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ceramic raw materials

| Second Edition |



understanding ceramic glaze materials and clay making ingredients

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Ceramic Raw Materials
Understanding Ceramic Glaze Materials and Clay Making Ingredients

Today, we live in an age of super abundance of ceramic raw materials. Far from understanding these clay and glaze materials as familiar rocks, feldspars, and clays, each with unique personalities of their own, we know them only as white, gray, or brown powders neatly packaged in uniform bags.

Fortunately, you don't need an intimate understanding of all of the hundreds of ceramic raw materials that come to us from every corner of the earth to make clay and glaze recipes that work. Ancient potters created their masterpieces from three or four ceramic materials, and, if we similarly narrow our choices, we can also achieve extraordinary results. ***Ceramic Raw Materials: Understanding Ceramic Glaze Ingredients and Clay Making Materials*** offers access to that knowledge.

Understanding Glazes Through Raw Materials: Using Glaze Cores

By Mimi Obstler

An analysis of certain beautiful Song Dynasty porcelain glazes revealed that a single feldspathic rock material (Petuntse) provided the core of the glaze. This single material contained nearly the right proportion of glassmaker, adhesive, and melter oxides. Only small amounts of wood ash and limestone materials were added to improve the color and melt of the glaze. I believe that this is still the most meaningful way to approach the stoneware glaze, or any glaze or clay body for that matter. The objective is to locate one single earth material that alone almost provides the desired surface, and then to add as few additional materials as possible. I call this primary material, which almost achieves the desired glaze surface, a "glaze core." The list of glaze cores is long and disparate and includes feldspars, mica, granitic rocks, some clays, volcanic ash, wood ash, boron minerals, and the artificial manufactured frits. The key characteristic of these materials is their combination of glassmaker, adhesive, and melter functions.

Feldspars and Rocks**: Stoneware test pots by Barbara Beck, fired to cone 9–10 reduction. Glaze: Feldspar 90%, Whiting 10%, Red iron oxide, ½%. Pots, left to right: Potash feldspar, Cornwall Stone, Soda feldspar. Pot, rear, center: Nepheline Syenite. Rocks, left to right: Soda feldspar, Potash feldspar, Nepheline Syenite, Cornwall Stone.**

Feldspars and feldspathic rocks contain a complex structure of silica, alumina, and the melter oxides of sodium, potassium, and calcium. This structure makes them ideal glaze cores at stoneware temperatures.

Mix powdered feldspar with water, apply this mixture to a clay form, fire it to stoneware temperatures, and there will appear a glossy, white surface on the clay. Thus, feldspars and feldspathic rocks with their complex chemical structure of silica, alumina, and melter oxides of sodium, potassium, and calcium possess the unique ability to form an "almost" acceptable glaze surface at stoneware firing temperatures.

Origin

Throughout earth's history, violent upheavals have forced silica-rich magma up toward the earth's outer layers. Under these outer layers, the magma cooled slowly for thousands of years to form the large-grained crystalline rocks known as granite. When exposed on the earth's surface, granites are subjected to two types of weathering. Mechanical weathering (physical disintegration of granites by expansion of water, tree roots, groundwater, animal footsteps, etc.) causes the granites to be broken down into their various minerals—mainly feldspars, quartz, and micas. Chemical weathering (chemical reaction of the granites to the air, living beings, earth, and water on the earth's surface and atmosphere) causes some feldspar and mica minerals to further decompose into clay minerals.

Granites are the basis of most of our ceramic materials and make up 75% of the earth's crust. They are rocks, which by definition are mixtures of one or more minerals. Granites consist of over 50% potash and soda feldspar and up to 25% quartz. They also contain as much as 20% mica and lesser amounts of magnesium-iron minerals. Some granites, if crushed to a fine particle size, will make exciting glaze surfaces at high stoneware temperatures.

Rock: Calcite: Calcium Carbonate (Collection of Department of Earth and Environmental Sciences, Columbia University, New York).
Tests: Feldspar and Whiting (Calcium Carbonate) on stoneware fired to cone 9–10 reduction.
Left: Potash feldspar 100%.
Center: Potash feldspar 90%, Whiting 10%.
Right: Whiting (Calcium Carbonate) 100%.

Left: Granite. Slow-cooled, coarse-grained, igneous rock containing 25% quartz, 50% feldspar (mostly potash in this sample), some muscovite, biotite, and/or amphibole.
Right: Rhyolite. Fast-cooled, fine-grained igneous rock with the same chemical composition as granite.
(Collection of Department of Earth and Environmental Sciences, Columbia University, New York).

General Characteristics of Feldspars

Feldspar includes an assortment of minerals of varying composition. Despite this range, the feldspars commonly used by potters tend to follow a fairly recognizable pattern when fired to stoneware temperatures.

