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Geochemical variability of the Yucatàn basement: Constraints from crystalline clasts in Chicxulub impactites

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Abstract–The 65 Ma old Chicxulub impact structure with a diameter of about 180 km is again in the focus of the geosciences because of the recently commenced drilling of the scientific well Yaxcopoil-1. Chicxulub is buried beneath thick post-impact sediments, yet samples of basement lithologies in the drill cores provide a unique insight into age and composition of the crust beneath Yucatàn. This study presents major element, Sr, and Nd isotope data for Chicxulub impact melt lithologies and clasts of basement lithologies in impact breccias from the PEMEX drill cores C-1 and Y-6, as well as data for ejecta material from the K/T boundaries at La Lajilla, Mexico, and Furlo, Italy. The impact melt lithologies have an andesitic composition with significantly varying contents of Al, Ca, and alkali elements. Their present day $^{87}Sr/^{86}Sr$ ratios cluster at about 0.7085, and $^{143}Nd/^{144}Nd$ ratios range from 0.5123 to 0.5125. Compared to the melt lithologies that stayed inside the crater, data for ejecta material show larger variations. The $^{87}Sr/^{86}Sr$ ratios range from 0.7081 for chloritized spherules from La Lajilla to 0.7151 for sanidine spherules from Furlo. The $^{143}Nd/^{144}Nd$ ratio is 0.5126 for La Lajilla and 0.5120 for the Furlo spherules. In an $\varepsilon^{t}_{CHUR}(Nd)$-$\varepsilon^{t}_{UR}(Sr)$ diagram, the melt lithologies plot in a field delimited by Cretaceous platform sediments, various felsic lithic clasts and a newly found mafic fragment from a suevite. Granite, gneiss, and amphibolite have been identified among the fragments from crystalline basement gneiss. Their $^{87}Sr/^{86}Sr$ ratios range from 0.7084 to 0.7141, and their $^{143}Nd/^{144}Nd$ ratios range from 0.5121 to 0.5126. The T^{Nd}_{DM} model ages vary from 0.7 to 1.4 Ga, pointing to different source terranes for these rocks. This leads us to believe that the geological evolution and the lithological composition of the Yucatàn basement is probably more complex than generally assumed, and Gondwanan as well as Laurentian crust may be present in the Yucatàn basement.

INTRODUCTION

The 65 Ma old (Swisher et al. 1992) and 185 km large Chicxulub structure (e.g., Morgan et al. 1997) on the Yucatàn peninsula is sealed under a thick cover of post-impact sedimentary rocks and, hence, is considered to be a fresh, not eroded crater. The target at the Chicxulub impact site was layered, consisting of shallow water and an ~3 km thick carbonate platform with sulfate bearing rocks resting on the crystalline basement (Fig. 1). This basement probably resembles the Maya terrane (e.g., Patchett and Ruiz 1987) postulated to be pan-African in age (Krogh et al. 1993a). Fragments of these lithologies occur in various types of impact breccias in and around the crater. These facts, and the world-wide presence of related, partly pristine ejecta deposits, make the Chicxulub structure an ideal object for systematic studies in the field of impact cratering. While the post-impact cover is the reason for the presumably excellent state of preservation, it also hinders access to samples. Therefore, only geophysical surveys and drilling can help to extend the limited knowledge on Chicxulub. Several wells were drilled into the structure and its environs by Petróleos Méxicanos (PEMEX) and the Universidad Nacional Autonoma de Mexico (UNAM). Recently, the Yaxcopoil-1 (YAX-1) well was completed within the frame of the International Continental Drilling Program (ICDP; see http://www.icdp-online.de/html/sites/chicxulub/news/news.html).

Study of these cores would provide a more detailed knowledge of the structure, composition, and age of the basement beneath Yucatàn. In this context, not only the geochemical-petrographic investigation of lithic clasts in impact breccias is important but also analysis of melt lithologies, which allows us to constrain precursor lithologies to the impact melt. Data for a more complete spectrum of

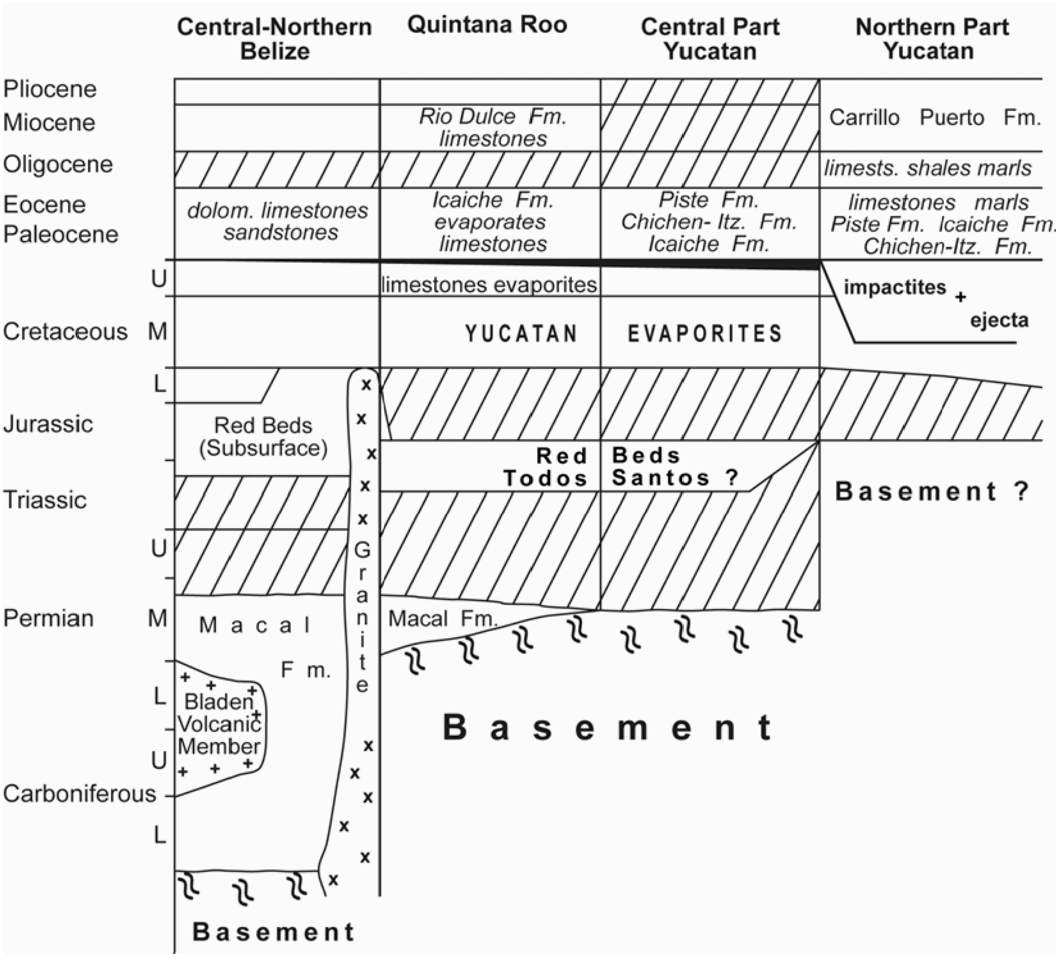

Fig. 1. Schematic stratigraphic correlation for central-northern Belize, Quintana Roo, and the Yucatàn Peninsula (modified after Lopes Ramos 1975). The hatching indicates gaps in sedimentation.

basement rocks and the different melt lithologies known to occur in Chicxulub may improve knowledge in the following fields: 1) composition of the sub-crater basement, variability of the lithologies laterally and with depth; 2) contributions of these different precursor lithologies to the impact melt; 3) mixing and homogenization of impact melts as part of the cratering process; and 4) variations in the clast population may help to enlighten the geological history of the Caribbean region in pre-Cretaceous times. Further, with the assumption that distal ejecta material is formed only from the uppermost part of the target, we can better constrain: 1) the composition of these surface layers and 2) the stratigraphy of the Chicxulub target at the Yucatàn peninsula (Fig. 1).

