THE AGES OF ANGRITES. Y. Amelin[1,2], [1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada (yamelin@nrcan.gc.ca), [2]Planetary Science Institute and Research School of Earth Sciences, The Australian National University, Canberra ACT 0200, Australia.

Introduction: Pb-Pb ages of angrites, a small yet remarkable group of meteorites, are commonly used as benchmarks of the early Solar System chronology. Angra dos Reis (AdoR, originally the prototypical meteorite of this group, which is now considered an anomalous angrite [1]) has been long known as one of the oldest rocks in our Solar System [2,3]. A Pb-Pb model age of pyroxene from the angrite Lewis Cliff (LEW) 86010 [4] serves as a reference point for the timescale based on the ^{53}Mn-^{53}Cr decay scheme [5]. A high-precision Pb-Pb isochron date for the angrite Sahara 99555 [6] has been proposed as a new reference point for the timescale and for calculation of the minimum age of our Solar System.

Recent developments in Pb isotopic analysis of meteorites: a new mineral washing procedure (described below) for more complete removal of common Pb, and a ^{202}Pb-^{205}Pb double spike analytical protocol optimized for analysis of sub-nanogram quantities of Pb [7], allow obtaining more precise and reliable dates of angrites. Here I report Pb isotopic data for pyroxenes and bulk rock samples from the angrites AdoR, LEW 86010 and D'Orbigny, as well as preliminary data for Sahara 99555, and discuss their implications for the early Solar System chronology.

Samples and procedures: Pyroxene fractions from AdoR and LEW 86010, provided by G.W. Lugmair, are splits of the mineral fractions analyzed by [4]. The fractions were additionally purified by hand-picking. A fragment of D'Orbigny, provided by M. Wadhwa, was crushed in an alumina mortar at the Geological Survey of Canada (GSC), and several fractions of euhedral and anherdal pyroxene were hand-picked from crushed material. Aliquots of the crushed material, without further separation, were analyzed as whole rock fractions. Fractions from Sahara 99555 separated at the Field Museum by grain size and magnetic susceptibility, were originally prepared for ^{26}Al-^{26}Mg and other isotopic studies. The fractions with medium magnetic susceptibility were mixtures of pyroxene, olivine, and intergrown pyroxene and olivine grains. Two pure pyroxene fractions were hand-picked from two of these mixed fractions. In addition to pyroxene and unseparated magnetic fractions, two aliquots of crushing fines were analyzed for U-Pb.

All fractions were rinsed with distilled acetone, weighted, and leached in 0.5M $HN0_3$ 4-5 times with 10-20 minute ultrasonic agitation during each leaching step (ultrasonic washes combined as Wash-1). Mineral fractions were further leached in hot 6M HCl and twice in hot 7M HNO_3 (hot washes combined as Wash-2).

Washes and residues were spiked with ^{202}Pb-^{205}Pb-^{233}U-^{235}U mixed tracer and analyzed for U-Pb at the GSC, using procedures of [7].

Results: Pb isotope data for acid-washed pyroxenes and whole rocks are summarized in Fig. 1 and Table 1.

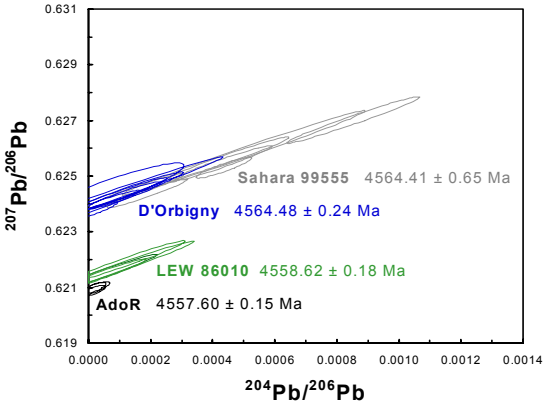

Fig. 1. Pb-Pb isochron plot for acid-washed pyroxene and whole rock fractions of angrites. Preferred ages, shown in the figure, and highlighted in Table 1, are weighted averages of ^{207}Pb/^{206}Pb model dates for AdoR, LEW and D'Orbigny, and isochron date for Sahara 99555.

Three meteorites, AdoR, LEW and D'Orbigny, contain no common Pb in excess of analytical blank after acid washing. The ^{207}Pb/^{206}Pb ratios are reproducible between fractions, and their weighted averages provide straightforward measures of the age. Meaningful Pb-Pb isochron dates could not be calculated, because there is no spread in ^{204}Pb/^{206}Pb outside of analytical errors.

The size fractions from Sahara 99555, and, in particular, two "fines" fractions with measured ^{206}Pb/^{204}Pb of 360-560, (not included in age calculations) contain variable common Pb in excess of analytical blank. The current best age estimate for Sahara 99555 of 4564.41 ± 0.65 Ma (MSWD = 4.2) is given by a ^{204}Pb/^{206}Pb-^{207}Pb/^{206}Pb isochron. This value is less reliable than the ages of other three angrites, because of excess scattering of the data in the isochron plot, probably as a result of minor Pb contamination during crushing. Additional analyses from a separate specimen of Sahara 99555 are in progress.

The U-Pb systems in the AdoR and LEW pyroxenes are concordant or nearly concordant, whereas pyroxenes and whole rocks of D'Orbigny and Sahara 99555 show up to ~5% reverse discordance.