1. The most striking characteristic of a feldspar that is fired to stoneware temperatures is the formation of a glassy, white surface. The heat of the stoneware kiln fire, combined with the feldspar's soda and potash melter oxides (14%–15%) have transformed its considerable silica content (60%–70%) into glass. The white color is a happy consequence of the selection of atoms by size—the atoms of the coloring minerals such as iron and copper are too large to fit into the feldspathic structure. The result is a relatively pure white material to which colorants can always be added.

2. The melting action of the feldspars has a very long range: 2138°F (cone 4) to 2381°F (well beyond cone 10).

3. Melted feldspars possess a high surface tension because of their considerable alumina content (17%–25%); they crawl and flow unevenly. This is especially noticeable with a thick coat of feldspar.

4. The surface of melted feldspars contains an intricate network of fine cracks alternately described as "crazes" if considered a glaze defect and "crackle" if considered aesthetically desirable. Melting oxides, contained in the oxide structure of the feldspar, are responsible for the craze/crackle network. These melting oxides are for the most part sodium and potassium, which undergo a high rate of expansion when heat converts them from a solid into a liquid state.

5. Feldspars do not remain evenly suspended in the liquid glaze mixture. The feldspathic powder settles at the bottom of the glaze bucket, forming a dense, rock-like substance that defies even the most vigorous attempts at disbursement.

It must now be apparent that although feldspar provides the basic core of a stoneware glaze, it does present certain problems for the potter. We can solve these problems by adding small quantities of three or four minerals to the feldspathic glaze.

Additions of limestone or calcium minerals will increase the

Cone 5–6 oxidation. Porcelain claybody. Left: Satin-matt surface: Nepheline Syenite 80%, Wollastonite 20%. Back: Gloss surface: Jacky's Clear: Nepheline Syenite, 50; Colemanite, 10; Wollastonite, 10; Flint, 20; Zinc oxide, 5; Ball Clay, 5; Bentonite, 2. Front: Matt surface: Ron's White Matt #5: F-4 Feldspar, 55; Whiting, 15; EPK, 16; Zinc oxide, 14.

melt at stoneware temperatures and thus quicken the flow of the feldspathic glaze.

Additions of the glassmaker (silica) will eliminate the craze/crackle network, should this be desired. Silica, unlike the sodium and potassium melters, has a minimal rate of contraction upon cooling, and thus inhibits the high contraction rate of these melters.

Physical suspension of the feldspar in the liquid glaze may be improved by adding 10% or more of clay materials such as kaolin or ball clays. The addition of the clay materials will also toughen the raw glaze coat and help it withstand the handling that takes place when the kiln is stacked. Suspension will be further improved by the addition of 2%– 3% superplastic clay (bentonite) or even smaller amounts of soda ash or Epsom salts (magnesium sulfate).

Minerals, such as copper, iron, or cobalt, may be added in oxide or carbonate form to achieve color.

This combination of materials spawns a broad range of standard stoneware glazes. Although a specific stoneware glaze formula may show four or even five ingredients in its recipe, in most cases the core of the glaze is the feldspar. The rest of the materials are present in order to cure the problems contained in the feldspar.

At the cone 5/6 oxidation temperatures, 70% F-4 feldspar and 30% Wollastonite creates a creamy, satin-matt surface. See also the example piece with Nepheline Syenite 80%, Wollastonite 20% above.

The oxide structure of a feldspar explains why it constitutes the central ingredient core of a stoneware glaze. Most feldspars contain about 60%–70% silica (the glassmaker), 17%–25% alumina (the adhesive), and 10%–15% sodium, potassium, and/or calcium oxide (the melters).

This text was excerpted from Out of the Earth, Into the Fire: A Course in Ceramic Materials for the Studio Potter, by Mimi Obstler. Available at www.ceramicartsdaily.org/bookstore.

Clay Making

by Dave Finkelnburg

For about 95% of ceramic history, nature did the mixing and potters simply mined the clay. If potters did anything, it was to screen out the trash and stones. "Designer" clay bodies are a very recent development, as is the knowledge of how to mix them properly.

Consistency is the Key

Any clay body is fundamentally a mixture of clay, flux, and glass formers. Various forms of temper may be added to influence forming and firing properties, but these are mostly inert materials that essentially go along for the ride. In the case of porcelains, the clay is usually kaolin or ball clay. The glass former is typically ground quartz (silica). The flux is usually supplied by some type of feldspar, which is a naturally occurring mineral composed of alumina, silica, and fluxes.

Mixing these ingredients together would be simple except that feldspar particles tend to stick to each other like socks with static cling from the dryer. Tiny bits of feldspar attach to each other and resist being mixed into the clay body as individual particles. The force holding the feldspar particles together is weak electrostatic attraction but the force is strong enough to form feldspar clumps that, if mixed into the clay body, will melt into pockets of glass and contribute to bloating and slumping when the clay body is fired.