At present, Chicxulub is the only crater for which a world-wide distribution of distal ejecta is documented. This ejecta material differs in mode of occurrence, texture, and composition, which may reflect differences in the mode of formation. Smit and Klaver (1981) were the first to describe sanidine-bearing spherules in the 1–2 mm thick clay layer at the K/T boundary near Caravaca, Spain. These spherules and crystalline spherules with a quench-crystal texture from other K/T boundary sites are alteration products of unknown precursor lithologies, which are collectively named microkrystites (e.g., Smit et al. 1992). Moreover, larger spherules have been found at the K/T boundary at many localities, mainly in the southern part of North America and around the Gulf of Mexico (Smit 1990). The K/T microkrystites are morphologically similar to the clinopyroxene quench crystals in microkrystites from upper Eocene sediments (e.g., Glass and Burns 1987), which have been related, on the basis of Sr-Nd isotope data, to specific target materials at the Popigai impact site (Kettrup et al. 2003). The K/T microkrystites occur globally and partly overlap the K/T strewnfield of (micro-) impact glass droplets, e.g., in drill core GPC-3, Pacific Ocean. According to Smit et al. (1992), the microkrystites are formed in the most energetic part of the vapor plume where they condense from a vapor consisting of target material and some projectile matter. This idea, however, seems to be at odds with results of numerical modeling (Artemieva 2002 and personal communication). A clear relation of the various microkrystites to precursor lithologies on the basis of geochemical data is not yet established. Impact glass is locally preserved in the interior of the altered spherules at Beloc, Haiti (e.g., Maurasse and Sen 1991; Kettrup et al. 2000) and Mimbral, Mexico. In contrast to the K/T microkrystites, these so-called tektites (Smit et al. 1992) lack any crystalline phases.

This paper presents major element, Rb/Sr, and Sm/Nd isotope data for spherules from the K/T boundary at La Lajilla and Furlo and for impact melt lithologies from the Chicxulub crater. The Chicxulub samples are from PEMEX wells Yucatàn 6 (Y-6) and Chicxulub 1 (C-1). In addition, data for Chicxulub target material, which form lithic clasts in these impact breccias, are given.

SAMPLES

Distal Ejecta

La Lajilla

Impact spherules from the La Lajilla sequence represent proximal Chicxulub ejecta in the controversial clastic deposits at the K/T boundary around the Gulf of Mexico (Smit et al. 1996; Schulte et al. 2002). The spherules at La Lajilla are embedded in a dense limestone and occur in the lower part (Unit 1) of the K/T sandstone complex at the top of the Mendez formation (Smit et al. 1996). The original glassy droplets, about 2 mm across, are altered to Fe-rich chlorite (Fig. 2). They show light and dark schlieren and contain tiny magnetite crystals. Vesicles in the spherules are filled by radial-grown chlorite and, to a minor degree, by carbonate. According to Schulte et al. (2003), similar spherules and originally glassy shards from La Sierrita consist of chlorite-smectite (smectite <10%) and iron-oxides with rare K-rich mafic glass (~50 wt% SiO_2) and μm-sized metallic and sulfidic Ni-, Co-rich inclusions.

Furlo

The K/T site at Furlo, Pietralata belongs—similar to Gubbio and Petriccio—to the famous K/T boundary outcrops in the Umbria-Marche region, Italy (Alvarez et al. 1980; Montanari 1991; Montanari and Koeberl 2000). At Furlo, the ~8 mm-thick red boundary clay carries shocked quartz grains, impact spherules, and the well-known Ir anomaly and resembles, in general, the distal ejecta layer at other European K/T boundary localities, e.g., at Caravaca, Spain (Smit and Klaver 1981; DePaolo et al. 1983). The well-rounded spherules at Furlo consist of sanidine, goethite, and pale green glauconite (Montanari and Koeberl 2000). Smit and Klaver (1981) originally interpreted the texture of these spherules—less than 1 μm-sized crystallites forming a porous structure—through the quenching of a K-rich melt. Montanari et al. (1983) proposed that this material crystallized from a basaltic melt quenched at high temperatures. DePaolo et al. (1983), however, demonstrated the authigenic origin of the sanidine formed at low temperatures.

Chicxulub Drill Cores

Impact Melt Lithologies and Impact Breccias

Continuing the Kettrup et al. (2000) study on Chicxulub impactites and target lithologies, we investigated additional samples from wells C-1 and Y-6 collected at the UNAM, Mexico City, in the spring of 1999. The samples include one crystalline melt rock (tagamite) from core C-1 bottom (i.e., bottom of the hole), one melt breccia from core Y-6 N19

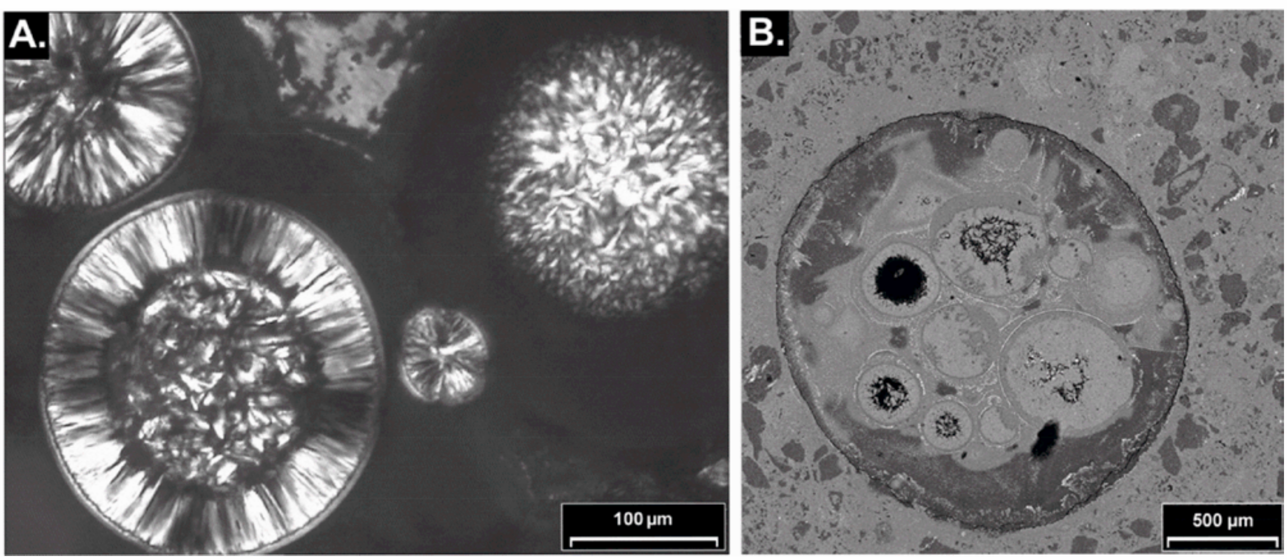

Fig. 2. Photomicrographs of a spherule-bearing limestone, K/T boundary, La Lajilla, Mexico: a) polarized light; b) SEM picture. The spherules are totally replaced by chlorite and the vesicles are filled by radially grown chlorite or carbonate aggregates.

part 6, altered impact glass separated from the suevite of core box Y-6 N14 part 4, and the clastic breccia Y-6 N13. The latter lacks melt lithologies and has a fine-grained calcitic matrix, which encloses mineral clasts (mainly quartz), fossils (foraminifera), and subordinate rock fragments, all less than 1 mm across. Layering is indicated by the alternation of dark and light sequences on the mm scale.

Target Lithologies

The impact breccias of the Chicxulub structure carry, in general, a wide spectrum of target lithologies that include Cretaceous platform sediments, granites, granitic gneisses, (meta-) quartzites, quartz-mica schists, and various basic rocks (e.g., Sharpton et al. 1992; Kettrup et al. 2000; J. Smit, personal communication; own observation on UNAM cores). The crystalline clasts analyzed in this study are all less than 10 mm across; they were hand-picked from suevites of core boxes Y-6 N14 and Y-6 N14 part 4 and from melt breccias Y-6 N16 part 7, and Y-6 N19 part 6. Figure 3 illustrates the different modal compositions of these fragments.

