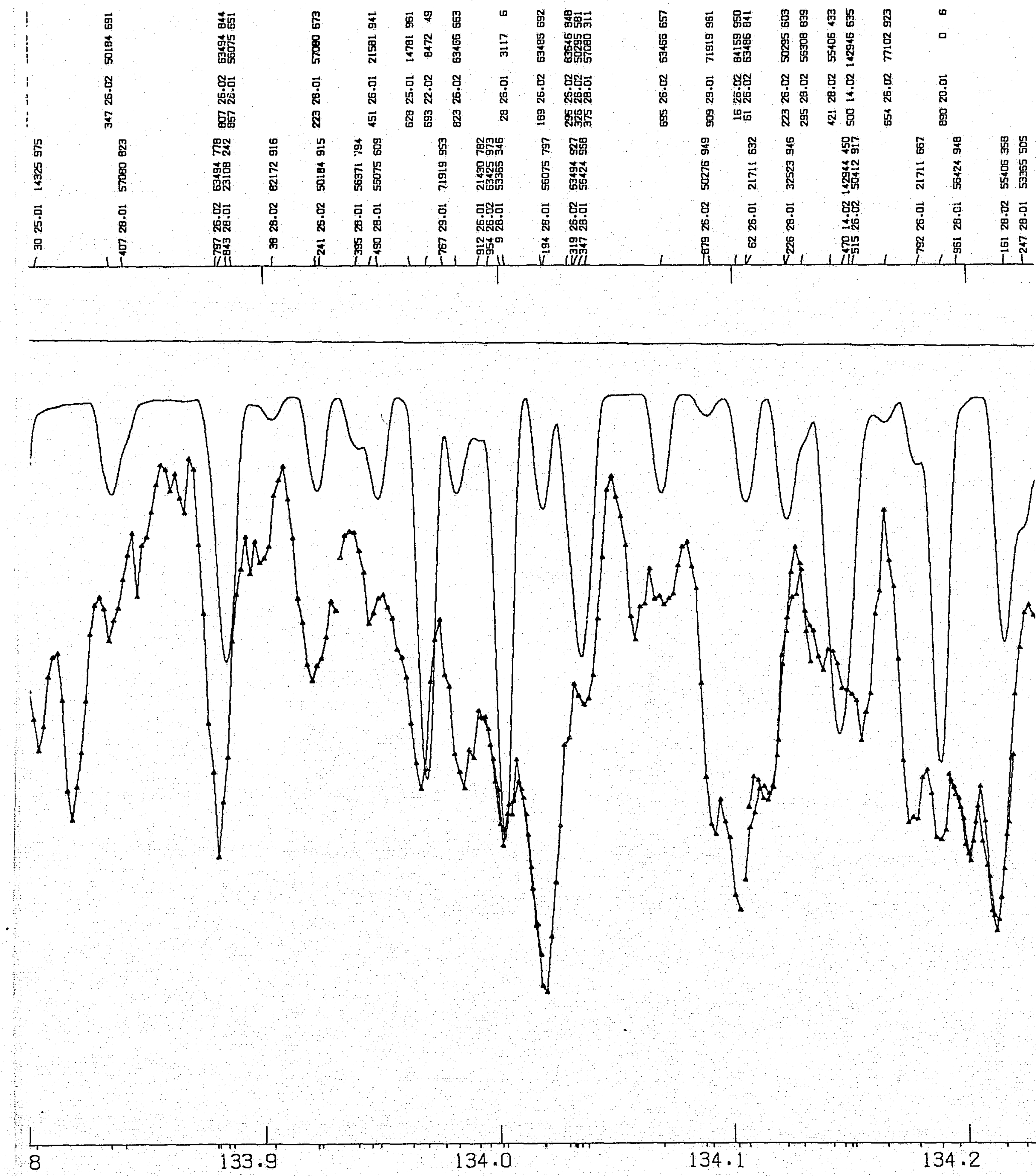

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