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955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 08003

SUBJECT: Relative Age Determination From Crater Morphology Studies - Case 340

DATE: August 4, 1970

FROM: A. F. H. Goetz

ABSTRACT

Soderblom's method for age dating mare surfaces by crater morphology is presented in condensed form. By observing the largest unshadowed crater in the 10 m to 1 km diameter range on an Orbiter photograph, and using the figures included, an area can be dated in a relative sense. Soderblom's results on maria and several large craters are summarized.

An estimate of the absolute ages of the surfaces can be obtained by applying the age data from the Apollo 11 and 12 points and making an assumption about the meteoroid flux history.

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MEMORANDUM FOR FILE

INTRODUCTION

Determination of the age of areas on the lunar surface by crater counts has been attempted with varying degrees of success in the past. This memo discusses, in shortened form, a method for relative age determination developed by Larry Soderblom[1] of the California Institute of Technology.

Soderblom developed the method to overcome the two major shortcomings of previous methods:

1. Plotting of the entire crater diameter - frequency distribution, which is very time consuming.

2. Poor statistics for small areas. Counts over areas large enough to produce good statistics often cover several units of possibly different ages, which meant that only an average age was obtained. Swarms of secondaries can also skew the distribution.

CRATER DISTRIBUTION

A plot of the size frequency distribution of craters on the lunar surface reveals several pertinent features. Shown in Figure 1 are representative curves for old and young surfaces. For small crater diameters the curves coincide and have a slope of -2.0. This curve defines the equilibrium or steady-state surface and has been found to persist at all Surveyor landing sites.[2] Between diameters of about 10 meters and one kilometer the distributions have a slope of approximately -3.0. Craters in this size range are formed primarily by secondary impacts from material ejected during the formation of craters larger than several kilometers in diameter. The distribution for larger craters has a slope of about -1.7 and is attributed largely to primary impacts. This portion of the curve is not shown in Figure 1.

The diameter of the largest size crater in the steady-state portion of the distribution is designated C_S and gives a measure of the relative age of the surface.[2] Determining C_S accurately is subject to the problems outlined in the introduction.

METHOD

Soderblom's method utilizes the time-dependent change of the slope profile of craters having diameters near C_S. This change of slope is produced by erosional impacts which produce craters small compared to the crater being eroded.

The erosion by small bodies which individually produce only minor changes in the shape of a crater being eroded is nevertheless the dominant process by which the shape of craters of diameter less than one kilometer is changed. Therefore, the slope of a crater is a good indication of the cumulate number of small particles recorded since its formation and, hence, its age. During the period in which a crater is eroded, random statistical variations in the distribution of the small eroding impacts are averaged out because of their high frequency. By determining the relative age of the oldest crater on a surface, that surface can be dated in terms of the integrated particle flux. Absolute ages can be determined only after the particle flux history is known.

From the analytical erosion model given by Soderblom, the lifetime, τ, of a crater is

$$\tau = C \ln^{1/2} (S_i/S_t) D \qquad (1)$$

where C is a constant, S_i is the initial slope ($\sim$tan 30°), S_t is the lower termination slope, and D is the crater diameter.

It is not practical to determine an age from the slope frequency distribution since precise measurements of slope are not possible. However, the crater size D_S, the diameter at which the slope frequency distribution is terminated at the local sun angle (S_S), can be measured directly from photography. All craters larger than D_S have shadowed interiors.

Equation 1 can then be written

$$\tau = C \ln^{1/2} (S_i/S_S) D_S \qquad (2)$$

To determine D_S photographically, the most precise way is to measure the ratio (P) of unshadowed to shadowed craters as a function of diameter. The ratio is zero for craters larger than D_S. The form of the ratio predicted by the erosion model is shown for different sun angles in Figure 2 and can be expressed as:

$$P = 0, \; D > D_S$$

$$P = \frac{D_S}{D} - 1, \; C_S < D < D_S \qquad (3)$$

$$P = \frac{D_S}{C_S} - 1, \; D < C_S$$

For $D < C_S$, the constant value of P is dependent on photographic print quality since C_S is controlled by the lower limit of slope at which a crater is recognizable.