Samples Y-6 N14# (cf., Kettrup et al. 2000), Y-6 N14b, and Y-6 N14 p4a are pinkish granitic gneiss clasts from two different parts of core Y-6 N14. Their original gneissic texture is still preserved (Fig. 4), alkali-feldspar is weakly annealed (Fig. 4). Quartz occurs as a major component in sample Y-6 N14 p4a. A minor phase in sample Y-6 N14# is rutile (Fig. 3).

Sample Y-6 N14 p4b is a dark colored, partly banded gneiss fragment (Fig. 4) separated from core Y-6 N14 part 4.

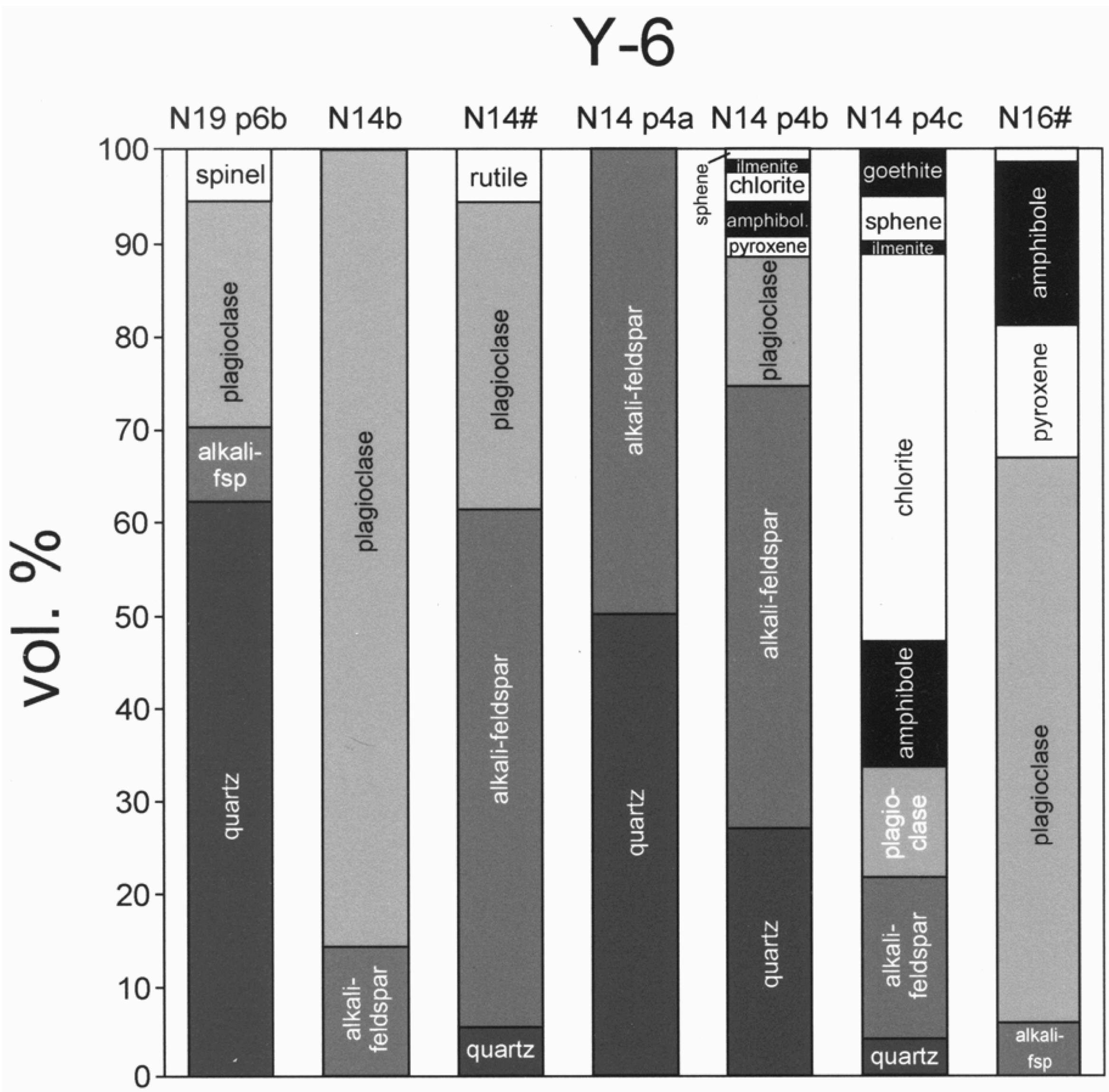

Fig. 3. Average modal compositions (vol%) of crystalline clasts in impact breccias of PEMEX drillcore Y-6. Counting was performed with the electron microprobe using a grid with 50 to 100 single spot analyses per sample.

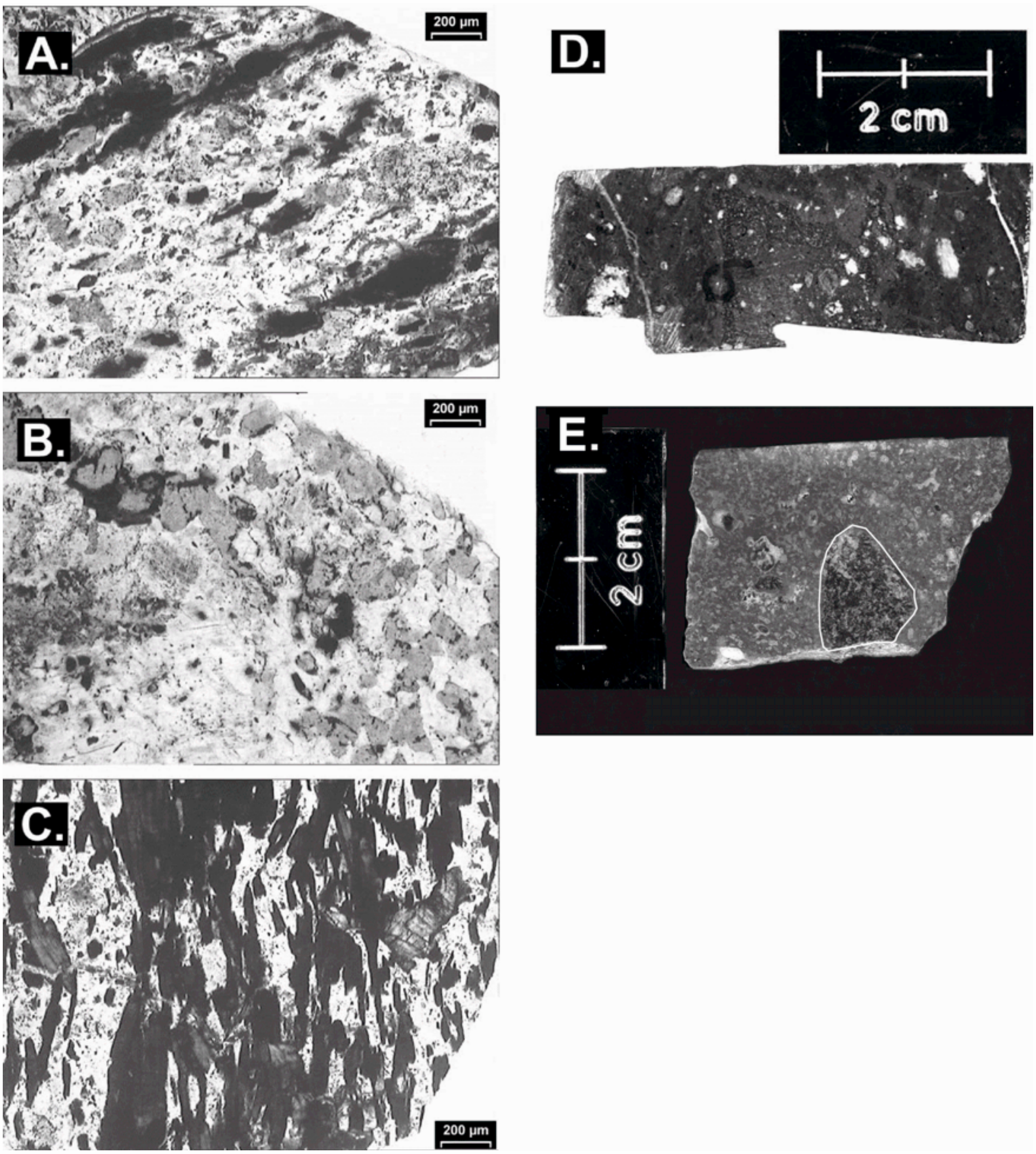

Fig. 4. Crystalline fragments from PEMEX drillcore Y-6 ([a] to [c]) photomicrographs of Y-6 N14; polarized light: a) granitic gneiss fragment Y-6 N14 p4a; b) gneiss fragment Y-6 N14 p4b; c) amphibolite fragment Y-6 N14 p4b; d) polished half of a drillcore sample of fragment-rich impact melt breccia Y-6 N19 p6; e) overview of a thin section of fragment-rich impact melt breccia Y-6 N16 p7 (small boxes are 1 mm wide). The gray, fine-grained crystalline fragment in the middle is Y-6 N16#, mainly consisting of plagioclase.

