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URANIUM-LEAD CONCORDIA-DISCORDIA INTERCEPTS:

A PROGRAM FOR THE TI-59 PROGRAMMABLE CALCULATOR

by

Gordon Haxel and James E. Wright

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INTRODUCTION

The concordia diagram is widely used to interpret discordant uranium-lead (U-Pb) isotopic dates. Concordia is the locus of points, on a diagram of $^{206}Pb^*/^{238}U$ versus $^{207}Pb^*/^{235}U$ (* denotes radiogenic lead), for which the $^{206}Pb^*/^{238}U$ and $^{207}Pb^*/^{235}U$ apparent ages are equal. For discordant zircons (and (or) other dated minerals), the observed Pb*/U isotopic ratios for several cogenetic size or magnetic fractions commonly define a straight line, called discordia, which will normally intersect the concordia curve at two points (fig. 1). These intercepts provide two dates, which in turn often yield or can be related to the age or ages of the rock(s) from which the zircons were separated (Faure, 1977, p. 48, chap. 12; Gebauer and Grunenfelder, 1979; Doe, 1970).

The program presented here provides a straightforward and convenient method for obtaining an analytical solution to the following problem:

Given: a data set of two or more (≤ 9) pairs of $^{207}Pb^*/^{235}U$ and $^{206}Pb^*/^{238}U$ ratios,

Find: the upper and lower intercepts with concordia of the discordia line defined by these data.

Each of the two intercepts thus obtained may or may not have any physical significance. The program is intended to complement, but not replace, graphical solution of the problem on a concordia diagram, and can be used in

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conjunction with the tables of Stacey and Stern (1973). The simple analytical method employed here or graphical solutions are useful tools for preliminary interpretation of U-Pb geochronologic data. Rigorous calculation of concordia-discordia intercept ages and their associated uncertainties requires more sophisticated analytical methods (Ludwig, 1980).

This program is written for the Texas Instruments TI-59 programmable calculator with PC-100A thermal printer. A simple modification permits the program to be used on the TI-59 without a printer (see Appendix). The Master Library Module must be in the calculator. The program is too long for the TI-58. A complete listing of the program is provided; once keyed into the calculator, this program can be recorded onto two magnetic cards for future use. The first of these cards can be labeled as shown in figure 2. It is advisable to record an extra set of cards. Directions for loading the program from magnetic cards into the calculator are included under INSTRUCTIONS FOR USE.

Data sets consisting entirely of normally discordant ($^{206}Pb^*/^{238}U$ apparent age < $^{207}Pb^*/^{235}U$ apparent age) points can be entered in any order. The program as written can handle data sets that include reversely discordant ($^{206}Pb^*/^{238}U$ apparent age > $^{207}Pb^*/^{235}U$ apparent age) points only if at least one point is normally discordant. The first data point entered must be normally discordant. A set consisting entirely of reversely discordant data would require a minor modification in the way the intercept limits (registers 01 and 02) are set up in function E.

