FINAL TECHNICAL REPORT

INVESTIGATIONS OF THE GEOCHEMICAL EVOLUTION OF THE STILLWATER COMPLEX AND ORIGIN OF PLATINUM GROUP ELEMENT DEPOSITS FROM ANALYSIS OF LEAD ISOTOPES

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Final Report of the project,

Investigations of the geochemical evolution of the Stillwater Complex and origin of platinum group element deposits from analysis of lead isotopes (USGS 05HQGR0155)

Edmond A. Mathez, Principal Investigator

Introduction

The objective of this project was to use Pb isotopes as a tracer of geochemical evolution of the crystallizing Stillwater Complex. In particular, we sought to (1) separate and characterize the Pb fractions of different reservoirs present in the rocks, (2) identify the Pb initial isotopic compositions of the Stillwater magmas and thus characterize their sources, and (3) determine when the original Pb isotopic compositions were modified. The research focused mainly on the *in situ* analysis of Pb isotopes by laser ablation multicollector inductively coupled plasma mass spectrometer (LA-MC-ICP-MS). In addition, we proposed to unpack, organize, and accession certain Stillwater drill cores donated to the American Museum of Natural History by the Stillwater Mining Company so that the cores would be more easily accessible for future research efforts.

As proposed, the core has been unpacked, organized, stored in a safe and easily accessible facility, and accessioned into the museum collections. The research has been largely accomplished, and a draft manuscript describing that research has been written and accompanies this report. The main findings of our research are as follows.

(1) We have documented the existence of a component in the Stillwater Complex characterized by much less radiogenic Pb than previously reported. We interpret this component to represent a primary magma that originated from a mantle source region from which a partial melt had been extracted long before the formation of the Stillwater magma.

(2) We have shown that the Stillwater sulfides exhibit wide ranges in initial Pb isotopic composition and that they contain a Pb component that has been acquired only recently, probably during Laramide uplift and alteration about 60 Ma ago.

(3) The research is leading us to a conception whereby the Stillwater Complex evolved by periodic injection of crystal –laden batches of magma rather than injection of just pure liquids. The process may account for some of the layering.

The draft manuscript is nearly complete (some of the background figures remain to be assembled). Before submitting it for publication, however, my coworkers and I shall acquire a limited number of additional Pb isotope analyses to confirm our conclusions. We shall acquire these data as soon as possible and at no additional cost to the USGS.

The following is a detailed account of our work and has been taken largely *verbatim* from the manuscript.

Samples

Samples were obtained from a variety of localities from drill core and from underground workings (Table 1). Several come from two cores (355-16 and 355-32) through the lower Ultramafic and Basal series, including the basal sulfide zone (Page, 1979; Zientek, 1983). The bore holes were originally drilled by AMAX many years ago and subsequently acquired by Stillwater Mining Company. A second set of samples come from Stillwater

Mining Company core 791-1, which penetrated a portion of the Lower Banded series. These cores are now part of the collections of the American Museum of Natural History. A third set of samples were collected by I.S. McCallum during tunnel boring operations through the Banded series. Brief descriptions of the samples are included in Table 1.

Analytical procedures

Prior to analysis for Pb isotopes, the sulfides were analyzed by electron probe utilizing synthetic and natural sulfides as standards and applying standard ZAF correction procedures. The major sulfide minerals present are pyrrhotite, pentlandite, and chalcopyrite.

Lead isotope analyses were obtained by LA-MC-ICP-MS using a 213 nm NewWave frequency-quintupled Nd-YAG laser in Q-switched mode coupled with a NuPlasma multicollector ICP-MS. Ablation was made under a He atmosphere. A He flow rate of ~0.80 l/m was maintained to sweep the ablated particulates from ablation chamber into the ICP-MS plasma.

Laser spot size, pulse frequency and translation rate were adjusted to optimize signal size while maintaining suitable spatial resolution and were generally in the range of 80-100 μm, 10-20 hz and 2-5 μm/s for plagioclase analyses and 50-100μm, 10-20 hz and 0-2 μm/s for sulfide analyses. Practically, this meant that plagioclase analysis required making a laser track typically 400 to 500 μm long, while it was possible to analyze most sulfides with a stationary beam (Fig. 1).

Faraday cups used to monitor ^{208}Pb, ^{207}Pb, ^{206}Pb ion beams and ion counters used for ^{204}Pb, ^{202}Hg and ^{200}Hg. Interference of ^{204}Hg on ^{204}Pb was corrected using both on-peak zero and in-run measurement of ^{202}Hg and ^{200}Hg ion beams. Mass bias and ion counter gains were measured throughout the analytical session from measurement of NIST 612 and NIST 610 silicate glass standards. Uncertainties in mass bias and ion counter gains are in the order, respectively, of 0.1%/amu and 0.4%.

Errors

The reported uncertainties (Table 2) reflect the standard error calculated from 4 to 10, 15 s measurement blocks. The errors for most analyses turned out to be relatively large due to the generally low Pb contents of both plagioclase and sulfides, which had been reported by Wooden et al. (1991) and McCallum et al. (1999). For example, McCallum et al. (1999, sample 93-2a, Table 1) reported that the primary magmatic sulfide fraction separated from one of their samples contained < 1.2 ppm Pb.

Variations in Pb isotopic ratios as functions of the magnitude of the analytical errors are plotted in Figure 2. While analyses characterized by high errors commonly lie within the $\pm 3\ \sigma$ envelope, many analyses with relatively small errors lie well beyond that envelope. This demonstrates that much of the compositional variability is not associated with analytical error but is a real feature of the data. The distribution of compositions with respect to their errors further justifies our use of analyses even with large errors. Despite the general consistency of all the analyses, however, we consider only those for which 1 σ errors < 1.2% for ^{208}Pb/^{204}Pb and < 1.6% for ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb, and for which the magnitude of the Pb signal was > 1.5 mV. These editing criteria reduced the number of analyses from 108 to 69. Only the latter are tabulated and plotted on the figures that follow.