Its major phases include weakly annealed quartz, alkali-feldspar (albite An_{05}, anorthoclase, and minor Na-sanidine), and oligoclase (Fig. 5). Some crystals are up to 1.5 mm large and show simple twins. The minor phases are amphibole, chlorite, pyroxene (high Al and Na), ilmenite, and sphene (Fig. 3).

Sample Y-6 N14 p4c is a banded amphibolite (Fig. 4) still displaying the original metamorphic texture. The main phases are feldspar (albite, anorthoclase, and Na-sanidine), chlorite and amphibole (Fig. 5); subordinate quartz, sphene, and ilmenite occur as well (Fig. 3).

The granite fragment Y-6 N19 p6b (about 7 mm across) was separated from melt breccia Y-6 N19 part 6. The sample has a well-preserved texture (Fig. 4) and corresponds to other granitic clasts from the Yucatàn crystalline basement, which are fairly abundant in the clast-load of the impactites. The fragment is rimmed by <1 mm-sized pyroxene laths. The main phases are quartz and plagioclase with subordinate K-

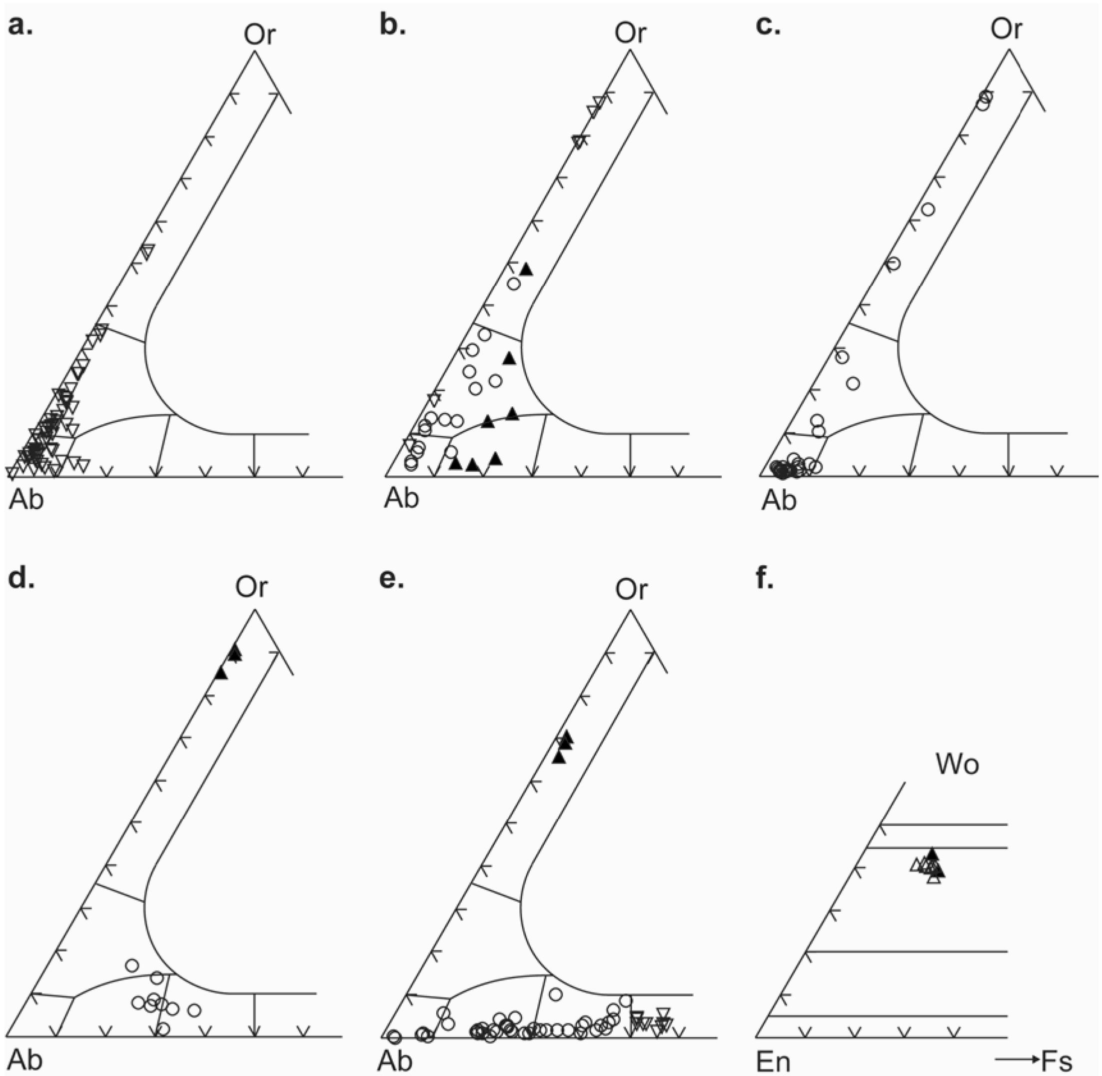

Fig. 5. Ternary diagrams for ([a] to [e]) feldspar (mol%; T = 900°C at 1 bar) and (f) pyroxene: a) sample Y-6 N14 p4b consists of alkali-feldspar (albite with An <5% and anorthoclase, minor Na-sanidine) and plagioclase (albite with Ab >5% and oligoclase); b) open circles represent the feldspar composition of fragment Y-6 N14# (mainly albite and anorthoclase), solid triangles that of Y-6 N14b (mainly oligoclase), and open triangles that of Y-6 N14 p4a (alkali-feldspar.); c) sample Y-6 N14 p4c—alkali-feldspar (albite with An <5%, anorthoclase and Na-sanidine) and minor plagioclase (albite with Ab >5%); d) sample Y-6 N19 p6b—oligoclase to andesine (open circle) and sanidine (solid triangles); e) sample Y-6 N16 p7—plagioclase with An <50% (open circles), An>50% (open triangles), and alkali-feldspar with Or >50% (solid triangles); f) pyroxene composition of sample Y-6 N16 p7 in the system $CaSiO_3$-$MgSiO_3$-$FeSiO_3$. The solid triangles represent augite with high Al_2O_3 of about 8 wt%.

feldspar and titano-magnetite (Figs. 3 and 5). The strongly annealed feldspars display a checkerboard texture. Only a few grains still retain the original twinning and antiperthitic intergrowth.

The gray, fine-grained crystalline fragment Y-6 N16# is part of the clast-rich melt breccia Y-6 N16 part 7 (Fig. 4; see Kettrup et al. 2000). Due to high temperature annealing in the melt, this fragment is recrystallized and its rim is partly dissolved. Its mode includes plagioclase, ranging from albite to labradorite, Na-sanidine, augite, and amphibole (Figs. 3 and 5); the feldspar/pyroxene ratio is 11/2. The mineral paragenesis indicates a maximum crystallization temperature of ~1350°C (1 bar).