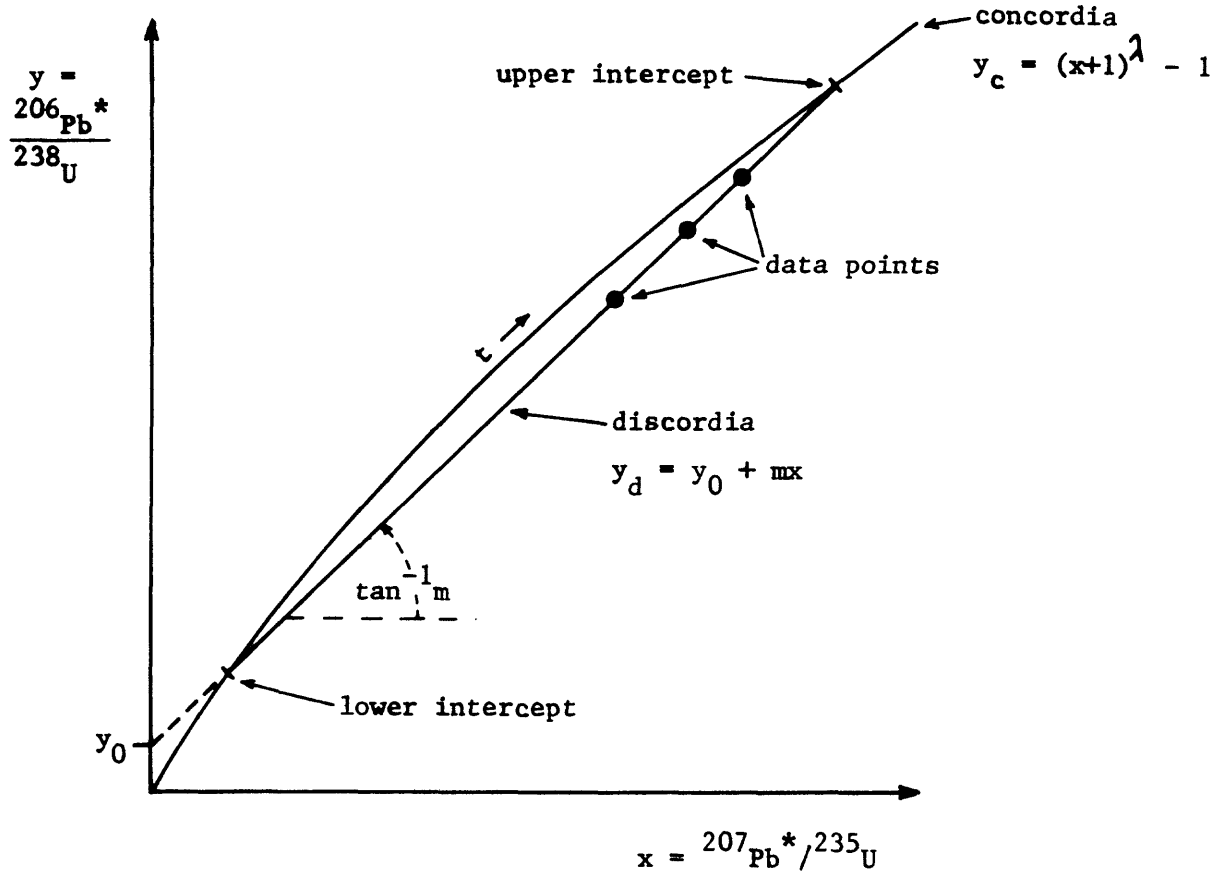

Figure 1. U-Pb concordia diagram.

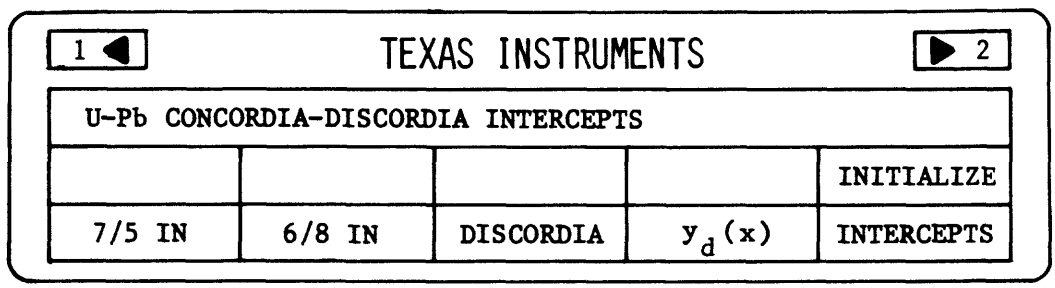

Figure 2. Suggested labeling of first magnetic card.