Results

The edited Pb data are listed in Table 2. Several interesting features of the data are illustrated in Figure 3. First, except for one, all plagioclase analyses lie within the 2σ error of the 2.7 Ga geochron. This confirms that the plagioclase is generally free of U and has not otherwise been burdened by inclusion of Pb from external sources after crystallization because, had U been present, it would have displaced the compositions to the right of the geochron.

The 2.7 Ga geochron refers to all permissible Pb isotopic compositions corresponding to a range of μ ($^{238}U/^{204}Pb$) ratios of Earth reservoirs that had evolved in terms of Pb by the same process, in this case by a single-stage evolution from 4.45 Ga (Zhang, 2002). It can be seen that while the plagioclase compositions lie on the geochron, they are dispersed along it, as are those sulfide compositions that fall near the geochron. The dispersion implies that the plagioclase and sulfide contain Pb originating from more than one reservoir in existence at 2.7 Ga.

On Figure 3a are also plotted the compositions of plagioclase mineral separates reported by Wooden et al. (1991). As noted, Wooden et al. (1991) argued that plagioclase crystallized from a single magma composition represented by the least radiogenic plagioclase. The latter is similar to the least radiogenic plagioclase analyzed by Bosch et al. (1991). Most of our sulfide and plagioclase analyses lying near the 2.7 Ga isochron are within analytical error of the least radiogenic Wooden—Bosch composition.

Several of the plagioclase and sulfide analyses reported here have considerably lower $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios than those determined by Wooden et al. (1991). A number of analyses fall, with error (Fig. 3b), on the bulk silicate Earth composition ($\mu = 9.0$), which would represent that of a 2.7 Ga old undifferentiated mantle. One plagioclase composition, however, lies well below the bulk silicate Earth composition, even taking into account the large analytical error (Fig. 3b). The analysis is of a plagioclase [791-1(130), #3, Table 1] from Gabbronorite II.

The sulfide data are plotted on Figure 3(c) and compared to analogous data of McCallum et al. (1999). The latter form an linear trend extending from the 2.7 Ga isochron to more radiogenic ratios, and McCallum et al. (1999) interpreted the array of compositions to be due to the mixing of original magmatic Pb with Pb taken up by sulfide during hydrothermal recrystallization at 1.6 Ga. Many of the sulfide compositions reported here contain Pb that appears to be much younger. The young Pb may have been introduced into the sulfide during the late Cretaceous Laramide orogeny, when the Stillwater Complex was uplifted, tilted, and faulted, and the rocks experienced low temperature alteration.

On Figure 3(c), the fields labeled 1 and 2 circumscribe, respectively, data from samples 355-32(117), a bronzitite from the Basal series, and 355-16(105.06), a dunite from near the base of the Ultramafic series (for clarity, the fields do not delineate analyses from these samples that lie near the 2.7 Ga geochron). It is obvious that the two different samples contain young Pb of two different compositions. The three points labeled GNII are gabbronorite II sample 791-1(88.29). The sulfides in this sample may contain Pb from these two different young sources.

With regard to $^{208}Pb/^{204}Pb$ ratios, most plagioclase compositions fall very close to the least radiogenic compositions of Wooden et al. (1991) and Bosch et al. (1991) (Fig. 4). Several, however, fall on the bulk silicate Earth composition, which is less radiogenic with a $^{208}Pb/^{204}Pb$ ratio of ≈ 33.1 and corresponding ω ($^{232}Th/^{204}Pb$) and κ ($^{232}Th/^{238}U$) values of 35 and 3.9, respectively. Furthermore, the least radiogenic Gabbronorite II plagioclase (^{208}Pb/^{204}Pb ratio ≈ 2.43) again falls well below the bulk silicate Earth composition.

Taken together, the ^{208}Pb/^{204}Pb and ^{206}Pb/^{204} ratios of plagioclase and sulfide comprise a diffuse, linear array that also includes the analyses of Wooden et al. (1991) and, except for two, of McCallum et al. (1999). Also plotted on Figure 4 is the evolution through time of the bulk silicate Earth with compositional parameters mentioned above. The coincidence of the bulk silicate Earth curve with the compositional array indicates that most of the Stillwater compositions can be accounted for by mixing of old and young Pb from reservoirs that are not too different in terms of U, Th, and Pb abundances from the bulk silicate Earth. Finally, the sulfides with young Pb that fall below the bulk silicate Earth curve are mainly from sample 355-32(117), which also forms the distinctive array of elevated ^{207}Pb/^{204}Pb compositions on Figure 3(c) (field 1).

Significance of Pb data

We interpret the array of plagioclase and sulfide compositions lying on or near the 2.7 Ga geochron to have crystallized from two different composition magmas. The one, represented by the composition of the least radiogenic plagioclase from Gabbronorite II on Figures 3(b) and 4, possessed ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb ratios of approximately 13.1, 14.1, and 33.8 respectively. The calculated values of μ, ω, and κ of this parent magma are 8.0, 22, and 2.9, respectively. These characteristics imply that the magma originated from a depleted mantle that had undergone fractionation well before 2.7 Ga. The second magma composition is represent by the array of points clustering around the Wooden—Bosch least radiogenic plagioclase ($\mu \approx 9.7$). This composition is considerably more radiogenic than the 2.7 Ga bulk silicate Earth, no matter what model one chooses to describe its evolution. Wooden et al. (1991) suggested that the parent magma had inherited its composition from a mantle source that had been enriched in crustal components by subduction processes.