ANALYTICAL TECHNIQUES

For the geochemical investigations, we have carefully separated ejecta material and crystalline clasts from the respective matrix under the stereo-microscope; the impactites were gently crushed to allow maximum removal of lithic and mineral clasts. To homogenize the matrix of tagamites (impact melt rocks) and impact melt breccias, the finepowdered material was fused in small molybdenum crucibles and the beads were embedded in a synthetic resin and finally polished. Major element analyses were performed with the JEOL JXA-8600 S electron microprobe of the Institut für Planetologie, Universität Münster. Compositions of the crystalline fragments were determined on polished thin sections in the grid mode.

For Rb-Sr and Sm-Nd analyses with thermal ionization mass spectrometers (Zentrallabor für Geochronologie, Universität Münster), the samples were cleaned according to procedures described by Ngo et al. (1985). For details of the analytical techniques, see the footnotes to Tables 2 and 3, Deutsch and Stöffler (1987), and Ostermann (1996).

RESULTS

Major Elements

The main constituents of the chloritized spherules from La Lajilla are SiO_2, Al_2O_3, FeO, and MgO with small amounts of TiO_2 and CaO. Alkali element contents are at or below the detection limits. The composition is in keeping with data given by Schulte et al. (2003) for Fe-rich clinochlore spherules from the K/T boundary outcrop at La Sierrita, Mexico.

The clastic impact breccia Y-6 N13 p9 is mainly composed of CaO (41.4 wt%) and SiO_2 (34.4 wt%) with significant amounts of Al_2O_3, FeO, and MgO. The suevite Y-6 N14a has 51.2 wt% SiO_2, which is low compared to other Chicxulub impactites (e.g., Kettrup et al. 2000), but this rock is fairly rich in CaO (18.3 wt%). The relatively high SiO_2 content (65.3 wt%) of melt breccia Y-6 N19 p6a is remarkable. In the ternary diagram of Fig. 6, the clastic matrix breccia Y-6 N13 p9 plots far off the cluster of other Chicxulub lithologies, indicating an unusually high amount of evaporites as precursors to this rock.

Target rock samples display quite different SiO_2 contents, ranging from 52 wt% (amphibolite Y-6 N14 p4c) to 84 wt% (granitic gneiss Y-6 N14 p4a); iron and magnesium are present only in traces in Y-6 N14 p4a but reach up to 14.5 wt% FeO and 7.9 wt% MgO in Y-6 N14 p4c (Table 1).

Figure 6 illustrates the relation of Chicxulub target rocks to various groups of impactites. Felsic gneiss samples form one group of precursor components. Another group of felsic precursors is represented by the granite Y-6 N19 p6b and (meta-) sediments, which, compared to the gneisses, are depleted in alkalies. The amphibolite Y-6 N14 p4c is the only mafic target rock analyzed so far. The evaporites plot near the calcium corner. Obviously, this material (together with various amounts of carbonates) was the major precursor for the breccia Y-6 N13 p9 and the yellow Haitian glasses (e.g., Chaussidon et al. 1996). All other impact lithologies, however, plot in the center of the diagram (Fig. 6): tagamites (impact melt rocks) from well C-1 and the black Haitian glass

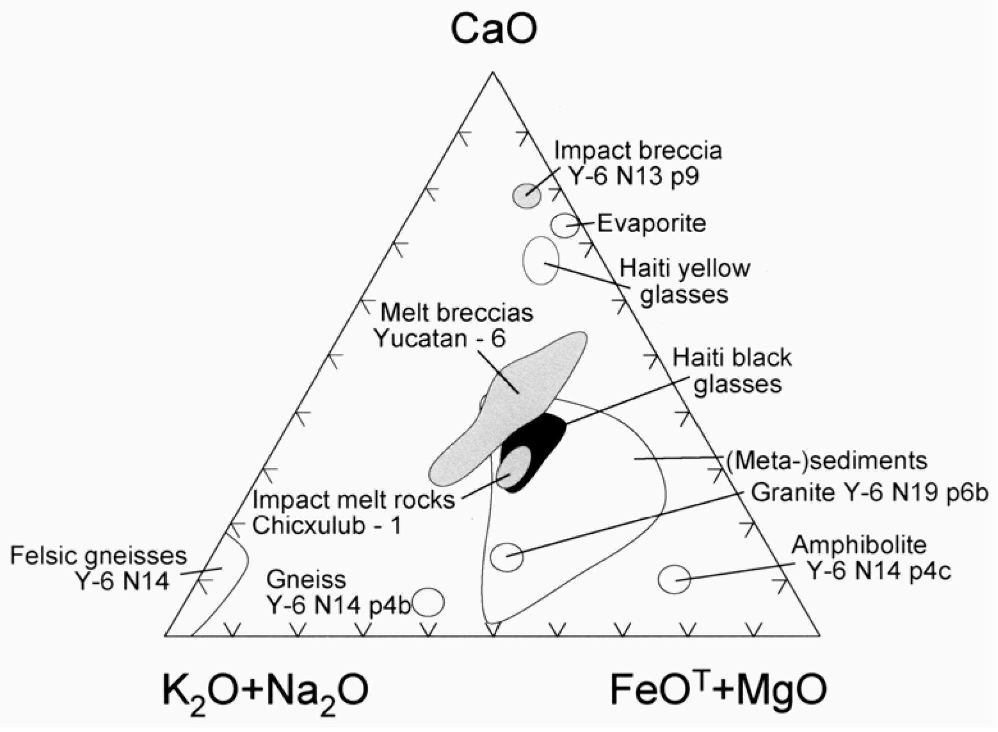

Fig. 6. Ternary diagram CaO, K^2O + Na_2O, and FeOT + MgO (in wt%) for Chicxulub impactites, ejecta and target material. Data sources: this study; C-1 impact melt rocks: Schuraytz et al. (1994) and this study; Haiti yellow glass: Koeberl and Sigurdsson (1992); Haiti black glass: Koeberl and Sigurdsson (1992); (meta-) sediments and evaporite: Koeberl (1993).

Table 1. Major element data for impactites and basement clasts from impact breccias (drill cores C-1 and Y-6) and ejecta from the K/T boundary, La Lajilla, Mexico.[a]

(wt%)	SiO_2	TiO_2	Al_2O_3	FeO[b]	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Chloritized spherules										
CHL-2 Lajilla[c]	31.8	1.1	23.4	29.3	–	10.6	3.7	–	tr.	n.d.[d]
Impact lithologies										
C-1 bottom[e]	61.1	0.8	15.9	5.5	n.d.	2.9	7.2	4.7	1.8	0.2
Y-6 N13 p9[fg]	34.4	0.4	9.6	3.0	n.d.	5.5	41.4	2.0	0.6	0.1
Y-6 N14a[eg]	51.2	0.8	12.4	6.3	n.d.	6.7	18.3	3.3	0.8	0.2
Y-6 N19 p6a[e]	65.3	0.3	14.5	4.1	n.d.	2.6	8.4	3.3	1.4	0.1
Crystalline fragments										
Y-6 N14b[h]	68.4	–	20.1	0.2	tr.	0.1	1.6	7.8	2.0	–
Y-6 N14 p4a[h]	84.3	–	8.9	tr.	tr.	–	0.1	2.2	4.5	–
Y-6 N14 p4b[h]	67.9	0.2	16.7	3.9	tr.	1.7	0.9	7.1	1.6	–
Y-6 N14 p4c[ig]	52.2	2.2	14.9	14.5	0.2	7.9	3.1	3.3	1.9	tr.
Y-6 N19 p6b[j]	81.9	0.2	8.5	4.1	tr.	0.1	1.3	2.3	1.6	tr.

[a]Wavelength dispersive electron microprobe analyses recalculated to 100 wt%. Analytical conditions: 15 keV acceleration volatage, 15 nA sample current; Standards: natural minerals and synthetic glass USNM 2213, ZAF correction. See Kettrup (2002) for further explanation.
[b]Total iron.
[c]Chlorite spherules.
[d]Not determined.
[e]Impact melt lithologies.
[f]Impact breccia.
[g]Low totals (~85–95 wt%), indicating presence of hydrous alteraton products.
[h]Gneiss.
[i]Amphibolite.
[j]Granite.

form a narrow cluster. Suevites and melt breccias of core Y-6 define an elongated field, indicating that their precursors were mostly felsic gneisses and platform sediments (evaporates, carbonates) in various proportions.