Equations (1) and (2) imply a time scale concomitant with a constant meteoroid flux history. Since a constant flux cannot be assumed, Soderblom has provided a standard for comparison of ages in terms of the size of crater, D_L, which would be eroded below some small slope S_f in the lifetime of the surface.

$$D_L = \frac{\ln^{1/2} (S_i/S_S)}{\ln^{1/2} (S_i/S_f)} D_S \qquad (4)$$

Soderblom found that D_S could be obtained from the photograph with nearly the same accuracy as obtained by completely defining the distribution shown in Figure 2.

TECHNIQUE

The method can be applied to any surface on which large-scale blanketing of the crater or slumping and mass wasting are not dominating factors in the erosion and destruction of craters. This criterion rules out almost any lunar region other than the maria.

In order to make consistent age determinations, the photographic definition of a shadow must be fixed. Soderblom has chosen the definition that a crater is unshadowed when features such as fractures and craterlets are visible in the nearly shaded portion of the wall.

The technique for determining D_S involves looking for the largest clearly unshadowed crater for the lower limit of D_S. The upper limit is defined as the largest crater whose shadow profile has just disappeared.

Anomalous depressions which may initially have had small slopes can be avoided by testing to see if the unshadowed craters smaller than the "largest unshadowed crater" become rapidly more abundant with decreasing size. Using this technique the uncertainty in D_S is about 10%. Of course, D_S varies with local sun angle. Figures 3 and 4 are look-up tables for determining D_L. S_f, the final slope, is taken as tan 4°. Figure 5 is a plot of the relative ages in the form of D_L for different maria and selected craters. If one wishes to assume a flux history, absolute ages can be assigned to the abscissa.

2015-AFHG-gmr

A. F. H. Goetz

Attachment
References
Figures 1-5

REFERENCES

1. L. A. Soderblom, The Distribution and Ages of Regional Lithologies in the Lunar Maria, Ph.D. thesis, California Institute of Technology, 1970.

2. E. M. Shoemaker, R. M. Batson, H. E. Holt, E. C. Morris, J. J. Rennilson, and E. A. Whitaker, Observations of the Lunar Regolith and the Earth From the Television Camera on Surveyor 7, Jour. of Geoph. Res., 74, 6081, 1969.