Inspection of figure 3(b) reveals that the plagioclase compositions from this and other studies are not evenly distributed along the 2.7 Ga isochron. Instead, there is a great preponderance of analyses centered on the relatively radiogenic Wooden-Bosch plagioclase, with only a few less radiogenic values from this study. One explanation for this distribution is that the least-radiogenic plagioclase grains had crystallized from a primitive magma before that magma had been injected into and mixed with a much larger mass of more radiogenic magma resident in the chamber represented by the now-exposed body. Whether the latter magma gained its radiogenic character by partial melting of a different, more radiogenic source, by a different pre-emplacement assimilation history, by assimilation of country rock surrounding the exposed fossil magma chamber, or by some other process is not known (but see below).

An alternative interpretation of the distribution of plagioclase compositions is that the Stillwater magmas had been contaminated by the surrounding, more radiogenic crust and that the contaminant was introduced during final solidification of the crystal pile or subsolidus cooling. The reason to consider such a possibility is that there is clear evidence from Os isotopes for contamination late in the crystallization/cooling history (Marcantonio et al., 1993). Had an such event modified plagioclase composition, one would expect a much greater and more even distribution of compositions along the geochron than observed. Therefore, this possibility is less likely.

There are abundant geochemical observations independent of the Pb data indicating that Stillwater parent magmas were in some manner contaminated with crustal material, either because they formed in a contaminated mantle or assimilated material in their passage through the crust (e.g., DePaolo and Wasserburg, 1979; Lambert and Simmons, 1987; Lambert et al., 1994). Yet other observations indicate that there existed a Stillwater magma that had originated from a depleted mantle source. In particular, Lambert et al. (1989, 1994) found that a number of samples from the Lower and Middle Banded series display ε_{Nd} values up to +1.9, implying derivation from a source that had been depleted in the LREEs long before Stillwater time (and adding support to the paradigm that the Stillwater Complex formed from "U" and "A" type magmas with distinct compositions and mantle sources). In addition, several analyses of Stillwater chromitites have yielded $^{187}Os/^{188}Os$ ratios less than the 2.7 Ga chondritic ratio of ≈ 1.090. Thus, the least radiogenic value reported is from a bulk-rock analysis of the G chromitite and possesses a $^{187}Os/^{188}Os$ ratio of 1.0608 (Lambert et al., 1994).

The relatively unradiogenic Pb isotopic compositions of individual plagioclase and sulfide grains reported here are consistent with the positive ε_{Nd} values and low $^{187}Os/^{188}Os$ ratios displayed by some of the rocks and reported in the literature.

Table 1. Samples used in this study

791-1 (88.3), 791-1(130). Gabbronorite II, Stillwater Mining Company core 791-1, 88.3 and 130.0 m depth, 126 and 84 m above Norite II—Gabbronorite II contact. Relatively fresh gabbro with 45-55% pl and subequal amounts of fresh to partially altered orthopyroxene and clinopyroxene.

355-16(105.1), 355-16(122). Dunite of lower Ultramafic series from Iron Mountain, AMAX drill core 355-16, 105.1 and 122.0 m depth. Rounded, partially serpentinized olivine grains with or without minor chromite in a 25-60% matrix of massive sulfide.

355-32(88.1), 355-32(117). Bronzitite of the Basal Series from Iron Mountain, AMAX drill core 355-32, from depths of 88.1 and 117.0 m. Massive, fresh, > 90% opx with 3% disseminated sulfides occupying intersticies between orthopyroxene and present as globular masses within individual pyroxene grains.

SW00-11 S25, S28b, S33, S36. Troctolite to plagioclase rich, olivine-bearing gabbro, JM reef, Stillwater Mining Company East Boulder Plateau Tunnel 6450 W core sample. Partially serpentinized with 1-2% disseminated sulfide.

SW00-12 S16, S18. Troctolite to olivine-bearing gabbro, JM reef, Stillwater Mining Company East Boulder Plateau Tunnel 6450 W core sample. Partially serpentinized, 5-10% sulfide.

SW99-13. Olivine gabbro, TGZ III, Stillwater Mining Company East Boulder Plateau Tunnel 6400W core sample. Partially serpentinized, traces of sulfide.

Table 2. Pb isotopic compositions of plagioclase and sulfide of the Stillwater Complex