INSTRUCTIONS FOR USE

1. Turn calculator on or, if already on, turn off and back on to clear for loading of program.
2. Press 4, 2nd, Op, 17. This partitions memory for storage of program and data. Display should be 639.39.
3. Press CLR, 1.
4. Insert magnetic card side 1 into slot (on right side of calculator) to load program.
5. Press CLR, 2. Insert card side 2 (the first card turned right-for-left).
6. Press CLR, 3.
7. Insert card side 3 (the second card).
8. Insert first card in display window at top of keyboard.
9. Enter sample number (optional).
10. Press E' (=2nd E) to initialize program. Computer will print sample number.
11. Enter $^{207}Pb^*/^{235}U$ ("7/5") isotopic ratio for first zircon data point.
12. Check display to see that 7/5 ratio is entered correctly. If incorrect, push CLR and reenter. Read step 17.
13. With correct 7/5 ratio in display, press A. Computer will print data point number and 7/5 ratio.
14. Enter 6/8 isotopic ratio for first zircon data point. If incorrectly entered, press CLR and reenter.
15. Press B. Computer will print 6/8 ratio.
16. Repeat steps 11 through 15 for each additional zircon data point. A maximum of 9 data points can be accommodated.

17. Note on errors in data entry: If you find, after pushing A or B, that any 7/5 to 6/8 isotopic ratio was incorrectly entered, you must reinitialize (press E') and start the whole data entry procedure (steps 10 through 16) all over again, beginning with the first data point. This is the reason for checking each ratio (steps 12 and 14) on the display before pressing A or B.

18. Press C to calculate discordia line by linear regression. Correlation coefficient will be printed. Slope and intercept (with 6/8 axis) are in registers 09 and 10, respectively. Should you want to print them, press INV, 2nd, Fix, RCL, 09, 2nd, Prt and (or) INV, 2nd, Fix, RCL, 10, 2nd, Prt.

19. Press E to calculate lower (LI on printout) and upper (UI) intercept of discordia with concordia. For each intercept the time (in millions of years) and 7/5 and 6/8 isotopic ratios are printed. Each intercept calculation requires 1 to 3 minutes.

20. To calculate points on discordia line, enter 7/5 isotopic ratio (x on printout) and press D. Corresponding 6/8 ratio (y) will be printed. Repeat as needed. This calculation can be done anytime after C is pressed.

21. Do a rough graphical solution on a concordia diagram to be sure that the calculated analytical intercepts are reasonable.

22. For next sample, start over at step 9.

USAGE ERRORS AND PROBLEMS

1. Data entry errors: see step 17 of instructions for use.

2. SE (printed error message): E or D was pressed before C; press C, then E and (or) D. Data entry was attempted before initialization; press E', then enter data.

3. LE (printed error message) in place of lower intercept: Time at lower intercept is less than zero. If this is unreasonable, be sure that data were entered correctly.

4. LE in place of upper intercept: Time at upper intercept is greater than 6 billion years. Check data entry.

5. Flashing display and (or) nonsensical results--some possible causes: Isotopic ratios entered incorrectly; check especially leading zeros and possible transpositions. Only one data point entered. Discordia is parallel to 6/8 axis. One of the undefined keys A', B', C', or D' was pressed; press CLR and carry on.

6. Flashing display after attempting to read magnetic card: Be sure steps 1 through 7 are followed exactly. Cards will be read only if partition is 639.39 (see step 2). If calculator still won't read card, keep trying.

EXAMPLE

A hypothetical data set, for sample number 14325.

ATOMIC RATIOS	
$\frac{^{207}Pb^*}{^{235}U}$	$\frac{^{206}Pb^*}{^{238}U}$
3.40	0.244
2.95	0.214
2.55	0.186

Resulting printout from TI-59 and PC 100A:

```
                14325.      SN

                    1.       N
            2.950000      7/5
            0.214000      6/8

                    2.       N
            3.400000      7/5
            0.244000      6/8

                    3.       N
            2.550000      7/5
            0.186000      6/8

               1.000      CC

                          LI
               145.7       T
            0.154247      7/5
            0.022852      6/8

                          UI
              1658.5       T
            4.121009      7/5
            0.293396      6/8
```

Explanation:

SN	**sample number**
N	**number of data point**
7/5	**$^{207}Pb^*/^{235}U$ isotopic ratio of data point**
6/8	**$^{206}Pb^*/^{238}U$ isotopic ratio of data point**
CC	**correlation coefficient for discordia line**
LI	**lower intercept**
UI	**upper intercept**
T	**time (millions of years) at intercept**
7/5	**$^{207}Pb^*/^{235}U$ isotopic ratio at intercept**
6/8	**$^{206}Pb^*/^{238}U$ isotopic ratio at intercept**

The upper and lower concordia-intercept ages are thus 1,658 m.y. and 146 m.y., respectively.