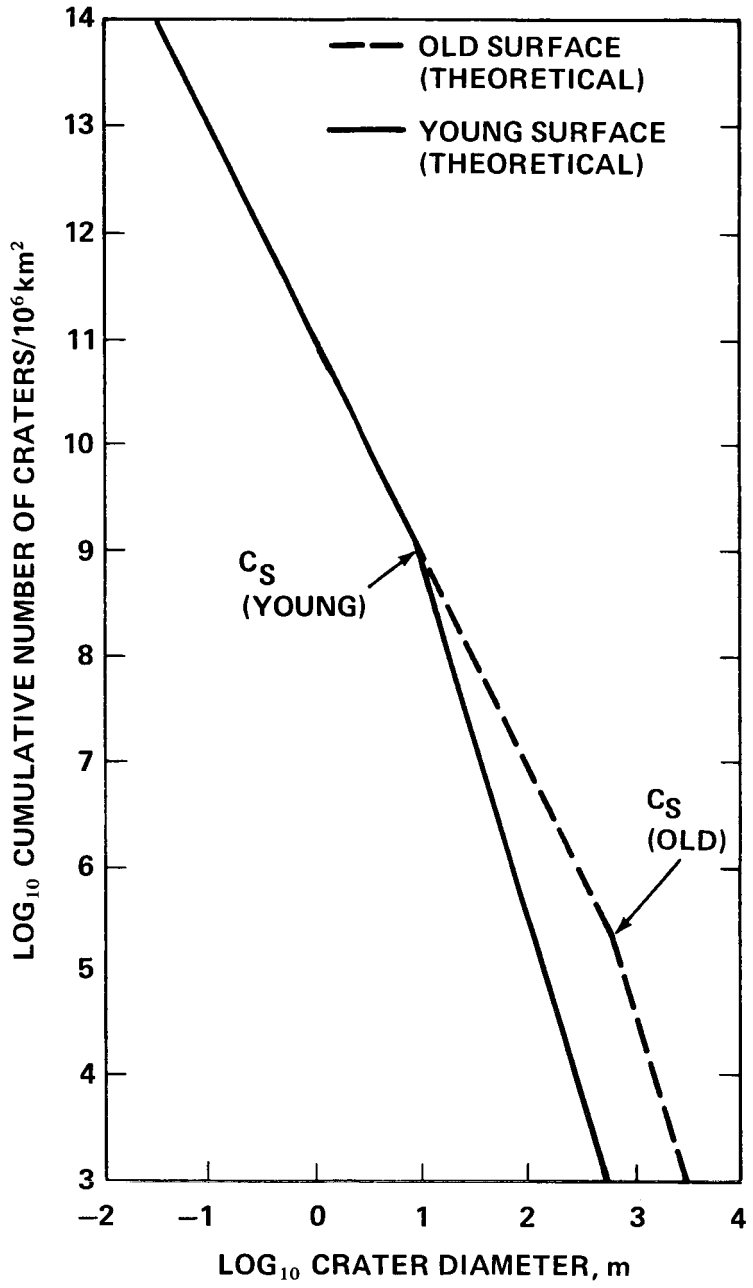

FIGURE 1 - THEORETICAL SIZE DISTRIBUTIONS OF CRATERS ON OLD AND YOUNG SURFACES. FOR OLDER SURFACES C_S, THE UPPER LIMIT OF THE STEADY STATE DISTRIBUTION, INCREASES.