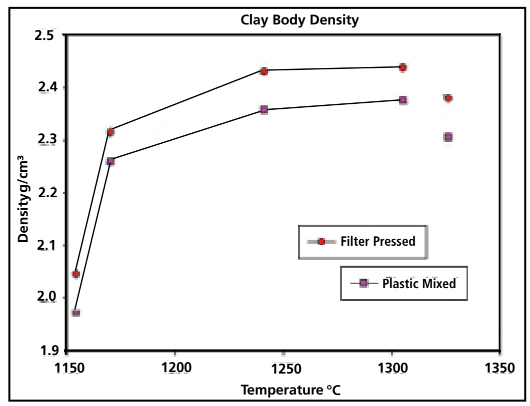


IMAGE: MATT AND DAVE'S CLAYS LLC.

To prove that feldspar clumping causes these problems, a scientist at Rio Tinto Borax (formerly U.S. Borax) tested bars of a clay body made from exactly the same recipe, but mixed by different methods. The best mixed test bars fired perfectly straight while the poorly mixed samples slumped to varying degrees in identical firings in a industrial computer-controlled kiln (see graph at right).

The slumping occurred at about 180°F below peak firing temperature, and slumping corresponded with the conversion of clay to mullite and the melting of the feldspar bits into glass. Slumping is exacerbated when feldspar particles are clumped together rather than dispersed by proper mixing.

The traditional method of mixing clay in large quantities is to use a mixer that runs at very low speed. These devices do an excellent job of incorporating coarse materials into an already mixed clay body so they are useful for changing the amount of grog in a body. However, they do not prevent the issue of feldspar clumping. This can only be addressed by slurry mixing that coats the feldspar particles with clay, thus preventing feldspar clumps.

Defining the Terms

Slake: To soak dry clay in water until the clay is fully wetted.

Electrostatic attraction: The relatively weak force between particles with opposite electrical charges that pulls the particles towards each other and, if they make contact, can hold them together.

Temper: An addition to clay bodies, such as sand or grog or natural fiber, which improves workability. These additions may affect the fired result but they are added essentially to assist in forming and drying.

Grog: Ground, fired clay body added to clay bodies, in either the wet or dry stage, to provide texture (both tactile and visual) along with tooth or bite for better control in forming. Grog opens a body up to aid in uniform drying and, because the grog is already fired, it proportionally cuts down on overall shrinkage and the tendency to crack or warp.

Slake Mixing 101

It is necessary to use a significant excess of water while mixing the batch to achieve optimum blending of clay body materials, according to Dr. William Carty of the New York State College of Ceramics at Alfred University. Mixing should be accomplished with a high shear mixer—one with a top speed in the range of 3000 feet per minute. The precise amount of water is not critical but it should be on the order of three times as much as will remain in the clay when the body is dewatered to a workable consistency.

Any plasticizer such as bentonite or Veegum should be added to the water first and slaked and mixed thoroughly. This may take up to 24 hours. Then approximately 20% of the clay in the recipe should be added. After it is slaked and mixed well, a process that takes a few minutes, the feldspar should be mixed in. This process coats the feldspar particles with clay and prevents them from clumping. The other non-plastic materials are then added, and finally the remaining clay is slaked and mixed in.

Since extra water has been used, the result is a slurry that must be dewatered to be usable. Industry typically accomplishes this with a filter press, but artists can pour the slurry into a plaster or bisque mold to pull out the water and achieve the same result. Using this process, Carty found, maximizes plasticity of the body, which is achieved within three days of mixing.

- Start with water (three times the amount necessary for plastic clay, temperature is not a factor in the final result)
- Add bentonites including macaloids (If pre-slaked and already wet, add it now. If adding dry, let it fully soak in warm water without agitation for 24 hours, then mix in.)
- Add up to 20% of the total clay in the recipe. (This keeps the feldspar from clumping)
- Add all the feldspars in the recipe.
- Add all the silica (quartz/flint).
- Add the rest of the clay in the recipe.
- Add any fillers (grog, sand, kyanite, molochite, pyrophyllite, fiber, etc). These can also be wedged or mixed in later provided the mixing is thorough and produces a uniform distribution.
- After each addition, the slurry must be thoroughly mixed.

Have a technical topic you want explored further in Techno File? Send your ideas to editorial@ceramicsmonthly.org.

Plasticity

What is it about clay that lets us shape it, pinch it between our fingers, roll coils, throw pots on a wheel, extrude endless shapes, and stretch it in every direction—all while the clay, hopefully, stays in one piece? We call this property of clay *plasticity*, and it takes a *plastic* clay to perform any of these forming processes. The very fine particle size of clay plus a liquid (in our case water and the chemistry of that water) control the plastic properties of any given clay body.

Defining the Terms

Plasticity: The property of clay that allows it to change shape without rupturing when force is applied to it. Plasticity of potters' clay cannot be measured by any scientifically repeatable test. Therefore its measurement is subjective.