Sample		**phase**	**208/204**		**207/204**		**206/204**		**208/206**		**207/206**	
791-1(88.29)	1	po	36.859	± 0.189	15.451	± 0.070	17.061	± 0.078	2.1604	± 0.0012	0.9057	± 0.0000
	2	pl	33.212	± 0.537	15.020	± 0.459	13.789	± 0.302	2.4103	± 0.0328	1.0890	± 0.0178
	3	pl	33.449	± 0.265	15.152	± 0.135	13.838	± 0.160	2.4190	± 0.0283	1.0959	± 0.0143
	4	pl	33.673	± 0.211	14.812	± 0.101	13.946	± 0.121	2.4155	± 0.0194	1.0625	± 0.0107
	5	pl	33.519	± 0.317	14.754	± 0.264	13.903	± 0.182	2.4123	± 0.0262	1.0619	± 0.0208
	6	pl	33.134	± 0.210	14.575	± 0.120	13.453	± 0.155	2.4649	± 0.0279	1.0840	± 0.0092
	7	pl	33.007	± 0.243	14.573	± 0.156	13.507	± 0.130	2.4447	± 0.0201	1.0791	± 0.0100
	8	ccp	35.403	± 0.255	15.582	± 0.052	16.467	± 0.102	2.1500	± 0.0115	0.9463	± 0.0055
	9	py	35.351	± 0.136	15.588	± 0.110	16.496	± 0.113	2.1432	± 0.0086	0.9450	± 0.0043
791-1(130)	1	pl	32.923	± 0.310	14.364	± 0.194	13.451	± 0.221	2.4493	± 0.0282	1.0683	± 0.0127
	2	pl	33.412	± 0.490	14.549	± 0.267	13.976	± 0.330	2.3944	± 0.0308	1.0427	± 0.0200
	3	pl	31.848	± 0.556	14.109	± 0.161	13.108	± 0.269	2.4315	± 0.0611	1.0769	± 0.0196
	4	pl	33.877	± 0.393	14.948	± 0.168	13.865	± 0.305	2.4463	± 0.0397	1.0785	± 0.0229
	5	pl	35.591	± 0.606	15.099	± 0.169	15.941	± 0.497	2.2370	± 0.0368	0.9499	± 0.0234
355-16(105.06)	1	po	37.056	± 0.189	15.432	± 0.097	17.368	± 0.263	2.1339	± 0.0218	0.8887	± 0.0164
	2	pn	38.536	± 0.614	15.785	± 0.297	18.613	± 0.531	2.0711	± 0.0291	0.8482	± 0.0092
	3	ccp	38.017	± 0.179	15.592	± 0.049	18.206	± 0.045	2.0882	± 0.0054	0.8564	± 0.0022
	4	po	36.899	± 0.389	15.303	± 0.129	17.274	± 0.433	2.1370	± 0.0318	0.8864	± 0.0174
	5	pn	38.175	± 0.524	15.632	± 0.186	18.294	± 0.303	2.0869	± 0.0061	0.8546	± 0.0048
	6	s	37.626	± 0.701	15.543	± 0.170	17.910	± 0.644	2.1024	± 0.0391	0.8689	± 0.0270
	7	s	37.766	± 0.528	15.429	± 0.161	18.124	± 0.378	2.0840	± 0.0147	0.8515	± 0.0098
	8	ccp	37.934	± 0.248	15.547	± 0.076	18.218	± 0.138	2.0824	± 0.0172	0.8535	± 0.0051
	9	po	32.587	± 0.384	14.401	± 0.220	13.785	± 0.276	2.3658	± 0.0200	1.0463	± 0.0190
	10	pn	37.731	± 0.153	15.380	± 0.071	18.132	± 0.072	2.0809	± 0.0069	0.8483	± 0.0019
	11	pn	37.801	± 0.437	15.496	± 0.093	18.039	± 0.379	2.0959	± 0.0204	0.8593	± 0.0150
	12	ccp	37.618	± 0.762	15.357	± 0.324	18.040	± 0.448	2.0856	± 0.0137	0.8514	± 0.0035
	13	s	38.072	± 0.308	15.471	± 0.106	18.252	± 0.192	2.0859	± 0.0084	0.8477	± 0.0032
355-16(122)	1	pn	33.135	± 0.445	15.193	± 0.435	14.071	± 0.154	2.3558	± 0.0063	1.0802	± 0.0248
	2	s	33.872	± 0.234	15.393	± 0.091	13.910	± 0.359	2.4366	± 0.0648	1.1074	± 0.0254
	3	pn	33.857	± 0.297	15.242	± 0.265	13.987	± 0.136	2.4242	± 0.0213	1.0882	± 0.0157
	4	pn	33.667	± 0.283	14.927	± 0.245	13.923	± 0.250	2.4181	± 0.0228	1.0721	± 0.0015
	5	ccp	33.797	± 0.284	15.100	± 0.068	14.015	± 0.148	2.4129	± 0.0354	1.0777	± 0.0092
	6	pn	33.867	± 0.557	15.107	± 0.320	14.136	± 0.220	2.3964	± 0.0234	1.0689	± 0.0067
	7	ccp	33.518	± 0.325	14.992	± 0.109	14.042	± 0.137	2.3871	± 0.0101	1.0677	± 0.0041
	8	s	33.590	± 0.182	15.003	± 0.032	14.075	± 0.186	2.3870	± 0.0285	1.0662	± 0.0155
	9	pn	33.204	± 0.238	14.786	± 0.267	13.680	± 0.260	2.4290	± 0.0299	1.0818	± 0.0110
	10	ccp	33.293	± 0.197	15.025	± 0.239	14.010	± 0.223	2.3769	± 0.0330	1.0725	± 0.0114
355-32(88.05)	1	ccp	33.507	± 0.584	15.088	± 0.261	14.892	± 0.386	2.2505	± 0.0207	1.0134	± 0.0131
	2	ccp	34.165	± 0.177	15.379	± 0.125	15.033	± 0.057	2.2728	± 0.0144	1.0230	± 0.0089
	3	ccp	34.363	± 0.434	15.376	± 0.183	15.069	± 0.064	2.2814	± 0.0324	1.0209	± 0.0139
355-32(117)	1	pn	35.620	± 0.332	15.729	± 0.180	16.634	± 0.216	2.1417	± 0.0173	0.9457	± 0.0066
	2	pn	35.827	± 0.456	15.687	± 0.194	17.056	± 0.282	2.1008	± 0.0210	0.9199	± 0.0129
	3	s	36.328	± 0.212	15.878	± 0.097	17.301	± 0.136	2.0998	± 0.0088	0.9178	± 0.0058
	4	s	36.612	± 0.225	15.847	± 0.049	17.743	± 0.231	2.0638	± 0.0199	0.8933	± 0.0119
	5	ccp	36.984	± 0.250	15.914	± 0.113	17.871	± 0.157	2.0696	± 0.0058	0.8905	± 0.0032
	6	pn	38.123	± 0.343	16.143	± 0.209	19.034	± 0.177	2.0021	± 0.0064	0.8481	± 0.0041
	7	pn	35.669	± 0.319	15.810	± 0.105	16.259	± 0.134	2.1937	± 0.0083	0.9724	± 0.0037
	8	ccp	34.886	± 0.444	15.752	± 0.113	16.087	± 0.150	2.1688	± 0.0131	0.9793	± 0.0105
	9	ccp	35.283	± 0.206	15.726	± 0.108	16.187	± 0.116	2.1797	± 0.0050	0.9715	± 0.0034
	10	pn	35.367	± 0.370	15.738	± 0.255	16.074	± 0.188	2.2005	± 0.0172	0.9792	± 0.0116
SW00-11 S25	1	s	34.931	± 0.541	15.459	± 0.253	14.897	± 0.242	2.3449	± 0.0057	1.0377	± 0.0013
	1	s	34.392	± 0.252	15.201	± 0.125	14.649	± 0.122	2.3477	± 0.0027	1.0377	± 0.0023
SW00-11 S28b	1	ccp	34.241	± 0.612	15.199	± 0.390	14.215	± 0.353	2.4090	± 0.0204	1.0692	± 0.0090
SW00-11 S33	1	pl	33.471	± 0.370	14.865	± 0.098	13.839	± 0.200	2.4214	± 0.0286	1.0758	± 0.0163
	2	ccp	32.696	± 0.375	14.676	± 0.253	13.544	± 0.262	2.4149	± 0.0441	1.0840	± 0.0182
	3	ccp	33.020	± 0.290	14.703	± 0.062	13.671	± 0.188	2.4157	± 0.0126	1.0758	± 0.0108
SW00-11 S36	1	pn	33.985	± 0.813	15.297	± 0.302	14.251	± 0.238	2.3855	± 0.0226	1.0735	± 0.0119
	2	pl	33.466	± 0.360	14.998	± 0.257	13.827	± 0.177	2.4242	± 0.0296	1.0860	± 0.0205
	3	ccp	33.460	± 0.526	14.923	± 0.346	13.812	± 0.273	2.4233	± 0.0161	1.0807	± 0.0060
	4	ccp	33.700	± 0.534	14.726	± 0.143	13.784	± 0.121	2.4453	± 0.0481	1.0685	± 0.0138
SW00-12 S16	1	pl	33.572	± 0.332	14.763	± 0.184	13.872	± 0.273	2.4246	± 0.0392	1.0659	± 0.0163
	2	s	34.104	± 0.693	15.024	± 0.162	14.411	± 0.447	2.3679	± 0.0330	1.0438	± 0.0242
	3	s	33.736	± 0.178	15.095	± 0.092	14.229	± 0.136	2.3707	± 0.0201	1.0613	± 0.0107
	4	s	34.106	± 0.286	15.129	± 0.104	14.387	± 0.097	2.3706	± 0.0044	1.0516	± 0.0026
	5	ccp	34.501	± 0.455	15.233	± 0.215	14.463	± 0.201	2.3856	± 0.0156	1.0532	± 0.0010
SW00-12 S18	1	pl	33.848	± 0.666	15.194	± 0.305	13.744	± 0.296	2.4650	± 0.0698	1.1073	± 0.0320
	2	pl	32.929	± 0.544	15.048	± 0.462	13.345	± 0.236	2.4691	± 0.0305	1.1286	± 0.0349
	3	s	34.276	± 0.789	15.153	± 0.379	14.481	± 0.335	2.3669	± 0.0052	1.0464	± 0.0026
SW99-13 381	1	s	35.891	± 0.267	15.119	± 0.176	16.347	± 0.251	2.1965	± 0.0286	0.9253	± 0.0120