Radiogenic Isotopes

Element concentrations and the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope ratios of the chloritized spherules from La Lajilla resemble data for the Chicxulub impactites (see Table 2; Kettrup et al. 2000). Obviously, hydration of the originally glassy ejecta did not significantly alter the isotope systems. In contrast, Nd data for the altered Furlo spherules differ significantly from those of all impactites and the La Lajilla spherules (Table 2). The $^{87}Sr/^{86}Sr$ ratio of the La Lajilla spherules corresponds to that for the sanidine spherules from Caravaca (DePaolo et al. 1983) and reflects the Sr isotope composition of the contemporaneous (=65 Ma) seawater.

The crystalline fragments display highly variable Sr-Nd systematics, further supporting the complex composition of the basement at the Chicxulub target site. The element concentrations range from 26 to 96 ppm Rb, 82 to 373 ppm Sr, 0.11 to 3.1 ppm Sm, and 0.6 to 19 ppm Nd. Isotope ratios range from 0.70836 to 0.73268 for $^{87}Sr/^{86}Sr$ and 0.51218 to 0.51264 for $^{143}Nd/^{144}Nd$ (Table 2).

Figure 7 shows the variability of T^{Nd}_{DM} and T^{Sr}_{UR} model ages for the analyzed samples. The crystalline fragments form 2 groups with T^{Nd}_{DM} at 0.65 Ga and between 1.0 and 1.4 Ga (Fig. 7a). The various impactites and the black glass from Haiti have, with one exception (i.e., T^{Nd}_{DM} of 1.6 Ga), very similar Nd model ages, while the altered spherules from K/T boundary locations display a larger variation with T^{Nd}_{DM} ranging from 0.8 to 1.7 Ga. The data indicate that one of the precursor components with a Nd model age of 1.7 Ga or higher has not yet been detected.

The Sr model ages of the crystalline fragments cluster at 0.4 to 0.9 Ga and 1.4 to 1.6 Ga (Fig. 7b). The model ages of the Chicxulub impactites range from 0.8 to 1.8 Ga, while the sanidine spherules have comparatively very young T^{Sr}_{UR} ages, reflecting interaction with and alteration by contemporaneous seawater. The simplest explanation for the high and widely varying T^{Sr}_{UR} ages is some post-impact disturbance of the Rb-Sr system, although we can not exclude totally that so far not analyzed precursor materials with high Sr model ages could have been present at the Chicxulub target site.

DISCUSSION

The new data for lithic clasts in Chicxulub impactites presented in this work strengthen the idea of a rather complex crystalline basement in the Yucatàn region. This conclusion was already derived by Kettrup et al. (2000) on the basis of O-Sr-Nd isotope data for Chicxulub impact melt lithologies. These data suggested the presence of a substantial mafic to intermediate component amongst the target lithologies.

Table 2. Rb-Sr and Sm-Nd isotopic data for impactites and basement clasts (drill core Y-6), K/T boundary ejecta from La Lajilla, Mexico, and Furlo, Italy.[a]

	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma^{bc}$	T^{Sr}_{UR} (Ga)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma^{dc}$	T^{Nd}_{DM} (Ga)
Altered spherules										
CHL-2 Lajilla[e]	4.79	37.85	0.3661	0.708089 ± 26	0.9	1.051	4.158	0.1528	0.51258 ± 2	1.2
SAN-1 Furlo[e]	63.3	21.40	8.570	0.71511 ± 23	0.1	0.08950	0.4534	0.1193	0.51200 ± 9	1.7
Impactites										
Y-6 N19 p6a[f]	47.0	566.2	0.2402	0.708884 ± 15	1.5	3.084	15.77	0.1182	0.512345 ± 23	1.12
Y-6 N14a[g]	45.3	255.6	0.5126	0.709151 ± 42	0.8	2.196	8.545	0.1554	0.512451 ± 41	1.54
Crystalline fragments										
Y-6 N14b[h]	52.3	356.5	0.4244	0.708544 ± 12	0.8	2.541	19.33	0.7952	0.512459 ± 12	0.67
Y-6 N14 p4a[h]	96.3	81.84	3.413	0.732676 ± 12	0.6	0.1125	0.5779	0.1177	0.512640 ± 27	0.65
Y-6 N14 p4b[h]	33.4	287.1	0.3367	0.710169 ± 16	1.6	3.064	16.89	0.1097	0.512180 ± 15	1.27
Y-6 N14 p4c[i]	26.6	113.4	0.6795	0.708356 ± 33	0.5	2.325	8.514	0.1651	0.512613 ± 30	1.34
Y-6 N19 p6b[j]	42.7	372.9	0.3315	0.709500 ± 14	1.4	0.7242	4.042	0.1083	0.512315 ± 18	1.06

[a]During the course of this work, analyses of NBS SRM 987 $SrCO_3$ yielded 0.710282 ± 12 for $^{86}Sr/^{87}Sr$ (unweighted mean $\pm 2\sigma_m$); analyses of the La Jolla Nd standard resulted in 0.511861 ± 15 for $^{143}Nd/^{144}Nd$ (unweighted mean $\pm 2\sigma_m$). Blanks were about 0.02 ng for Rb, 0.04 ng for Sr, 125 pg for Nd, and 73 pg for Sm. The decay constants used in this paper are 1.42×10^{-11} a^{-1} for ^{87}Rb (Steiger and Jäger 1977) and 6.54×10^{-12} a^{-1} for ^{147}Sm (Lugmair and Marti 1978). T^{Sr}_{UR}, T^{Nd}_{CHUR}, T^{Nd}_{DM} = last time at which a rock had the Sr, Nd isotopic composition of the model reservoirs UR, CHUR, or DM (depleted mantle; see DePaolo 1981).
[b]Normalized to $^{86}Sr/^{88}Sr = 0.1194$.
[c]Normalized to $^{146}Nd/^{144}Nd = 0.7219$.
[d]Uncertainties refer to the last significant digits.
[e]Ejecta.
[f]Impact melt breccia.
[g]Altered suevite glass.
[h]Gneiss.
[i]Amphibolite.
[j]Granite.

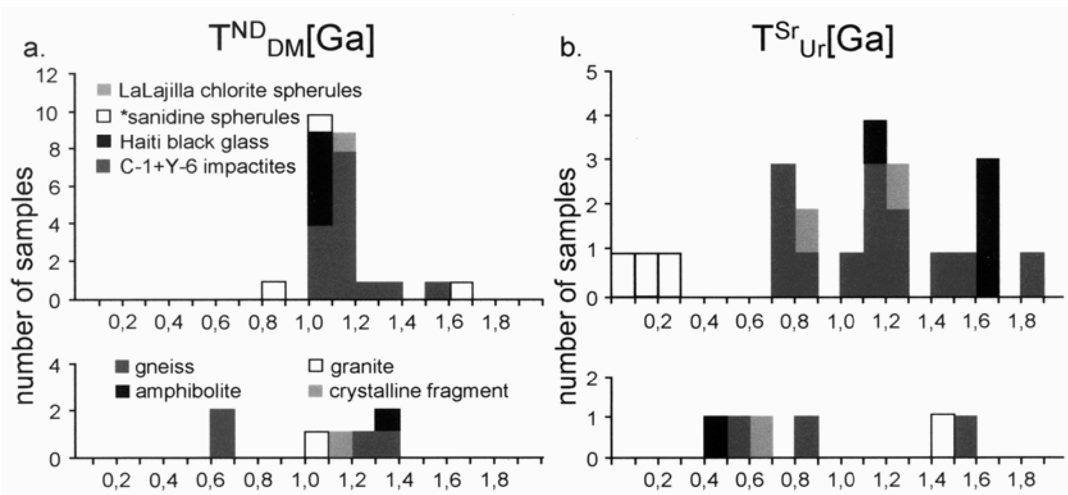

Fig. 7. Histogram of (a) T^{Nd}_{CHUR} and (b) T^{Nd}_{DM} model ages for Chicxulub (upper) impactites and (lower) target material. Data sources: basement fragments from impact breccias and chloritized spherules from La Lajilla: this study; sanidine spherules from Furlo and Caravaca: DePaolo et al. (1983) and this study; C-1, Y-6 impactites and Haiti tektites: Premo and Izett (1992) and Kettrup et al. (2000).