Workability: The character of a clay that is a combination of plasticity and wet strength. The addition of grog or sand may permit a plastic clay to stand up taller without slumping, thus making it more workable even though it is not more plastic.

Short: Clays and clay bodies lacking plasticity. A coil rolled or extruded from a short clay, when bent sharply or tied in a knot, will show signs of tearing and cracking.

Particle Packing: A percent, always less than one hundred, representing the volume fraction of solids in a given volume of a material.

Flocculation: The process very small particles like clay exhibit in forming loose clumps due to weak electrostatic attraction between the particles. These clumps are called flocs or agglomerates.

Particular Particles

Without some water, clay is just a powder. While that seems obvious, the role of water in the plasticity of clay has not been clearly understood. Without going into the complex theories scientists have used to explain this, it is apparent that clay needs the right amount of water to become plastic. This is usually on the order of 20% water by weight. Clay particles are attracted to each other by weak electrostatic forces. Water conducts these forces. Thus, dry clay mixed with a fifth of its weight in water, becomes the plastic material clay artists use. Water also can be thought of as a lubricant that permits clay particles to slip past each other without breaking away from each other.

Clay particle size has the greatest influence on plasticity of clay bodies. Clay particles are ordinarily about 1 micron (one millionth of a meter or one thousandth of a millimeter) in size. Such tiny particles have a lot of surface for their weight. All of the particles in one gram of kaolin, for example, typically have a combined surface area of 20 square meters! For comparison, the non-plastics in a clay body, such as feldspar and silica, are usually about 40 microns in diameter and have a surface area of 1 square meter per gram. Recent research at Alfred University has demonstrated that efficient packing of the clay particles in a body dramatically improves plasticity of the body. It is thought the improvement is due to more electrostatic attraction between particles that are packed more closely together.

Packing efficiency can be controlled by blending clay body ingredients by particle size. Stoneware clay bodies, without grog, typically have a packing efficiency of about 62%. Porcelains frequently are packed as poorly as 56%. Tile bodies used in industry, packed as high as 72%, become too stiff for hand use. An ideal packing efficiency is found in grogged stoneware and is about 68%. This is the gold standard for clay plasticity because this results in as little space between clay particles as possible while still allowing easy movement against one another.

Further research at Alfred University shows that the amount of water necessary for plasticity is related to the packing efficiency of a given body—the higher the packing efficiency, the less water necessary for plasticity. This helps explain why the amount of water for plasticity is not the same for every body.

The pH (whether acid or base) of the water in a clay body affects its plasticity. Very mild acidity (a pH of 6.5—typical pH of drinking water) is ideal for clay plasticity. Keep in mind that potable water (i.e., drinking water) may contain additives that suppress bacterial growth, thus reducing the contribution of naturally occurring organic matter on the aging of clays.

Plasticity in the Studio

Clay artists tend to think of aging clay as a process of improving the clay's plasticity by storing it for a long time. Clay that is mixed with a minimum amount of water (so called dry mixed) behaves this way and exhibits increasing plasticity for the first two to four weeks of storage as it becomes fully wetted. Clay mixed in a significant excess of water (slurry mixed) ages much faster. Slurry mixed clay appears to achieve full plasticity within three days of being mixed, because it is thought that the clay is wetted more efficiently by the excess water used in the process.

Commercially manufactured organic materials claim to improve plasticity but, in general, testing has not proven the cost of these materials is justified by any significant improvement in plasticity.

There is also potter folklore about organic materials added to clay bodies to make them more plastic. These materials have included milk, beer, urine, and vinegar, among others. There is no objective evidence that any of these additives, by themselves, actually improve clay plasticity. It is likely that bacteria in the clay feed on these organic additives and give off wastes that lower the pH of the water in the clay body. This can and does improve the clay's plasticity, but has the unfortunate side effect of developing unpleasant odors, and some additives can promote the growth of unhealthy bacteria and/or molds.

Finally, consider that boxed clays are mixed and crated days, weeks, even months before use. Further aging in the studio is likely not necessary, as the aging process continues in the clay until completed—a process that typically takes only a few days.

Clay Materials We Use

There are probably as many kinds of clay as there are riverbanks, creekbeds, roadcuts, abandoned coal mines and backyard gullies, but most of the clays that many of us use on a regular basis are commercially mined.

Because not all materials are available through all suppliers, this chart is meant to provide data for the most common clays used in recipes you are likely to come across. You can use these data to compare the materials available through your supplier, or those you have on hand, with materials in the published recipes.

While the satisfaction, discovery and personal control that is possible through prospecting and processing your own clay are certainly valid reasons for the effort, most of us rely on the consistency and (relative) reliability of air-floated materials mined in large quantities. Even though the reasons for using commercially mined clays are most often based on a desire for a trouble-free product, the properties of clay as a natural material can make this goal somewhat elusive. The following chart contains the most recent information available.