pl, plagioclase; po, pyrrhotite; pn, pentlandite; ccp, chalcopyrite; py, pyrite

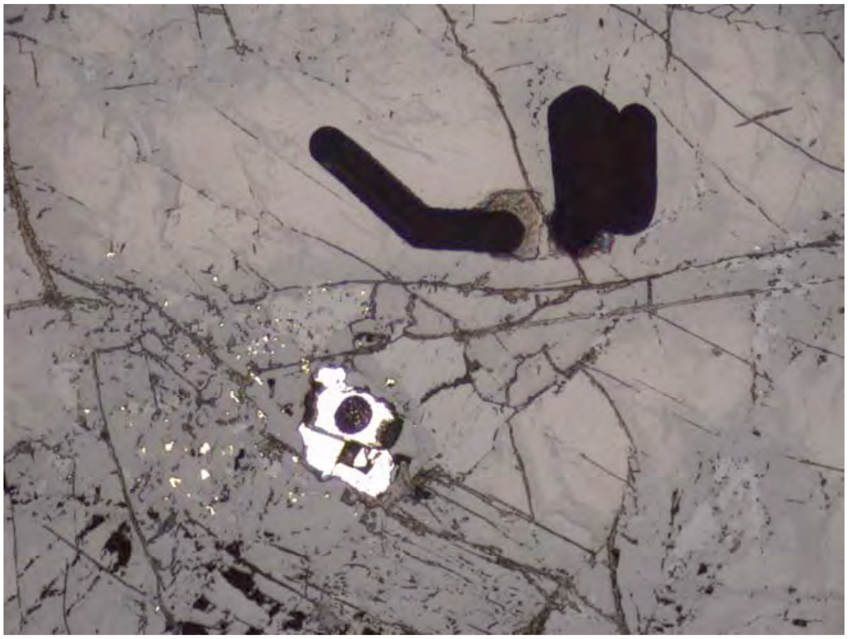

Fig. 1. Two laser ablation tracks in plagioclase and an ablation pit in a nearby sulfide, illustrating one element of the analytical protocol. The ablation tracks and pit are 100 µm across.