One of these components, represented by the amphibolite Y-6 N14 p4c, has now been detected in the clast population of the suevite Y-6 N14 p4. This amphibolite has a high ε_{Nd} value of −0.24. In the time-corrected $\varepsilon^t_{CHUR}(Nd)$-$\varepsilon^t_{UR}(Sr)$ diagram of Fig. 8, the data point of this amphibolite plots close to the La Lajilla spherules—perhaps this mafic lithology presents an important precursor component for ejected glass droplets at K/T boundary localities in northeastern Mexico (e.g., La Lajilla, La Sierrita). A mafic precursor lithology was proposed by Schulte et al. (2003) for ejecta at La Sierrita as well, although these authors state that carbonaceous sediments, intermediate to felsic rocks, and probably

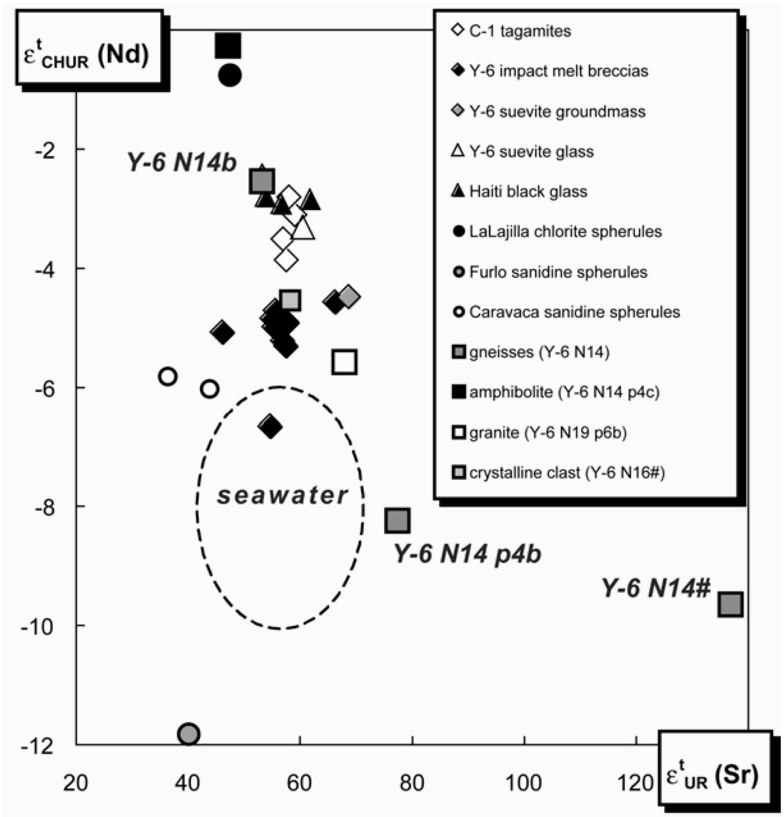

Fig. 8. Time-corrected (t = 65 Ma) diagram of ε^t_{CHUR}(Nd) versus ε^t_{UR}(Sr) for Chicxulub impactites, ejecta material from various K/T boundary sites, lithic fragments in impact breccias, and 65 Ma seawater, considered as equivalent to the average Sr and Nd isotope composition of the continental crust 65 Ma ago. Data sources: basement fragments from impact breccias and altered spherules from La Lajilla: Kettrup et al. (2000) and this study; sanidine spherules: DePaolo et al. (1983) and this study; C-1, Y-6 impactites and Haiti glass: Premo and Izett (1992) and Kettrup et al. (2000); seawater: Stille et al. (1996) and Vonhof (1998).

projectile matter could have contributed to the composition of the impact melt droplets.

The new Sr-Nd isotope data for the microkrystites from La Lajilla differ significantly from data for the Haitian black glass from Beloc (Blum et al. 1993; Kettrup et al. 2000). At this locality, at Mimbral (Mexico), and in drill cores from the Gulf of Mexico, the black glass with an andesitic composition occurs together with yellow high-Ca glass, and rare high-Si-K glass. The high sulfur content, as well as sulfur and boron isotope data provide evidence that the yellow glasses had a large amount of sedimentary rocks amongst their precursors (Chaussidon et al. 1996). Obviously, the microkrystites from La Lajilla originated from impact melting of rocks in a deeper level of the target.

Figure 8 illustrates that, beside the amphibolite (and most probably, other mafic lithologies), the impact lithologies have 2 major precursor components: Cretaceous platform sediments, represented by the field "contemporaneous (=65 Ma) seawater," and gneisses, similar to fragment Y-6 N14 p4a, as well as granites (e.g., fragment Y-6 N19 p6b). Strongly recrystallized gneissic and granitic clasts, however, plot in Fig. 8 close to the field defined by impactites—they no longer allow the constraint of precursor components, probably because annealing was not isochemical. The Sr-Nd-systematics of all melt lithologies and impact breccias are explained sufficiently by the current data (Fig. 8), with the exception of the highly altered sanidine spherules from the Furlo and Caravaca sites. Their Sr and Nd no longer reflect the chemical composition of precursor lithologies.

To constrain the origin of the Chicxulub ejecta better, data are plotted in a T^{Sr}_{UR} versus $1/f_{(Rb/Sr)}$ diagram (Fig. 9) as proposed by Shaw and Wasserburg (1982): the data points for black Haitian glass define a regression line intercepting the y-axis at 400 Ma. This age corresponds to the time of the last Rb/Sr fractionation event in the precursor lithologies, and is consistent with the intrusion age of late Silurian dioritic-granodioritic, monzonitic and granitic plutons at Yucatàn (see Table 3; Steiner and Walker 1996). According to the data alignment in Fig. 9, Haitian ejecta material could have such rocks or sediments derived from these plutons among its precursors. Impact spherules from other K/T boundary locations define a second regression line, intercepting the ordinate at 65 Ma, which is the time of the Chicxulub impact. Melting, vaporization, and ejection obviously caused

Table 3. Compilation of age data for lithologies from the Chicxulub impact site, K/T boundary localities, and the Yucatàn region.[a]

Material/locality[b]	Impact age (Ma)	Basement age[c] (Ma)	Protolith age (Ma)	Method (reference)
Zircons (shocked)/Chicxulub crater,	57 ± 4	545 ± 5	–	U/Pb (Krogh et al. 1993a)
KTB Beloc, KTB Colorado	–	418 ± 6	–	–
Zircons (shocked)/KTB Colorado	66 ± 3	550 ± 10	–	U/Pb (Krogh et al. 1993b)
Zircons (shocked)/KTB Colorado	65.2 ± 9.2	571 ± 6	–	U/Pb (Premo and Izett 1993)
Zircons (shocked)/KTB Saskatchewan	59 ± 10	548 ± 8	–	U/Pb (Kamo and Krogh 1995)
Zircons/Silurian plutons, Maja Mountains	–	418 ± 4	–	U/Pb (Steiner and Walker 1996)
	–	404 ± 3	1210 ± 136	–
	–	420	(1600)	–
Zircons/granite pebbles from Paleozoic flysch beds, NE Mexico	–	595 ± 69	1224 ± 3	U/Pb (Lopez et al. 2001)
	–	680 ± 69	1221 ± 29	–
		–	580 ± 4	–
Black glass/KTB Beloc	64.5 ± 0.1	–	–	$^{40}Ar/^{39}Ar$ (Izett et al. 1991)
Sanidine/KTB Montana	64.6 ± 0.2	–	–	–
Impact melt rock/C-1	65.2 ± 0.4	–	–	$^{40}Ar/^{39}Ar$ (Sharpton et al. 1992)
Impact melt rock/C-1	64.98 ± 0.05	–	–	$_{40}Ar/^{39}Ar$ (Swisher et al. 1992)
Tektite glass/KTB Beloc	65.01 ± 0.08	–	–	–
Tektite glass/KTB Mimbral	65.07 ± 0.02	–	–	–

Material/locality	T^{Nd}_{DM} (Ma)[d]	Reference
Black glass/KTB Beloc	1050 ± 12	Premo and Izett (1992)
Impact melt rock/C-1 N10	1050	Blum et al. (1993)
Black glass/KTB Beloc	1100	Kettrup et al. (2000)
Impact melt rock/C-1 bottom	1100 ± 15	
Impact melt breccias/Y-6 (N15/N16/N17/N19)	1120 ± 26	

[a] 2σ errors. The ages in brackets refer to an inherited component.
[b] KTB = K/T boundary localities.
[c] Intercept age.
[d] Last time at which a rock had the Nd isotopic composition of the model reservoirs DM (depleted mantle; see DePaolo 1981).

complete resetting of the Rb/Sr isotope system of these lithologies. Alternatively, the isotope composition of the spherules may simply reflect a strong alteration by contemporaneous (=65 Ma) seawater.