However, because the chemical and physical makeup of naturally mined materials can change across a given deposit, this chart is meant to be used as a starting point for clay substitutions. In order to precisely recalculate a recipe using a substituted clay, you will need to obtain a current data sheet for all materials you purchase from your supplier.

Please note that the clays are presented in alphabetical order, and the formulae are presented with alumina (Al_2O_3) in unity (totalling 1). This makes it easier to immediately see the ratio of alumina to silica, and also more accurately compares the relative amounts of all other components in the clays.

Clay Name	Al:Si	M.Wt.	BaO	CaO	MgO	K2O	Na_2O	TiO	MnO	Al_2O_3	Fe_2O_3	P_2O5	SiO_2
54-S Ball Clay	1:3.28	314.3		.009	.027	.039	.006	.074		1	.023		3.28
6 Tile Clay	1:2.03	267.72		.019	.033		.002	.047		1	.005		2.03
A.P. Green Fireclay	1:2.85	327.92		.021	.029	.017	.027	.083		1	.041		2.85
Albany Slip Clay	1:4.44	462.93		.479	.304	.157	.06	.046	.004	1	.15		4.44
Alberta Slip	1:7.66	742.12		.785	.574	.230	.229			1	.219		7.66
Avery Kaolin	1:2.12	234.35				.026	.007	.002		1	.013		2.12
Barnard Clay	1:10.51	1343		.136	.227	.162	.123	.038		1	2.845		10.5
Bell Dark Ball Clay	1:3.58	368.23		.02	.018	.016	.006	.069		1	.023		3.58
Blackbird Clay	1:9.3	937.53		.045	.174	.204	.018	.079	.367	1	.860		9.33
C&C Ball Clay	1:3.51	327.16		.007	.018	.028	.012	.074		1	.023		3.51
Carbondale Red Clay	1:4.97	531.21	.005	.053	.085	.029	.051	.069	.002	1	.4	.003	4.97
Cedar Heights Bonding Clay	1:3.16	311.57		.012	.026	.063	.011	.069		1	.037		3.16
Cedar Heights Goldart	1:3.53	373.17		.015	.039	.074	.01	.082		1	.033		3.53
Cedar Heights Redart	1:7.11	626.27		.05	.26	.29	.04	.09		1	.29	.01	7.11
Edgar Plastic Kaolin	1:2.09	272.29		.006	.008	.012	.002	.01		1	.012	.002	2.09
Fremington Clay	1:5.04	507.14		.441	.5	.214	.036	.06		1	.19		5.04
Grolleg Kaolin	1:2.2	271.38		.005	.021	.009	.004	.001		1	.012		2.21
Hawthorn Bond Fireclay	1:2.51	268.80		.017	.023	.026	.005	.070		1	.033	.004	2.51

Continued

Clay Name	Al:Si	M.Wt.	BaO	CaO	MgO	K2O	Na_2O	TiO	MnO	Al_2O_3	Fe_2O_3	P_2O5	SiO_2
Helmer Kaolin	1:2.22	283.33		.024	.018	.016	.004	.040		1	.023		2.22
Hymod A1	1:3.05	306.76		.012	.034	.101	.022	.043		1	.030		3.06
Hyplas 71	1:5.86	481.54		.009	.051	.103	.033	.109		1	.029		5.86
Jordan Fireclay	1:5.64	500.69		.014	.065	.033	.05	.075		1	.063		5.64
Kaopaque 20 Kaolin	1:1.56	253.14		.01	.002	.002	.001	.021		1	.005		1.96
Kentucky Special Clay	1:3	354.88		.023	.031	.035	.01	.066		1	.019		2.98
Kentucky Stone	1:5.51	492.75		.035	.037	.068	.016	.068		1	.043		5.51
KTS-2 Ball Clay	1:4.28	419.75		.022	.042	.058	.014	.074		1	.026		4.28
Lincoln 60 Fireclay	1:3.76	372.15			.006	.089	.022	.036		1	.05		3.76
Lizella Clay	1:4.8	488.93		.048	.098	.068	.048	.068		1	.154		4.82
New Foundry Hill Creme Clay	1:3.94	353.89		.014	.030	.030	.013	.070		1	.025		3.94
Ocmulgee Red Clay	1:4.2	401.5		.048	.034	.064	.027	.07		1	.187		4.2
OM #4 Ball Clay	1:3.36	365.59		.020	.036	.039	.018	.055		1	.025		3.36
PBX Fireclay	1:2.49	262.47		.017	.023			.05		1	.029		2.5
PBX Valentine Clay	1:2.5	278.74		.001	.019	.004	.002	.07		1	.125		2.49
Pine Lake Fireclay	1:3.64	338.13		.02	.009	.02	.018	.089		1	.035		3.64
Pioneer Kaolin	1:2.02	265.03		.009	.007	.003	.002	.047		1	.007		2.02
Plainsman Fireclay	1:3.49	332.19		.013	.009	.081	.059	.032		1	.034		3.49
Plastic Vitrox	1:8.64	686.51		.027	.034	.496	.032			1	.004		8.64
Ravenscrag Slip	1:8.28	686.42		.639	.339	.257	.058	.039		1	.04		8.28
Redstone	1:8.93	736.21		.028	.138	.202	.001	.06		1	.191		8.93
Remblend Kaolin	1:8.28	686.42		.639	.339	.257	.058	.039		1	.039		8.28
Sagger XX Ball Clay	1:3.3	349.68		.031	.026	.033	.017	.075		1	.015		3.30
Taylor	1:4.17	367.29		.003	.021	.022	.007	.092		1	.023		4.17
Tennessee #10 Ball Clay	1:2.67	309.89		.005	.015	.036	.01	.07		1	.015		2.67
Thomas Clay	1:3.8	443.58		.004	.019	.016	.005	.077		1	.025		3.81
TN#1-SGP Ball Clay	1:3.52	365.59		.013	.027	.047	.012	.069		1	.018		3.52
Troy Clay	1:2.51	261.54		.011	.015		.005	.046		1	.021		2.51
Velvacast Kaolin	1:2.01	265.76		.003	.011	.008	.004	.044		1	.004		2.01
Yellowbanks #401	1:3	294.24		.022	.079	0	.002	.034		1	.030		3