PROGRAM

Method

The abcissa and ordinate of the concordia diagram are the isotopic ratios $x = {}^{207}Pb^*/{}^{235}U$ and $y = {}^{206}Pb^*/{}^{238}U$. The parametric equations for the overall decay of uranium to lead are

$$x(t) = e^{\lambda 5 t} - 1 \text{ (a)} \quad \text{and} \quad y(t) = e^{\lambda 8 t} - 1 \text{ (b)} \qquad (1)$$

where t is time and λ_5 and λ_8 are the decay constants for ^{235}U and ^{238}U. Solving (1)(a) for t gives

$$t(x) = \log (x+1)/\lambda_5 \qquad (2)$$

and substitution of (2) into (1)(b) yields a nonparametric equation for concordia:

$$y_c(x) = (x+1)^{\lambda} - 1 \qquad (3)$$

where $\lambda = \lambda_8/\lambda_5$. The equation for discordia is:

$$y_d(x) = y_o + mx \qquad (4)$$

where m and y_o are the slope and y-intercept of the linear regression line through the data points representing the observed Pb*/U isotopic ratios (fig. 1). Let $Y(x) = y_c - y_d$; then

$$Y(x) = (x+1)^{\lambda} - mx - y_o - 1 \qquad (5).$$

The intercepts of discordia with concordia are the zeros (roots) of Y(x).

Description

In the following description, the isotopic ratios $^{207}Pb^*/^{235}U$ and $^{206}Pb^*/^{238}U$ are abbreviated as 7/5 and 6/8. R_{ij} denotes data register number ij or the contents of that register, depending upon the context. Some familiarity with TI-59 programming (Farish and others, 1977) is assumed.

Program steps 000-003. Final steps of initialization function E'. Flag 01 indicates that initialization has been done.

Steps 003-030. This subroutine, which is called by the root-finding program ML (Master Library) 08, computes Y(x) using equation (5).

031-088. User-defined function E'. Initializes program. Prints sample number, clears calculator, initializes running indices (R_{01} and R_{02}) for keyboard data entry, and defines $R_{35} = 9.98485 \times 10^{-4} = \lambda_5 \times 10^6$ for time in millions of years, and $R_{36} = \lambda = \lambda_8 / \lambda_5 = 0.1575113$. Values of decay constants are from Jaffey and others (1971). RST at end causes branch to step 000.

089-136. Function A. Stores and prints 7/5 isotopic ratio and label. R_{10+i}=7/5 ratio for i th data point (i = 1, 2, 3,...R_{00}). Indirect addressing is used; R_{01} = running index for 7/5 storage = 10+i. R_{00}counts the number of data points entered, and is also printed. Flag 01 is checked to be sure that initialization (E') was done.

137-165. Function B. Stores and prints 6/8 isotopic ratios and label. $R_{20+i} = (6/8)_i$; $R_{02} = 20+i$.

166-225. Function C. Calculates slope, y-intercept, and correlation coefficient of discordia line. The linear regression function built into the TI-59 is used. PGM 01 SBR CLR is a Master Library program that initializes the calculator for linear regression. R_{07} and R_{08} are used for indirect addressing of R_{10+i} and R_{20+i}. R_{00} originally contains the number of data points, and is decremented to zero. The correlation coefficient is printed. Flag 03 is set.

226-275. Function D. Calculates and prints coordinates of point on discordia line, using equation (4). Flag 03 (set in function C) is checked.

276-316. Function E. Sets up for calculating intercepts of discordia with concordia, that is for finding the zeros of Y(x) (equation (5)). The x-axis intercept limits transmitted to the root-finding program ML08 (Texas Instruments, 1977) are R_{01} = 0 and $R_{02} = R_{11}$ (=7/5 isotopic ratio of the first data point entered) for the lower intercept, and R_{02} = 370 (=7/5 ratio at 6 billion years) and $R_{01} = R_{11}$ for the upper intercept. R_{34} = 2, =1 for lower and upper intercept, respectively.