Table 3 summarizes published age data for the basement in the Yucatàn region and neodymium model ages for Chicxulub impactites and ejecta material. Shocked zircons separated from K/T boundary layers gave, with one exception, upper intercept ages between 545 and 572 Ma (Krogh et al. 1993a), corresponding to the pan-African orogenic cycle (750 to 530 Ma; e.g., Lopez et al. 2001). Grenvillian granites affected by pan-African metamorphism and pan-African granites occur in a late Paleozoic flysch bed (Lopez et al. 2001) ~1000 km off the impact site in northeastern Mexico.

Another upper intercept age of ~418 Ma for shocked zircons from the K/T boundary (Krogh et al. 1993a) is in keeping with the intrusion age of the Silurian plutons in the Maya mountains, Yucatàn (see Bateson 1972; Steiner and Walker 1996). The protolith age of these rocks was estimated at ~1200 Ma, corresponding roughly to the Grenvillian crust forming cycle (Lopez et al. 2001).

The T^{Nd}_{DM} ages of impactites and ejecta material vary between about 1050 and 1120 Ma, which is in general agreement with the above protolith ages. Neodymium model ages of the crystalline fragments and zircon data (Table 3) provide evidence for the formation of continental crust during the Grenville orogeny (cf., Lopez et al. 2001). Later, at the end of the Proterozoic during the Assyntian orogenic cycle, Gondwana (South America and Africa) was affected by the pan-African, and Laurentia (North America) was affected by the Cadomian orogeny. We know that new continental crust was formed in both orogenic cycles (e.g., Shaw and Wasserburg 1984; Lopez et al. 2001).

Beginning in the late Silurian-early Devonian, the super-continent Pangea was formed by a continent-continent collision, and thrust faulting occurred in Gondwana and Laurentia (Scotese and Golonka 1992). The late Silurian plutonism in the Maya mountains took place in this context (Steiner and Walker 1996). Widespread K-Ar ages of ~230 Ma obtained for the igneous rocks of this phase indicate a resetting of this isotope system due to the opening of the Gulf of Mexico and the breakup of Pangea in Jurassic times (cf., Steiner and Walker 1996).

The accretion of material to the basement at Yucatàn ended with this episode, and platform sedimentation started. This thick sedimentary cover hampers a proper assessment of the Yucatàn crystalline basement. With the existing data, we cannot determine if this basement consists of material from either Gondwana or Laurentia only or of crust from both continents.

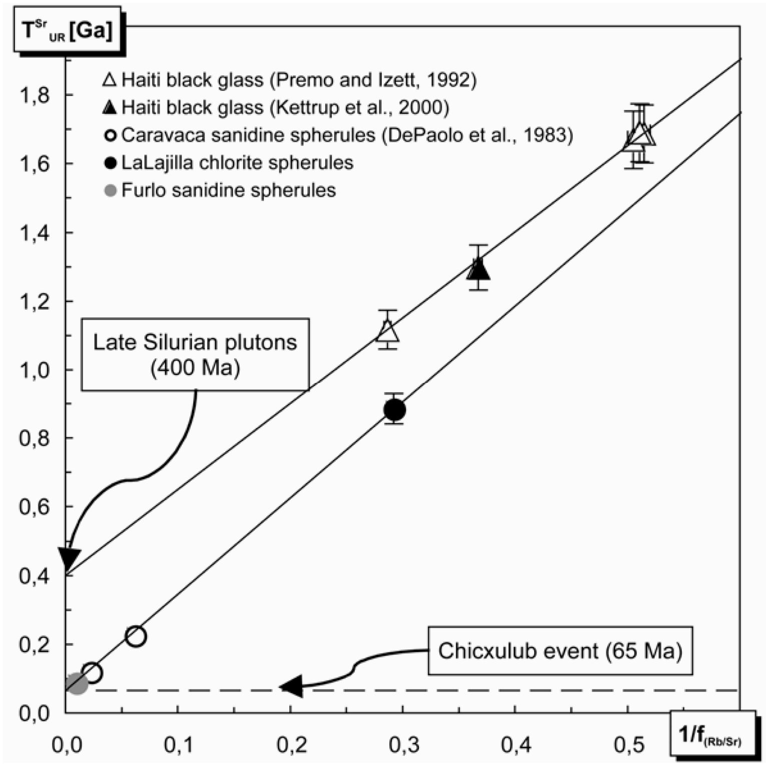

Fig. 9. T^{Sr}_{UR} versus $1/f_{(Rb/Sr)}$ plot of ejecta material from K/T boundary ejecta layers. The respective intercept of the regression lines (upper line $R^2 = 0.998$; lower line $R^2 = 0.999$) corresponds to the time of last Rb/Sr fractionation. The upper line for Haiti glass intercepts at about 400 Ma. This age corresponds to the intrusion age of late Silurian plutons, Yucatàn (Steiner and Walker 1996). The lower line for impact spherules from the K/T boundary intercepts at 65 Ma, which is the time of impact. The errors used for calculations are 1% for $1/f_{(Rb/Sr)}$ and 5% for T^{Sr}_{UR}. Rb enrichment factor $f_{(Rb/Sr)} = ([^{87}Rb/^{86}Sr]sample/[^{87}Rb/^{86}Sr]UR)-1$; see footnotes to Table 2 and DePaolo and Wasserburg (1976).

CONCLUSIONS

Impact melt products of the Chicxulub event display large variations in Nd isotope compositions (this study; Kettrup et al. 2000; Blum et al. 1993). These variations reflect the different contributions of various components of the heterogeneous crystalline target to specific melt volumes, which were not totally mixed and homogenized, thus, pointing to certain geochemical variations in the impact melt sheet. So far, the presence of a thick melt sheet at Chicxulub is only inferred from geophysical modeling (e.g., Ebbing et al. 2001). Yet, at other craters, for example, Popigai (Kettrup et al. 2003) or Zhamanshin (Ostermann et al. 1996), the geochemical variations in the melt sheet are well-documented. On the other hand, seemingly well-homogenized impact melt sheets exist, for example, in the 23 km large Lake St. Martin impact structure, Canada (Reimold et al. 1990). Likewise, in the case of the Sudbury structure, Canada, with a diameter of about 250 km (Deutsch et al. 1995), considerable variations have not been detected in the Nd isotope composition of the differentiated impact melt sheet (Sudbury "Igneous" Complex; e.g., Ostermann 1996; Ariskin et al. 1999). We tentatively explain these observations to reflect only how heterogeneously the target at the respective impact sites was composed—they can not be used to evalute the degree of mixing in a specific volume of impact melt.

The geochemical composition of Chicxulub impact melt lithologies cannot be explained by simple binary mixing of Cretaceous platform sediments with a homogeneous crystalline basement. This basement beneath Yucatàn turned out to be rather complex; the oldest identified parts of the crust in this region originated during the Grenvillian event about 1.2 Ga ago. The affiliation of the Yucatàn basement to either Laurentia or Gondwana remains an open question. Due to the consolidation of Pangea, material from both continents may be present beneath Yucatàn.

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