Feldspar

by Dave Finkelnburg

Except for clay and silica, feldspar is the most common raw material in ceramics. It is also the most common mineral on the face of the earth—making up more than half the earth's crust. Most feldspar has an almost perfect ratio of flux, alumina, and silica to make a glass at high-fire temperatures.

Defining the Terms

Feldspar—Any of a group of natural crystalline aluminum silicate minerals containing sodium, potassium, calcium or barium. Alkali feldspars (those containing sodium and potassium) are used most in ceramics.

Albite—Pure sodium feldspar with the chemical formula $Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$. Very rare in nature.

Orthoclase and Microcline—The two crystalline forms of pure potassium feldspar, both with the chemical formula $K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$. Very rare in nature.

Frit—A synthetic source of glaze flux and frequently of alumina and silica, manufactured by melting the ingredients together, cooling the resulting glass, and grinding it to a fine powder.

A Natural Frit

As a crystalline mineral precipitated from molten rock over geologic time, feldspar is definitely not a designer material. Feldspar is sometimes called a natural frit and is composed entirely of crystals, but a commercial frit is made up of a finely ground glass manufactured with a specific composition. More energy is needed to melt crystals than glass, so to give it time to melt, feldspar requires a somewhat slower firing, most often to higher temperatures. While a frit can be manufactured with any desired ratio of flux, alumina, and silica, with feldspar what you mine is what you get. Thus feldspar is a sort of good-news bad-news story.

The good news is that the natural laws controlling how silicon, aluminum, and oxygen link to form the feldspar crystal ensure that the ratio of silica and alumina in *pure* feldspar is fixed.* More good news is that the flux elements exist in a fixed ratio to the alumina and silica.

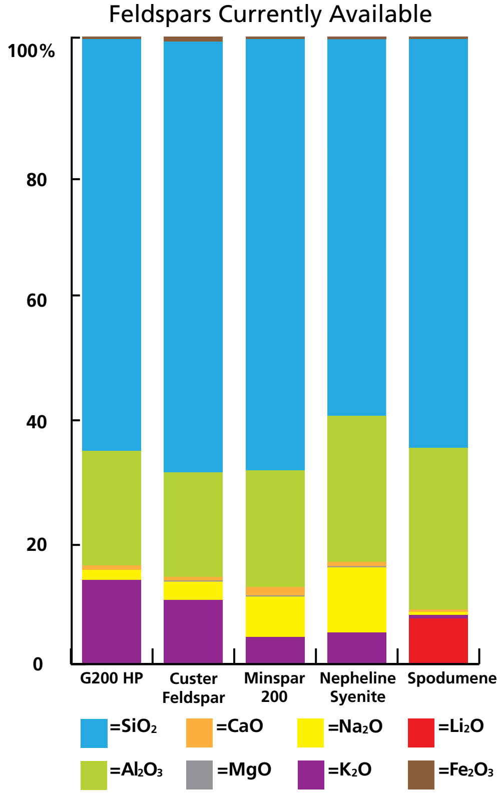
Part of the bad news, however, is that nature permits sodium and potassium to occupy that flux amount in infinitely variable proportions to one another. The amount of either in a given feldspar depends entirely on what was handy when the feldspar precipitated from the molten rock in the earth's crust. Virtually every alkali feldspar deposit on earth has at least some difference in analysis.