317-427. Subroutine INT. Calls program ML08 (at steps 326 to 328) to compute a zero of Y(x) (that is, an intercept of discordia with concordia), and prints the time and 7/5 and 6/8 isotopic ratios at this intercept. Labels for these data are also printed. If no intercept is found between the limits set up in function E, that is, if flag 07 is set by Op 19, then no values are printed; instead processing branches to error routine IxI. R_{37} = x at intercept = root of Y(x) (equation(5)). R_{38} = y at intercept, calculated by subroutine $\sqrt{x}$. R_{39} = time at intercept, calculated by subroutine DEG. Steps 346 to 376 generate the printed labels LI and UI for the lower and upper intercepts; the label is selected by testing of R_{34}(=1 or 2) defined in function E.

428-447. Routine IxI. Prints error message LE (limit error) if no intercept is found within limits set by function E. This error condition is signaled by flag 07.

448-461. Subroutine DEG. Calculates t(x) using equation (2).

462-476. Subroutine $\sqrt{x}$. Calculates y(x) on concordia using equation (3).

477-492 (end of program). Routine π. Prints error message SE (sequence error) if functions A or B (data entry) are used before function E' (initialization); this error condition is signaled by flag 01 in function A and B. Also prints SE if functions D or E are used before function C, as signaled by flag 03 in D or E.

LISTING

```
000  86 STF
001  01  01
002  91 R/S
003  76 LBL
004  16 A'
005  42 STO
006  30  30
007  53  (
008  53  (
009  53  (
010  24 CE
011  85  +
012  01  1
013  54  )
014  45 Y^x
015  43 RCL
016  36  36
017  54  )
018  75  -
019  43 RCL
020  09  09
021  65  x
022  43 RCL
023  30  30
024  75  -
025  43 RCL
026  10  10
027  75  -
028  01  1
029  54  )
030  92 RTN
031  76 LBL
032  10 E'
033  98 ADV
034  98 ADV
035  98 ADV
036  98 ADV
037  98 ADV
038  42 STO
039  08  08
040  22 INV
041  58 FIX
042  22 INV
043  52 EE
044  69 DP
045  00  00
046  03  3
047  06  6
048  03  3
049  01  1
050  69 DP
051  04  04
052  43 RCL
053  08  08
054  69 DP
055  06  06
056  47 CMS
057  29 CP
058  25 CLR
059  01  1
060  00  0
061  42 STO
062  01  01
063  02  2
064  00  0
065  42 STO
066  02  02
067  93  .
068  01  1
069  05  5
070  07  7
071  05  5
072  01  1
073  01  1
074  03  3
075  42 STO
076  36  36
077  09  9
078  93  .
079  08  8
080  04  4
081  08  8
082  05  5
083  52 EE
084  94 +/-
085  04  4
086  42 STO
087  35  35
088  81 RST
089  76 LBL
090  11  A
091  22 INV
092  87 IFF
093  01  01
094  89  π
095  69 DP
096  20  20
097  69 DP
098  21  21
099  72 ST*
100  01  01
```

```
101   98 ADV
102   22 INV
103   52 EE
104   22 INV
105   58 FIX
106   69 DP
107   00  00
108   03  3
109   01  1
110   69 DP
111   04  04
112   43 RCL
113   00  00
114   58 FIX
115   00  00
116   69 DP
117   06  06
118   22 INV
119   58 FIX
120   69 DP
121   00  00
122   01  1
123   00  0
124   06  6
125   03  3
126   00  0
127   06  6
128   69 DP
129   04  04
130   73 RC*
131   01  01
132   58 FIX
133   06  06
134   69 DP
135   06  06
136   91 R/S
137   76 LBL
138   12  B
139   22 INV
140   87 IFF
141   01  01
142   89  π
143   69 DP
144   22  22
145   72 ST*
146   02  02
147   22 INV
148   58 FIX
149   69 DP
150   00  00
```

```
151   00  0
152   07  7
153   06  6
154   03  3
155   01  1
156   01  1
157   69 DP
158   04  04
159   73 RC*
160   02  02
161   58 FIX
162   06  06
163   69 DP
164   06  06
165   91 R/S
166   76 LBL
167   13  C
168   86 STF
169   03  03
170   01  1
171   00  0
172   42 STO
173   07  07
174   02  2
175   00  0
176   42 STO
177   08  08
178   36 PGM
179   01  01
180   71 SBR
181   25 CLR
182   76 LBL
183   90 LST
184   69 DP
185   27  27
186   69 DP
187   28  28
188   73 RC*
189   07  07
190   32 X:T
191   73 RC*
192   08  08
193   78 Σ+
194   97 DSZ
195   00  00
196   90 LST
197   69 DP
198   12  12
199   42 STO
200   10  10
```

```
201  32 X:T
202  42 STO
203  09  09
204  69 OP
205  13  13
206  42 STO
207  20  20
208  98 ADV
209  22 INV
210  58 FIX
211  69 OP
212  00  00
213  01  1
214  05  5
215  01  1
216  05  5
217  69 OP
218  04  04
219  43 RCL
220  20  20
221  58 FIX
222  03  03
223  69 OP
224  06  06
225  91 R/S
226  76 LBL
227  14  D
228  22 INV
229  87 IFF
230  03  03
231  89  π
232  42 STO
233  08  08
234  53  (
235  43 RCL
236  08  08
237  65  ×
238  43 RCL
239  09  09
240  85  +
241  43 RCL
242  10  10
243  54  )
244  42 STO
245  07  07
246  98 ADV
247  22 INV
248  58 FIX
249  69 OP
250  00  00
```

```
251  04  4
252  04  4
253  69 OP
254  04  04
255  43 RCL
256  08  08
257  58 FIX
258  06  06
259  69 OP
260  06  06
261  22 INV
262  58 FIX
263  69 OP
264  00  00
265  04  4
266  05  5
267  69 OP
268  04  04
269  43 RCL
270  07  07
271  58 FIX
272  06  06
273  69 OP
274  06  06
275  91 R/S
276  76 LBL
277  15  E
278  22 INV
279  87 IFF
280  03  03
281  89  π
282  00  0
283  36 PGM
284  08  08
285  11  A
286  43 RCL
287  11  11
288  36 PGM
289  08  08
290  12  B
291  02  2
292  42 STO
293  34  34
294  71 SBR
295  59 INT
296  43 RCL
297  11  11
298  36 PGM
299  08  08
300  11  A
```