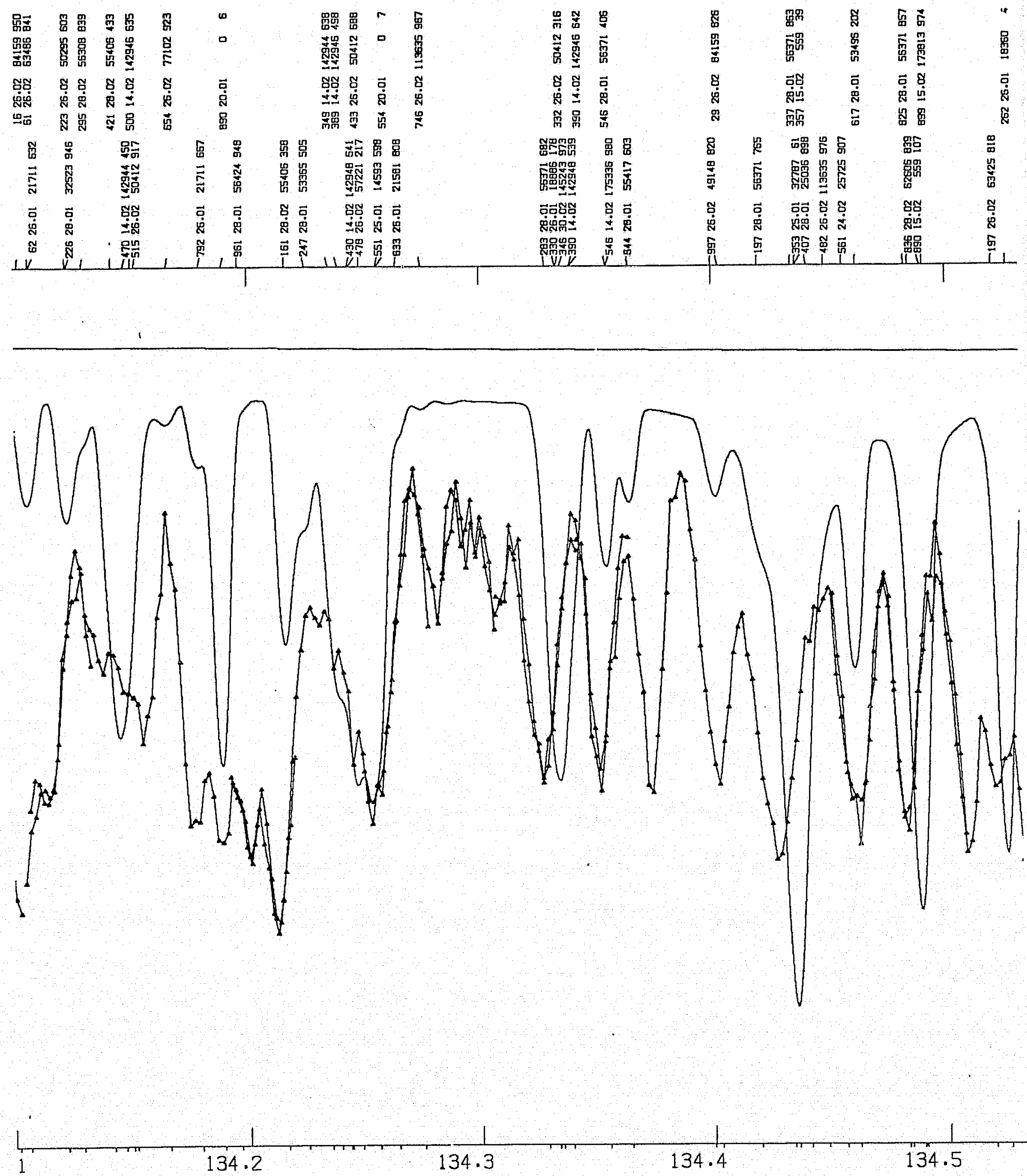

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