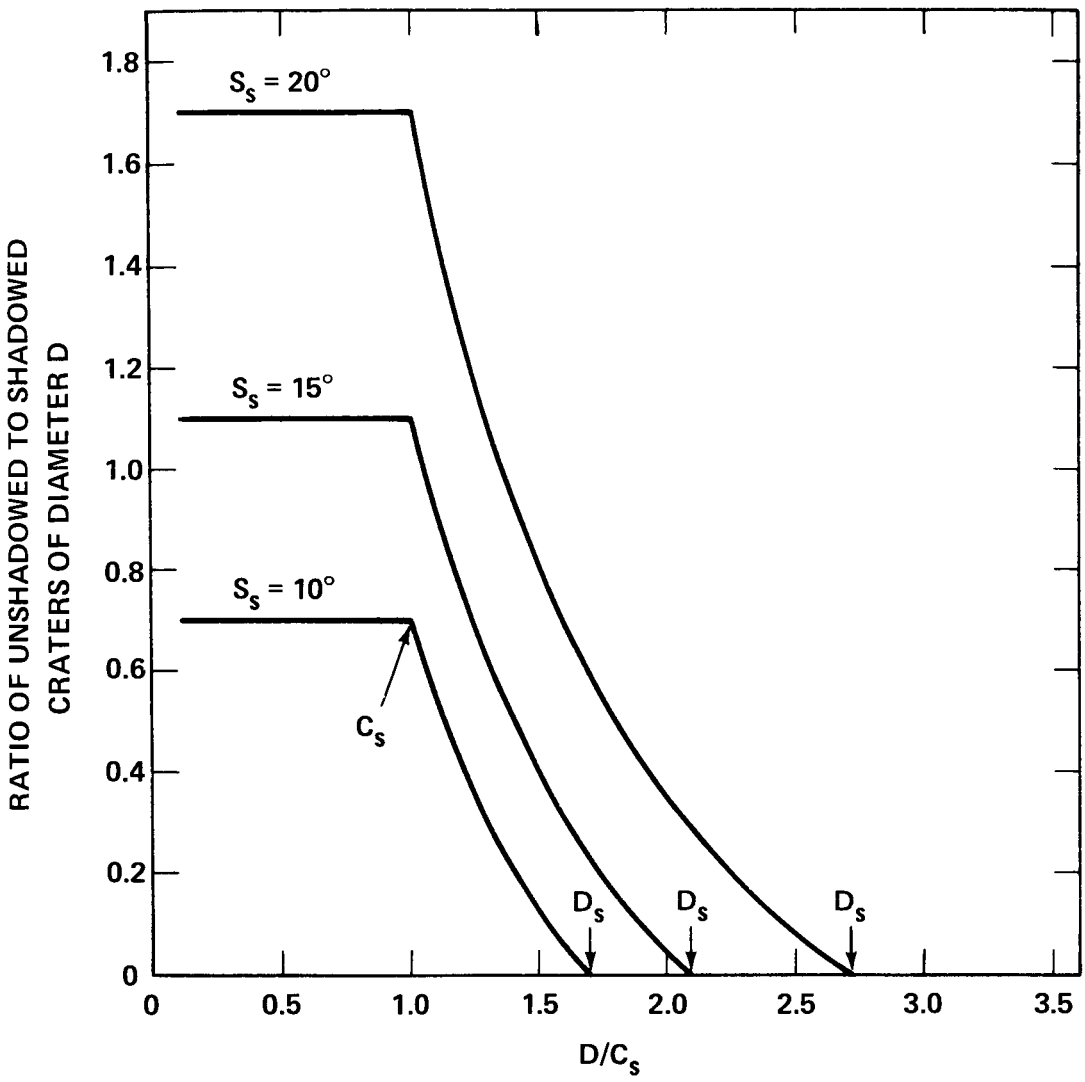

FIGURE 2 - THE RATIO OF UNSHADOWED TO SHADOWED CRATERS AS A FUNCTION OF CRATER DIAMETER, AS CALCULATED FROM THE EROSION MODEL. THIS RATIO, P, IS SHOWN FOR THREE SOLAR ELEVATION ANGLES, S_S. D_S IS THE DIAMETER OF THE LARGEST UNSHADOWED CRATER AND INCREASES WITH INCREASING S_S. C_S IS THE UPPER LIMIT OF DIAMETER OF CRATERS IN STEADY STATE. IT WAS ASSUMED THAT C_S DOES NOT VARY WITH SOLAR ELEVATION ANGLE. (SODERBLOM)

D_s (FIELD)

S_s SUN ELEVATION ANGLE IN DEGREES

DIAMETER OF CRATER ERODED TO BELOW 4° (METERS)

D_L	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5
10.	24	22	21	20	19	18	17	16	15	15	14	13	13	12	12	11	11	10
20.	48	45	42	40	38	36	34	33	31	30	29	27	26	25	24	23	22	21
30.	72	68	64	60	57	54	52	49	47	45	43	41	40	38	36	35	33	31
40.	97	90	85	80	76	72	69	66	63	60	58	55	53	51	48	46	44	42
50.	121	113	106	101	95	91	86	82	79	75	72	69	66	63	61	58	55	52
60.	145	136	128	121	114	109	104	99	95	91	87	83	80	76	73	70	66	63
70.	170	159	149	141	134	127	121	116	110	106	101	97	93	89	85	81	77	74
80.	194	181	171	161	153	145	138	132	126	121	116	111	106	102	97	93	89	84
90.	218	204	192	181	172	164	156	149	142	136	130	125	120	114	110	105	100	95
100.	243	227	213	202	191	182	173	165	158	151	145	139	133	127	122	116	111	105
110.	267	250	235	222	210	200	191	182	174	166	159	153	146	140	134	128	122	116
120.	291	272	256	242	229	218	208	198	190	182	174	167	160	153	146	140	133	126
130.	316	295	278	262	249	236	225	215	206	197	188	181	173	166	158	151	144	137
140.	340	318	299	282	268	255	243	232	221	212	203	194	186	178	171	163	155	148
150.	364	341	320	303	287	273	260	248	237	227	218	208	200	191	183	175	166	158
160.	389	363	342	323	306	291	277	265	253	242	232	222	213	204	195	186	178	169
170.	413	386	363	343	325	309	295	281	269	257	247	236	226	217	207	198	189	179
180.	437	409	385	363	344	328	312	298	285	273	261	250	240	229	220	210	200	190
190.	462	432	406	383	364	346	329	315	301	288	276	264	253	242	232	221	211	200
200.	486	454	427	404	383	364	347	331	317	303	290	278	266	255	244	233	222	211
210.	510	477	449	424	402	382	364	348	332	318	305	292	280	268	256	245	233	222
220.	534	500	470	444	421	400	382	364	348	333	319	306	293	281	268	256	244	232