The content of leachable common Pb varies greatly among the four angrites. LEW 86010 contains large amount of acid soluble Pb with uniform isotopic composition, similar to modern terrestrial crustal Pb ($^{206}Pb/^{204}Pb$=18.7, $^{207}Pb/^{206}Pb$=0.848), first described in [4]. The content of leachable common Pb in D'Orbigny and Sahara 99555 is 10-100 times smaller. There is almost no leachable common Pb in AdoR.

The chemical and mineralogical occurrence of abundant leachable Pb in LEW 86010 is unclear. The Pb-rich phase must be volumetrically minor, but very efficient absorber of Pb and selected other elements. A possible candidate is a thin film of Mn-oxide.

Comparison with previous Pb-isotopic dates: The age of AdoR obtained in this study agrees with the values reported in more recent studies [4,8], and is more precise than the previously reported values.

The age of LEW 86010 obtained here is 0.8±0.5 Ma older than reported in [4]. This disagreement, slightly outside analytical error, is easily explained, if the pyroxene fraction with most radiogenic Pb analyzed in [4] contained residual acid-soluble Pb abundant in the LEW 86010, rather than primordial Pb as was assumed in the model age calculation in [4].

The age of D'Orbigny is consistent with the values reported in [8], but not with the previously reported younger ages (e.g., [9]).

The isochron age of Sahara 99555 obtained here is 1.8±0.7 Ma younger than the high-precision age for the same meteorite reported by [6]. The cause of this disagreement is unclear and requires further investigation.

Age intervals between angrite formation from Pb-isotopic and Mn-Cr data: new Pb-isotope data yield the following ages of angrites relative to LEW 86010: -1.02±0.23 Ma for AdoR, 5.86±0.30 Ma for D'Orbigny, and 5.79±0.67 Ma for Sahara 99555. Younger Pb-Pb age of AdoR compared to LEW 86010 is consistent with the AdoR olivine analysis plotting below the LEW mineral isochron in the ^{53}Mn-^{53}Cr isochron plot [5], although the ^{53}Mn-^{53}Cr data for AdoR are not sufficiently precise to resolve the ages. The age intervals for D'Orbigny and Sahara 99555 from the Pb-isotopic data are larger than from Mn-Cr data: 5.1±0.3 Ma [10] and 4.4±0.5 Ma [11] for D'Orbigny, and 4.4±0.7 Ma for Sahara 99555 [11]. This difference may be explained by closing Cr diffusion in olivine at lower temperature than Pb diffusion in pyroxene [12,13], if D'Orbigny and Sahara 99555 cooled more slowly than LEW 86010.

References: [1] Mittlefehldt D. W. et al. (2002) *Meteoritics & Planet. Sci., 37,* 345-369. [2] Tatsumoto M. et al. (1973) *Science 180,* 1279-1283. [3] Wasserburg G. J. et al. (1977) *EPSL 35,* 294-316. [4] Lugmair G. W. and Galer S. J. G. (1992) *GCA 56,* 1673-1694. [5] Lugmair G. W. and Shukolyukov A. (1998) *GCA 62,* 2863-2886. [6] Baker J. et al. (2005) *Nature 436,* 1127-1131. [7] Amelin Y. and Davis W. J. (2006) *J. Analyt. Atomic Spectrom. 21,* 1053-1061. [8] Zartman R. E. et al. (2006) *LPS 37,* abstract # 1580. [9] Jagoutz E. et al. (2002) *LPS 33,* abstract # 1043. [10] Glavin D. P. et al. (2004) *Meteoritics & Planet. Sci., 39,* 693-700. [11] Sugiura N. et al. (2005) *Earth Planets Space 57,* e13-e16. [12] Ito M. and Ganguly J. (2006) GCA70, 799-809. [13] Cherniak D. J. (2001) *Chem. Geol. 177,* 381-397.

Table 1. Summary of ^{207}Pb-^{206}Pb dates of angrites (preferred ages in bold)

Meteorite	Fractions analyzed	The range of measured $^{206}Pb/^{204}Pb$ ratios	The range of blank-corrected $^{206}Pb/^{204}Pb$ ratios	Weighted average of $^{207}Pb/^{206}Pb$ model dates	Pb-Pb isochron date	U-Pb 3D-linear isochron date
Angra dos Reis	3 Px	11,234-14,100	55,300-75,800	**4557.60 ± 0.15 MSWD=0.80**	(4556.8 ± 7.6) MSWD=0.0044	4557.39 ± 0.54 MSWD=0.12
Lewis Cliff 86010	4 Px	2,547-4,553	7,849-42,400	**4558.62 ± 0.18 MSWD=0.37**	(4558.48±0.57) MSWD=0.046 4558.66±0.15 MSWD=0.71 (resid.+washes)	4558.74 ± 0.20 MSWD = 1.4
D'Orbigny	5 Px + 3 WR	1,746-8,495	7,877-247,000	**4564.48±0.24 MSWD=1.9**	4564.63±0.28 MWSD=3.5	4565.0±2.3 MSWD=62
Sahara 99555	2 Px + 5 WR	889-2,793	1,173-6,674	4563.76±0.42 MSWD=6.0	**4564.41±0.65 MSWD=4.2**	4564.65±0.67 MSWD=7.8