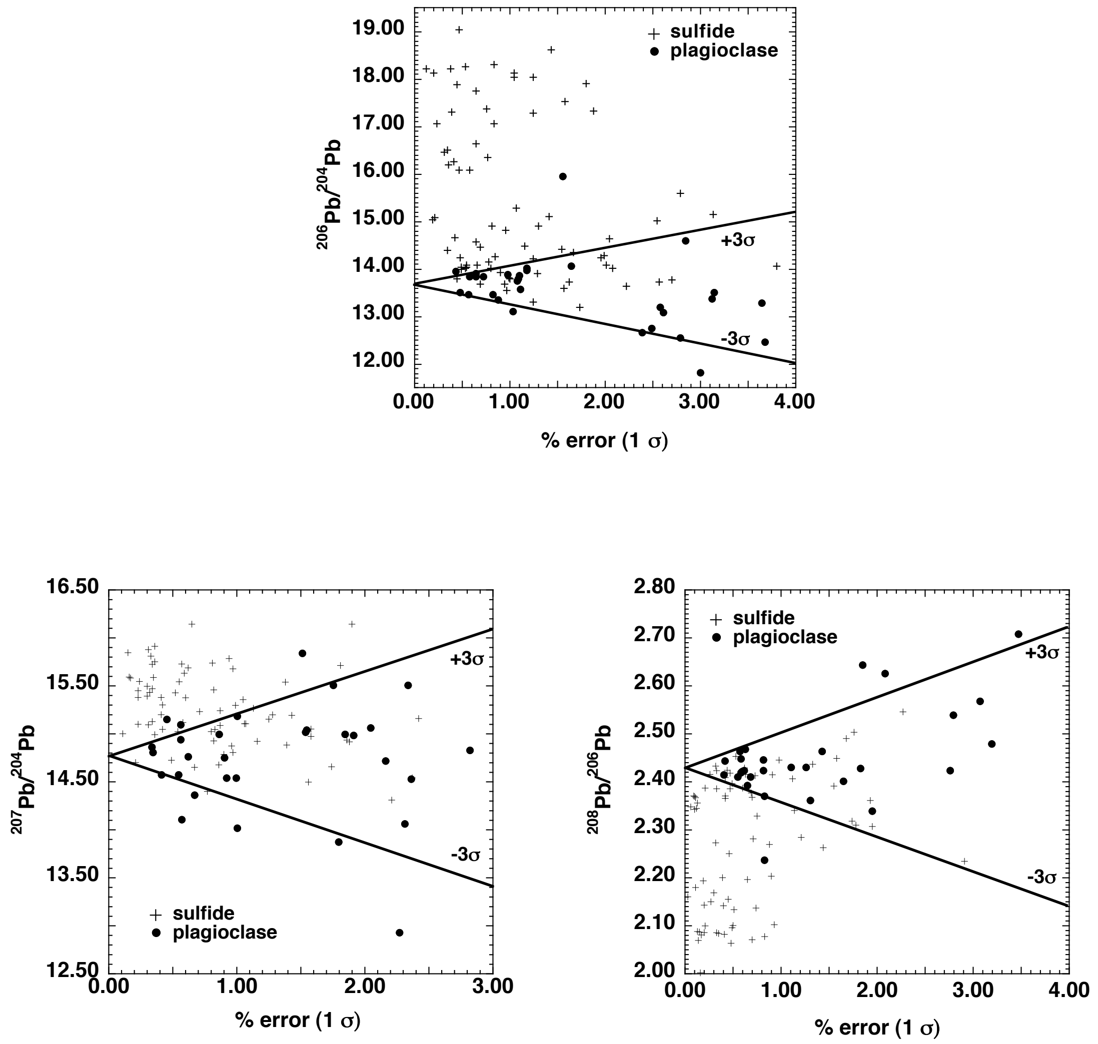

Fig. 2. (a) ^{206}Pb/^{204}Pb, (b) ^{207}Pb/^{204}Pb, and (c) ^{208}Pb/^{204}Pb ratios as functions of 1 σ analytical errors.