In scientific terms, albite and microcline/orthoclase can form a solid solution. That is, an alkali feldspar can theoretically vary from 100% sodium to 100% potassium as its flux constituent. Soda feldspars actually tend to have at least 30% of their flux as potassium, while potash feldspars usually have at least 15% of their flux as sodium.

The rest of the bad news is that feldspar most commonly occurs as a rock, usually along with mica, quartz, and other minerals. In a feldspar mine, the rock is ground to a powder and sophisticated techniques are used to separate the minerals. How well and how consistently mining companies clean and concentrate the feldspar that artists use has virtually nothing to do with artists and focuses on the folks who buy 100-ton rail-car loads of feldspar to make literally millions of tons of glass per year. Quality control good enough to make beer bottles may not be as good as we would like in the studio, but who is ultimately the bigger end user of feldspar—studio artists or folks molding beer bottles? Feldspar is ultimately an industrial mineral and we have to accept that its quality is controlled by what's good enough for industry.

* (Note the difference in the ratio of silica and alumina between feldpars, spodumene, and nepheline syenite. There is less silica in the latter two. The crystal structure explains this. This also explains the differences between potash feldspars to nepheline syenite and spodumene.)

Chemical Compositions of Common Feldspars Currently Available



Lifespan of Feldspars

Bernard Leach used Varcoe feldspar in a clay body recipe he published in *A Potter's Book* in 1940. Have you ever heard of that feldspar? Not likely. Varcoe and Sons was sold to English China Clays, Ltd., and Leach's feldspar disappeared from the market.

Have you ever heard of Oxford feldspar? Daniel Rhodes' book *Clay and Glazes for the Potter*, published in 1957, used a feldspar from Oxford County, Maine, in almost every clay and glaze recipe. Oxford feldspar, too, is long gone. In the fifth edition of *Ceramics: A Potter's Handbook*, Glenn C. Nelson listed analyses of nine feldspars. None are available today. Feldspars such as Keystone, Kingman, K200, Kona F-4, A-3, Bell, Eureka, Chesterfield, Buckingham, and most recently G-200, have all vanished.

Currently there are five common feldspars available in the US: G200 HP ("HP" for high potassium), Custer, Minspar 200, Nepheline Syenite, and Talison Spodumene (formerly Gwalia). The relatively subtle differences in their chemical compositions are shown to the left.

Making Adjustments in the Glaze Lab

Commercial frits have generally consistent analyses. Naturally occurring feldspars are less consistent and subject to change over time. While all raw materials should be tested before use, this needs to be a requirement before using each new batch of feldspar in the studio.

When feldspar is added to a clay body, it helps to melt very fine quartz into a glass phase that provides strength in the fired body. The amount of feldspar needed in a stoneware body depends entirely upon the flux level of the clays composing the body. For a fixed recipe of clays, various amounts of feldspar are tested to achieve a body with the desired level of vitrification from a given firing cycle.

The difference in silica content between Custer and G-200HP feldspars (see graph on previous page) is enough to change glaze fit. While these two potash feldspars can generally be substituted one-for-one, if one wants precise control of glaze chemistry, then a more accurate substitute for Custer is G-200HP plus 3% silica. When an existing feldspar disappears or a new one enters the market, some substitution such as this is likely to be necessary to achieve consistent results.