301	03	3
302	07	7
303	00	0
304	36	PGM
305	08	08
306	12	B
307	01	1
308	42	STO
309	34	34
310	71	SBR
311	59	INT
312	22	INV
313	86	STF
314	01	01
315	25	CLR
316	91	R/S
317	76	LBL
318	59	INT
319	01	1
320	52	EE
321	94	+/-
322	07	7
323	36	PGM
324	08	08
325	14	D
326	36	PGM
327	08	08
328	15	E
329	69	OP
330	19	19
331	87	IFF
332	07	07
333	50	I×I
334	42	STO
335	37	37
336	71	SBR
337	34	FX
338	42	STO
339	38	38
340	43	RCL
341	37	37
342	71	SBR
343	60	DEG
344	42	STO
345	39	39
346	22	INV
347	52	EE
348	22	INV
349	58	FIX
350	98	ADV
351	69	OP
352	00	00
353	01	1
354	32	X:T
355	43	RCL
356	34	34
357	67	EQ
358	98	ADV
359	02	2
360	07	7
361	02	2
362	04	4
363	61	GTO
364	49	PRD
365	76	LBL
366	98	ADV
367	04	4
368	01	1
369	02	2
370	04	4
371	76	LBL
372	49	PRD
373	69	OP
374	04	04
375	69	OP
376	05	05
377	22	INV
378	58	FIX
379	69	OP
380	00	00
381	03	3
382	07	7
383	69	OP
384	04	04
385	43	RCL
386	39	39
387	58	FIX
388	01	01
389	69	OP
390	06	06
391	22	INV
392	58	FIX
393	69	OP
394	00	00
395	01	1
396	00	0
397	06	6
398	03	3
399	00	0
400	06	6