230.	559	523	491	464	440	419	399	381	364	349	334	320	306	293	281	268	256	243
240.	583	545	513	485	459	437	416	397	380	364	348	334	320	306	293	280	267	253
250.	607	568	534	505	479	455	434	414	396	379	363	348	333	319	305	291	278	264
260.	632	591	555	525	498	473	451	431	412	394	377	362	346	332	317	303	289	275
270.	656	614	577	545	517	492	468	447	428	409	392	375	360	344	330	315	300	285
280.	680	636	598	565	536	510	486	464	443	424	406	389	373	357	342	326	311	296
290.	705	659	620	586	555	528	503	480	459	440	421	403	386	370	354	338	322	306
300.	729	682	641	606	574	546	521	497	475	455	436	417	400	383	366	350	333	317
310.	753	705	663	626	594	564	538	514	491	470	450	431	413	396	378	362	345	327
320.	778	727	684	646	613	583	555	530	507	485	465	445	426	408	391	373	356	338
330.	802	750	705	666	632	601	573	547	523	500	479	459	440	421	403	385	367	349
340.	826	773	727	687	651	619	590	563	539	515	494	473	453	434	415	397	378	359
350.	851	795	748	707	670	637	607	580	554	531	508	487	466	447	427	408	389	370
360.	875	818	770	727	689	656	625	595	570	546	523	501	480	459	440	420	400	380
370.	899	841	791	747	709	674	642	613	586	561	537	515	493	472	452	432	411	391
380.	924	864	812	767	728	692	659	630	602	576	552	529	506	485	464	443	423	401
390.	948	886	834	788	747	710	677	646	618	591	566	543	520	498	476	455	434	412
400.	972	909	855	808	766	728	694	663	634	607	581	557	533	511	488	467	445	423
410.	997	932	877	828	785	747	712	679	650	622	595	570	546	523	501	478	456	433
420.	1021	955	898	848	804	765	729	695	665	637	610	584	560	536	513	490	467	444
430.	1045	977	919	869	824	783	746	713	681	652	624	598	573	549	525	502	478	454
440.	1069	1000	941	889	843	801	764	729	697	667	639	612	586	562	537	513	489	465
450.	1094	1023	962	909	862	820	781	746	713	682	654	626	600	574	550	525	500	475
460.	1118	1046	983	929	881	838	798	762	729	698	668	640	613	587	562	537	512	486
470.	1142	1068	1005	949	900	856	815	779	745	713	683	654	627	600	574	548	523	497
480.	1167	1091	1026	970	919	874	833	795	761	728	697	668	640	613	586	560	534	507
490.	1191	1114	1048	990	939	892	851	812	776	743	712	682	653	625	598	572	545	518
500.	1215	1137	1069	1010	958	911	868	829	792	758	726	696	667	638	611	583	556	528