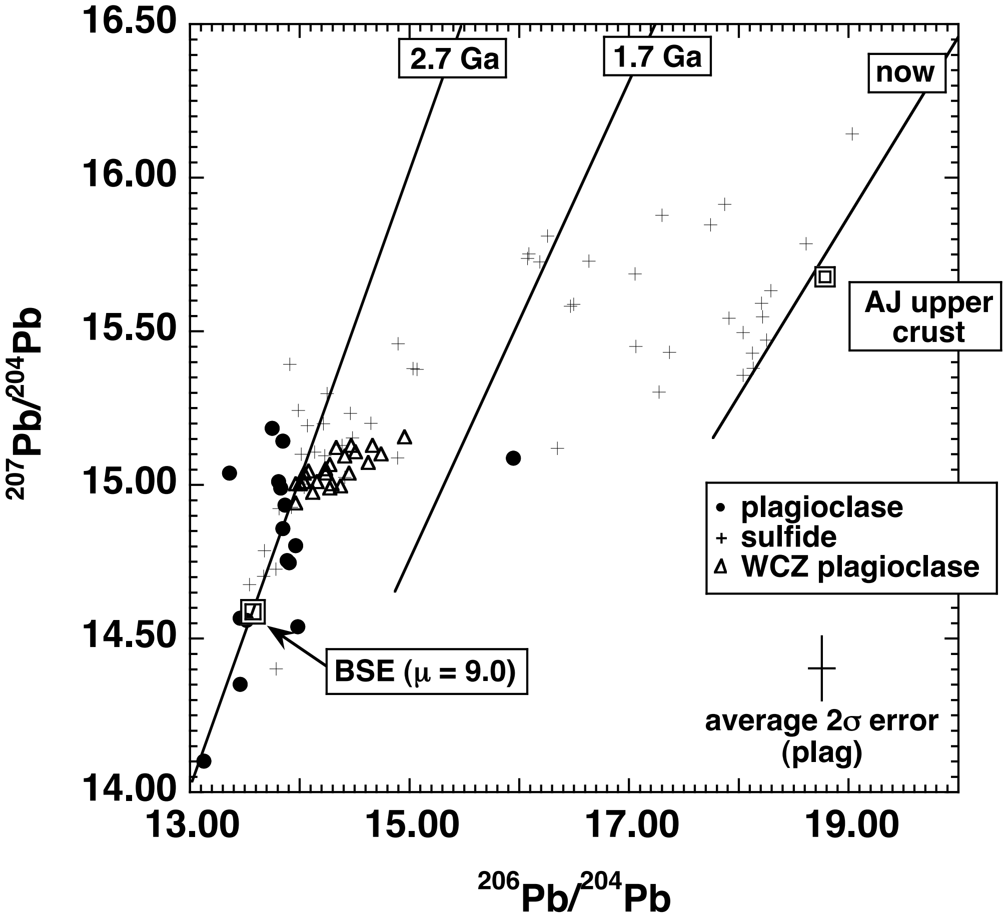

Fig. 3a. ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb of Stillwater plagioclase and sulfide compared to those on plagioclase separates of Wooden et al. (1991, (*triangles, labeled WCZ*). Also shown are the 2.7 Ga, 1.7 Ga, and present-day geochrons for the bulk silicate Earth (BSE). The BSE μ (^{238}U/^{204}Pb) = 9.0 is from Galer and Goldstein (1996). *AJ upper crust* refers to the upper crust composition estimated from analysis of river waters by Asmerom and Jacobsen (1993). On this and other figures, the calculated geochrons assume a single-stage evolution of Pb beginning 4.45 Ga (Zhang, 2002) from initial (^{206}Pb/^{204}Pb)$_0$, (^{207}Pb/^{204}Pb)$_0$ and ^{208}Pb/^{204}Pb)$_0$ ratios deduced by Chen and Wasserburg (1983).

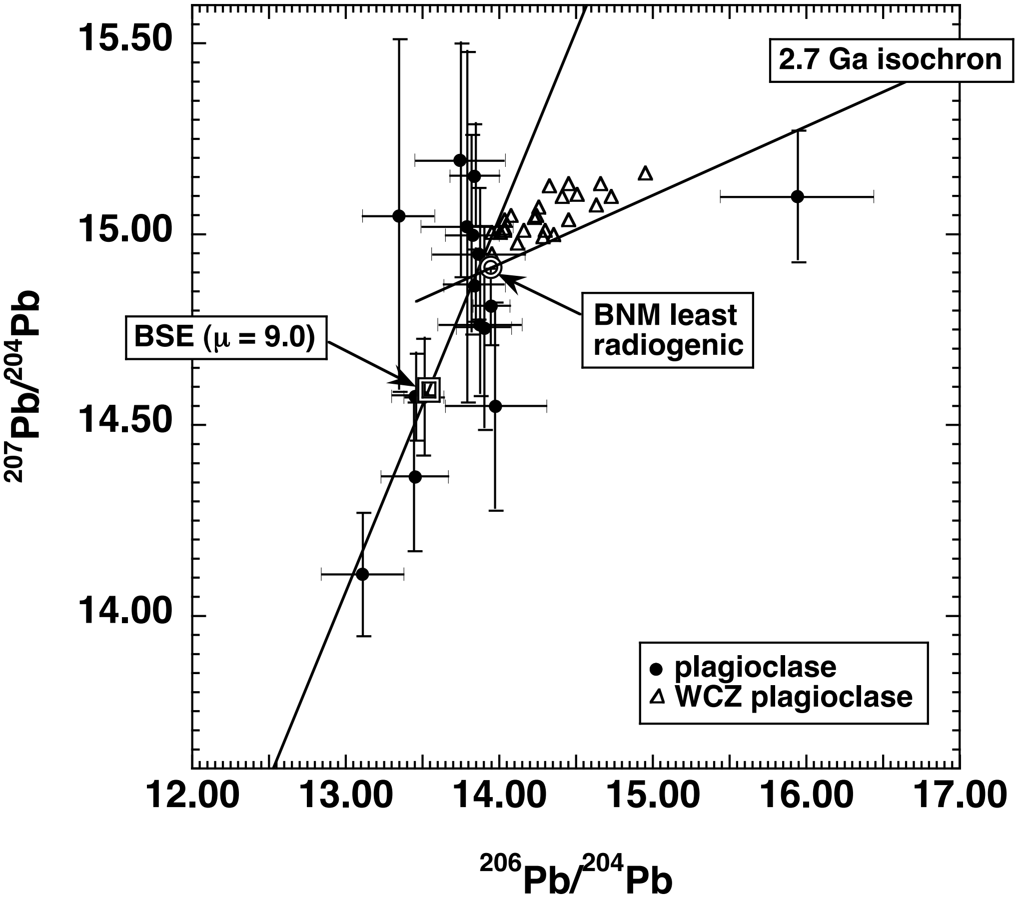

Fig. 3b. Plagioclase compositions with 2 σ errors. *BNM least radiogenic* refers to the least radiogenic plagioclase composition reported by Bosch et al. (1991).