401	69	OP
402	04	04
403	43	RCL
404	37	37
405	58	FIX
406	06	06
407	69	OP
408	06	06
409	22	INV
410	58	FIX
411	69	OP
412	00	00
413	00	0
414	07	7
415	06	6
416	03	3
417	01	1
418	01	1
419	69	OP
420	04	04
421	43	RCL
422	38	38
423	58	FIX
424	06	06
425	69	OP
426	06	06
427	92	RTN
428	76	LBL
429	50	I×I
430	25	CLR
431	98	ADV
432	22	INV
433	58	FIX
434	69	OP
435	00	00
436	02	2
437	07	7
438	01	1
439	07	7
440	69	OP
441	02	02
442	69	OP
443	05	05
444	22	INV
445	86	STF
446	07	07
447	92	RTN
448	76	LBL
449	60	DEG
450	53	(
451	53	(
452	24	CE
453	85	+
454	01	1
455	54	)
456	23	LNX
457	55	÷
458	43	RCL
459	35	35
460	54	)
461	92	RTN
462	76	LBL
463	34	Γx
464	53	(
465	53	(
466	24	CE
467	85	+
468	01	1
469	54	)
470	45	Y×
471	43	RCL
472	36	36
473	75	-
474	01	1
475	54	)
476	92	RTN
477	76	LBL
478	89	π
479	98	ADV
480	22	INV
481	58	FIX
482	69	OP
483	00	00
484	03	3
485	06	6
486	01	1
487	07	7
488	69	OP
489	02	02
490	69	OP
491	05	05
492	91	R/S
493	00	0
494	00	0
495	00	0
496	00	0
497	00	0
498	00	0
499	00	0
500	00	0

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APPENDIX: USE WITHOUT PRINTER

Program modification

1. **Load program as in steps 1 through 7 of INSTRUCTIONS FOR USE (p. 6).**

2. **Enter this series of key strokes:**

GTO
391
LRN
2nd
Ins
R/S
LRN
GTO
410
LRN
2nd
Ins
R/S
LRN
GTO
429
LRN
2nd
Ins
R/S
LRN

3. **The program sequence from steps 385 to 435 should now look like this:**

```
385  43 RCL
386  39  39
387  58 FIX
388  01  01
389  69 □P
390  06  06
391  91 R/S
392  22 INV
393  58 FIX
394  69 □P
395  00  00
396  01  1
397  00  0
398  06  6
399  03  3
400  00  0
401  06  6
402  69 □P
403  04  04
404  43 RCL
405  37  37
406  58 FIX
407  06  06
408  69 □P
409  06  06
410  91 R/S
411  22 INV
412  58 FIX
413  69 □P
414  00  00
415  00  0
416  07  7
417  06  6
418  03  3
419  01  1
420  01  1
421  69 □P
422  04  04
423  43 RCL
424  38  38
425  58 FIX
426  06  06
427  69 □P
428  06  06
429  91 R/S
430  92 RTN
431  76 LBL
432  50 I×I
433  25 CLR
434  98 ADV
435  22 INV
```

4. To check modified program against this listing, press GTO, 385, LRN, and then use SST key to single step through program past step 427. After verification of modification, press LRN. Modified program can now be used as is and (or) can be loaded onto new magnetic cards for future use. (Modification just described does not affect original magnetic cards.)

Instructions for use (without printer)

1. Load unmodified program from magnetic cards and modify as above, or load previously modified program. See INSTRUCTIONS FOR USE (p. 6)., steps 1 through 8 for loading.
2. Initialize and enter data as in INSTRUCTIONS FOR USE, steps 9 through 17.
3. Press C. Correlation coefficient is displayed.
4. Press E. Time (in millions of years) at lower intercept will be displayed (after 1 to 3 minutes wait).
5. Press R/S. 7/5 isotopic ratio at lower intercept is displayed.
6. Press R/S again, for 6/8 ratio at lower intercept.
7. Press R/S again. Time at upper intercept will be displayed.
8. Press R/S: 7/5 ratio at upper intercept.
9. Press R/S: 6/8 ratio at upper intercept.