FIGURE 3

D_s (FIELD)

S_s SUN ELEVATION ANGLE IN DEGREES

DIAMETER OF CRATER ERODED TO BELOW 4° (METERS) D_L	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5
510.	1240	1159	1090	1030	977	929	885	845	808	773	741	710	680	651	623	595	567	539
520.	1264	1182	1112	1050	996	947	903	862	824	789	755	724	693	664	635	607	578	550
530.	1288	1205	1133	1071	1015	965	920	878	840	804	770	738	707	677	647	618	589	560
540.	1313	1228	1155	1091	1034	984	937	895	856	819	784	751	720	689	660	630	601	571
550.	1337	1250	1176	1111	1053	1002	955	912	872	834	799	765	733	702	672	642	612	581
560.	1361	1273	1197	1131	1073	1020	972	928	887	849	813	779	747	715	684	653	623	592
570.	1386	1296	1219	1151	1092	1038	989	945	903	865	828	793	760	728	696	665	634	602
580.	1410	1319	1240	1172	1111	1056	1007	961	919	880	843	807	773	740	708	677	645	613
590.	1434	1341	1262	1192	1130	1075	1024	978	935	895	857	821	787	753	721	688	656	624
600.	1459	1364	1283	1212	1149	1093	1042	994	951	910	872	835	800	766	733	700	667	634
610.	1483	1387	1304	1232	1168	1111	1059	1011	967	925	886	849	813	779	745	712	679	645
620.	1507	1410	1326	1253	1188	1129	1076	1028	983	940	901	863	827	792	757	724	690	655
630.	1532	1432	1347	1273	1207	1148	1094	1044	998	956	915	877	840	804	770	735	701	666
640.	1556	1455	1368	1293	1226	1166	1111	1061	1014	971	930	891	853	817	782	747	712	676
650.	1580	1478	1390	1313	1245	1184	1128	1077	1030	986	944	905	867	830	794	759	723	687
660.	1604	1500	1411	1333	1264	1202	1146	1094	1046	1001	959	919	880	843	806	770	734	698
670.	1629	1523	1433	1354	1283	1220	1163	1111	1062	1016	973	932	893	855	818	782	745	708
680.	1653	1546	1454	1374	1303	1239	1180	1127	1078	1031	988	946	907	868	831	794	756	719
690.	1677	1569	1475	1394	1322	1257	1198	1144	1094	1047	1002	960	920	881	843	805	768	729
700.	1702	1591	1497	1414	1341	1275	1215	1160	1109	1062	1017	974	933	894	855	817	779	740
710.	1726	1614	1518	1434	1360	1293	1233	1177	1125	1077	1031	988	947	907	867	829	790	750
720.	1750	1637	1540	1455	1379	1312	1250	1193	1141	1092	1046	1002	960	919	880	840	801	761
730.	1775	1660	1561	1475	1398	1330	1267	1210	1157	1107	1061	1016	973	932	892	852	812	772
740.	1799	1682	1582	1495	1418	1348	1285	1227	1173	1123	1075	1030	987	945	904	864	823	782
750.	1823	1705	1604	1515	1437	1366	1302	1243	1189	1138	1090	1044	1000	958	916	875	834	793
760.	1848	1728	1625	1535	1456	1384	1319	1260	1205	1153	1104	1058	1013	970	928	887	846	803
770.	1872	1751	1647	1556	1475	1403	1337	1276	1220	1168	1119	1072	1027	983	941	899	857	814
780.	1896	1773	1668	1576	1494	1421	1354	1293	1236	1183	1133	1086	1040	996	953	910	868	825
790.	1921	1796	1689	1596	1513	1439	1372	1311	1252	1198	1148	1100	1053	1009	965	922	879	835
800.	1945	1819	1711	1616	1533	1457	1389	1326	1268	1214	1162	1114	1067	1022	977	934	890	846
810.	1969	1842	1732	1636	1552	1476	1406	1343	1284	1229	1177	1127	1080	1034	990	945	901	856
820.	1994	1864	1754	1657	1571	1494	1424	1359	1300	1244	1191	1141	1093	1047	1002	957	912	867
830.	2018	1887	1775	1677	1590	1512	1441	1376	1316	1259	1206	1155	1107	1060	1014	969	923	877
840.	2042	1910	1796	1697	1609	1531	1458	1392	1331	1274	1220	1169	1120	1073	1026	980	935	888
850.	2067	1933	1818	1717	1628	1549	1476	1409	1347	1289	1235	1183	1133	1085	1038	992	946	899
860.	2091	1955	1839	1738	1648	1567	1493	1426	1363	1305	1249	1197	1147	1098	1051	1004	957	909
870.	2115	1978	1860	1758	1667	1585	1510	1442	1379	1320	1264	1211	1160	1111	1063	1015	968	920
880.	2139	2001	1882	1778	1686	1603	1528	1459	1395	1335	1279	1225	1173	1124	1075	1027	979	930
890.	2164	2024	1903	1798	1705	1621	1545	1475	1411	1350	1293	1239	1187	1137	1087	1039	990	941
900.	2188	2046	1925	1818	1724	1640	1563	1492	1427	1365	1308	1253	1200	1149	1100	1050	1001	951
910.	2212	2069	1946	1838	1743	1658	1580	1509	1442	1381	1322	1267	1214	1162	1112	1062	1013	962
920.	2237	2092	1967	1859	1762	1676	1597	1525	1458	1396	1337	1281	1227	1175	1124	1074	1024	973
930.	2261	2115	1989	1879	1782	1694	1615	1542	1474	1411	1351	1295	1240	1188	1136	1086	1035	983
940.	2285	2137	2010	1899	1801	1712	1632	1558	1490	1426	1365	1308	1254	1202	1148	1097	1046	994
950.	2310	2160	2032	1919	1820	1731	1649	1575	1506	1441	1380	1322	1267	1213	1161	1109	1057	1004
960.	2334	2183	2053	1940	1839	1749	1667	1591	1522	1456	1395	1336	1280	1226	1173	1121	1068	1015
970.	2358	2206	2074	1960	1858	1767	1684	1608	1538	1472	1409	1350	1294	1239	1185	1132	1079	1025
980.	2383	2228	2096	1980	1877	1785	1702	1625	1555	1487	1424	1364	1307	1251	1197	1144	1090	1036
990.	2407	2251	2117	2000	1897	1804	1719	1641	1569	1502	1438	1378	1320	1264	1210	1156	1102	1047
1000.	2431	2274	2139	2020	1916	1822	1736	1658	1585	1517	1453	1392	1334	1277	1222	1167	1113	1057