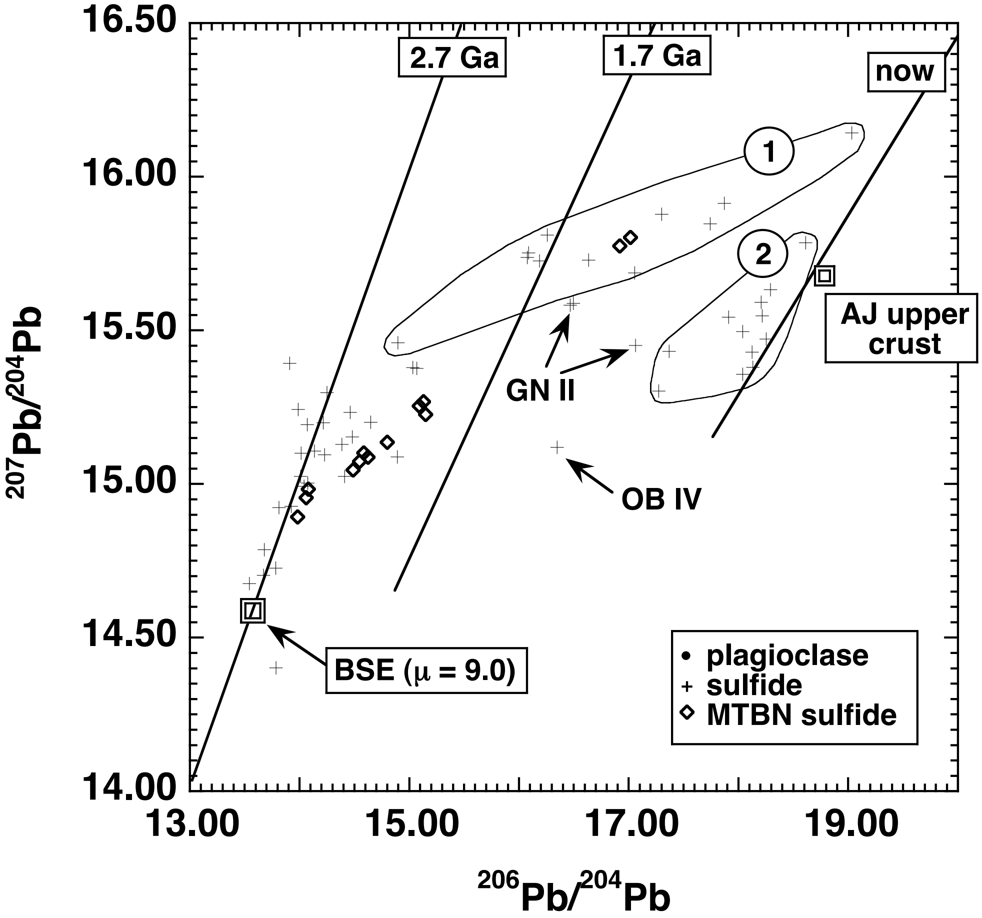

Fig. 3c. Sulfide compositions. Also plotted are the least radiogenic sulfide leaching experiments of McCallum et al. (1999) (*diamonds, labeled MTBN*).

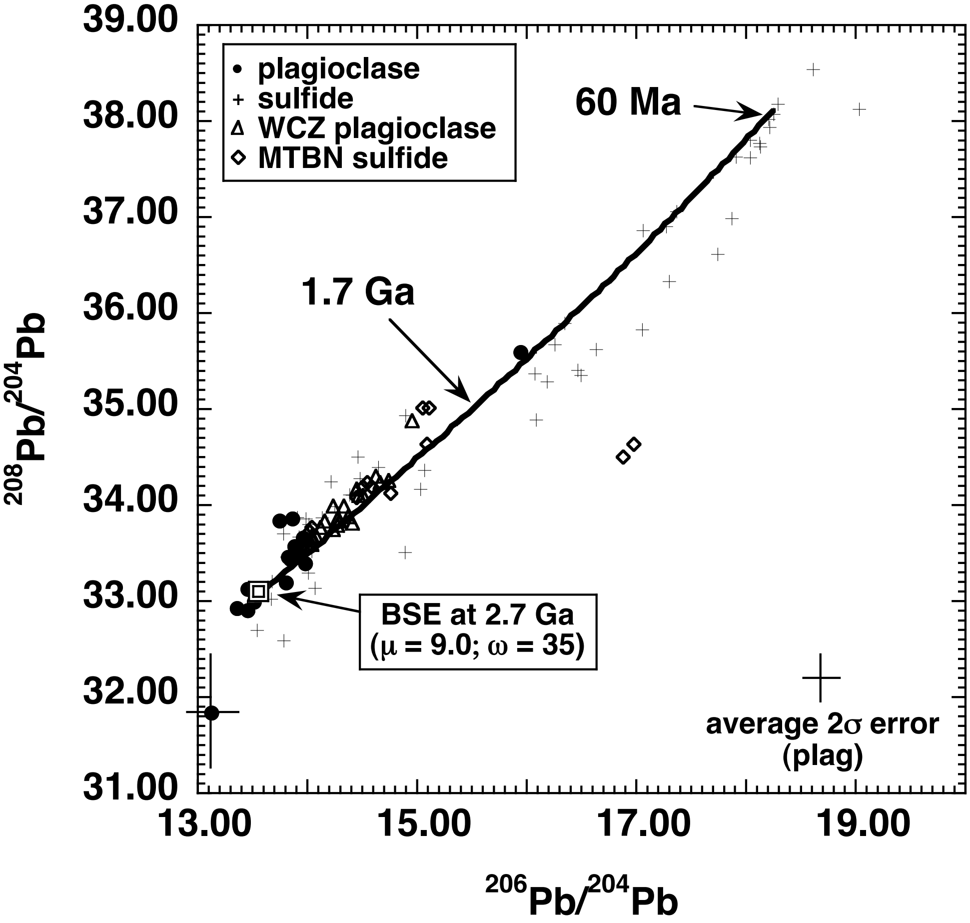

Fig. 4. ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb of Stillwater plagioclase and sulfide. Symbols as on Figure 3. The curve illustrates the evolution of the bulk silicate Earth (Zhang, 2002) from 2.7 Ga to the present.

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