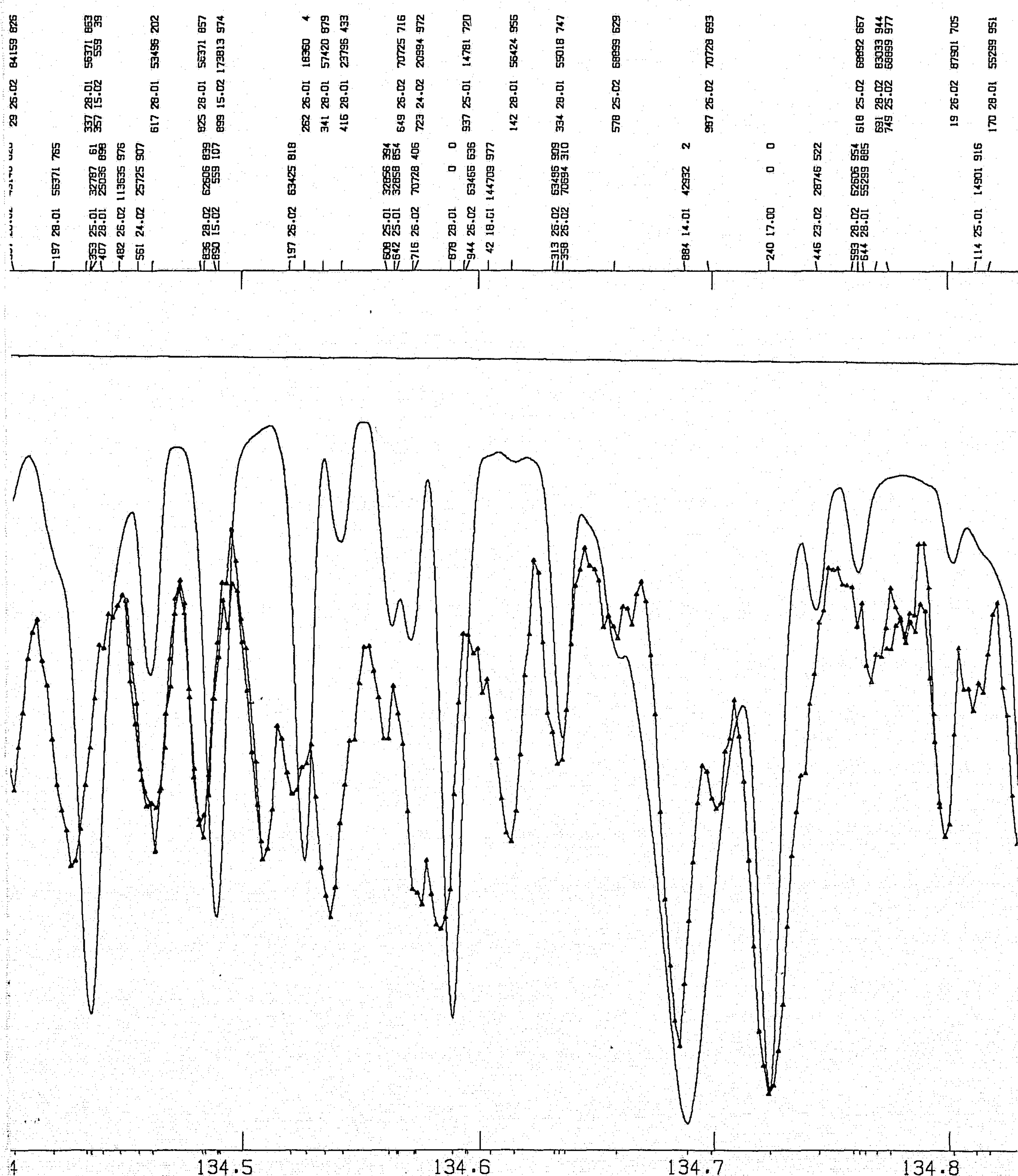

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