FIGURE 4

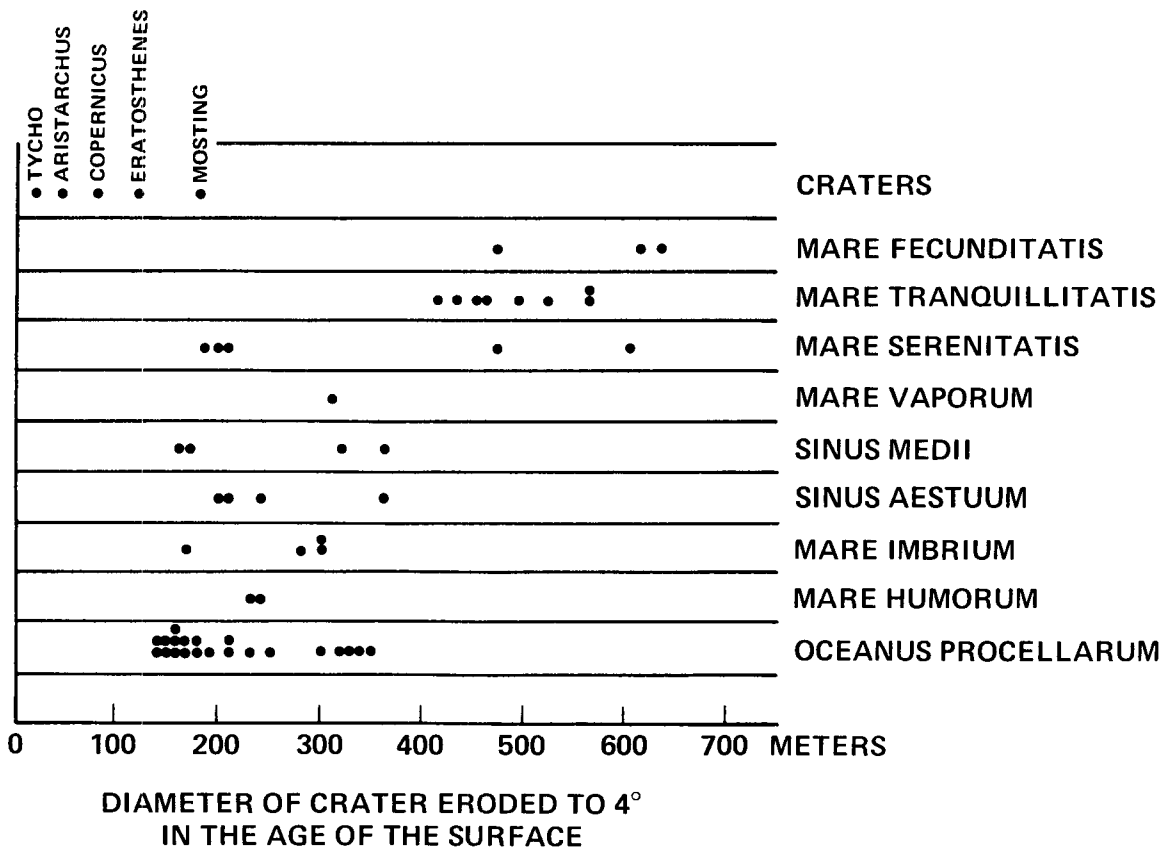

FIGURE 5 - RELATIVE AGES OF MARE UNITS AND MAJOR CRATERS. THE DIAMETER OF A CRATER WHOSE WALLS WOULD BE ERODED TO 4° IN A TIME EQUAL TO THE AGE OF THE SURFACE IS SHOWN FOR EACH AREA STUDIED IN NINE MARE REGIONS. ALSO SHOWN ARE THE RELATIVE AGES OF FIVE MAJOR CRATERS. (SODERBLOM)

BELLCOMM, INC.

SUBJECT: Relative Age Determination From Crater Morphology Studies

FROM: A. F. H. Goetz

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