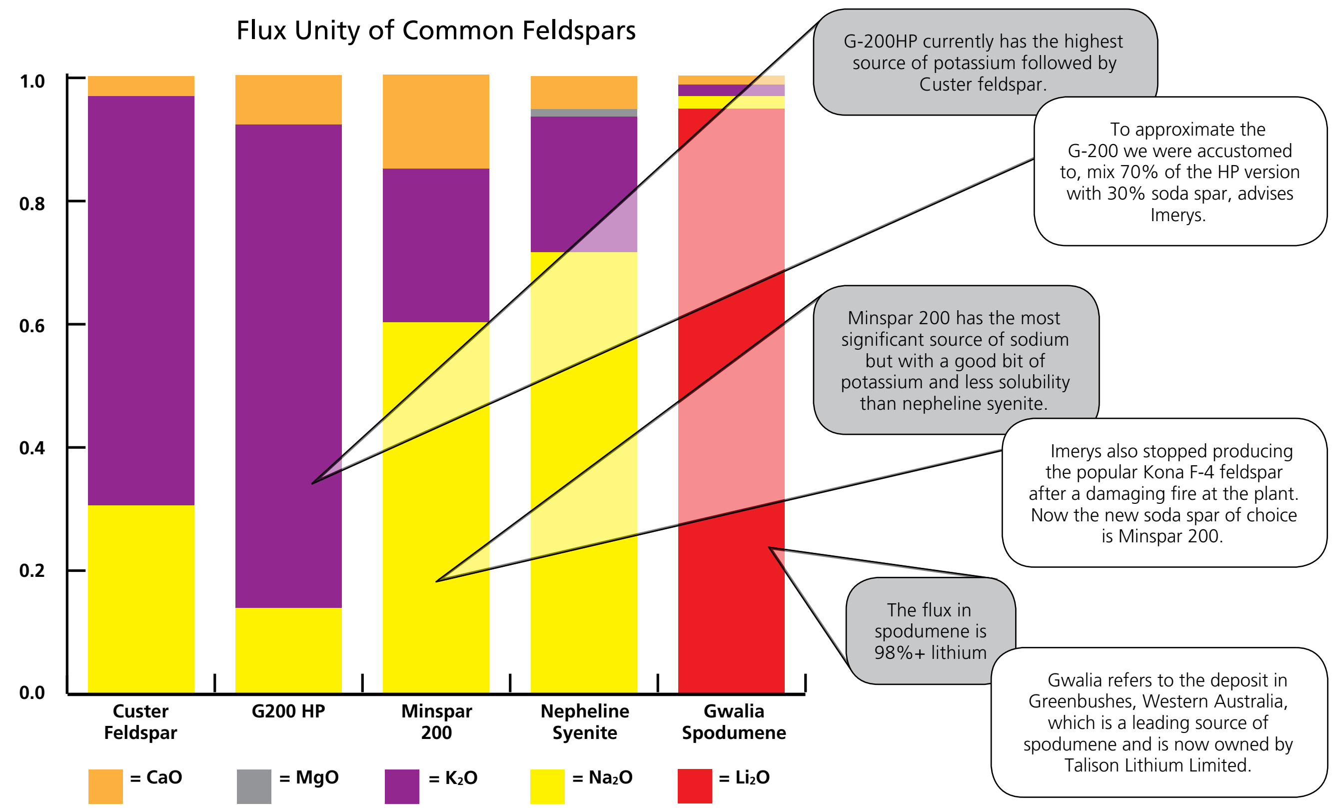
Time is also a factor. The landscape varies and as industry excavates from one mine to another the composition of feldspar changes along with it. The feldspar you were using five or ten years ago is most likely not exactly the same as what you are using today, even if it is the same brand name. Fusion button tests of the new and old material will guide you in whether and how to substitute other materials to accommodate the new feldspar's chemistry. To start:

1 Get a full chemical analysis of the new and old feldspars, if they are available.

2 Fire fusion buttons (a few grams of feldspar pressed into a small mold such as a crucible) of both materials side by side to get a visual indication of the differences in the two materials. Note color changes, melting temperatures, opacity, and surface effects.

3 Adjust recipes as these differences indicate and fire recipe tests to confirm that the adjustments are correct.

Some ceramic artists use chemistry to adjust clay and glaze recipes before testing. Others rely entirely on testing. The method chosen may say something about an artist's working style, but not the results, both methods work equally well.



Feldspars Used in Ceramic Glazes and Clay Making

Feldspars are important ingredients in clay bodies and glazes. In both applications, their primary function is to supply fluxes to the formulations, but they also provide additional alumina (Al_2O_3) and silica (SiO_2). Feldspars are naturally occurring minerals and are generally classified as either potash (potassium) or soda (sodium) feldspars based upon the predominant alkali metal element (the flux) that is present. The minerals commonly referred to as lithium feldspars are not true feldspars, but they are aluminosilicates like feldspars and contain the fluxing element lithium, and are used for the same purposes as the feldspars.

The following table presents typical chemical analyses (in weight percent) provided by the suppliers, for a number of common feldspar products and related materials. Most of the names are trade names, with the exceptions of lepidolite, petalite, and spodumene, which are true mineral names. Nepheline syenite is actually a rock composed of potash and soda feldspars plus the mineral nepheline (a sodium aluminum silicate). In the table, the trade names for the feldspars are grouped according to the actual type of feldspar that they contain. Distinguishing between the different types of feldspars based upon the fluxes that they provide is important because of the different characteristics that each of the fluxes contributes to a wide variety of properties such as melting point, thermal expansion, glaze color and hardness. For each analysis, the remaining percentage needed to bring the total of all the elements to 100% is the ignition loss (not shown in the table).

The analyses will allow you to compare the compositions of different raw materials when it is desirable to make substitutions in clay body and glaze recipes. The weight percent values will be useful in the conversion of glaze recipes from Seger molecular formulas to weight percent recipes when using these raw materials.

The theoretical formulas and molecular weights for the different types of minerals present in the products are as follows:

Potash feldspars	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	556.66
Soda feldspars	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	524.45
Lepidolite	$(Li,Na,K)_2 \cdot (F,OH)_2 \cdot Al_2O_3 \cdot 3SiO_2$	(varies w/alkalis)
Petalite	$Li_2O \cdot Al_2O_3 \cdot 8SiO_2$	612.52
Spodumene	$Li_2O \cdot Al_2O_3 \cdot 4SiO_2$	372.18

However, all of these naturally occurring mineral products often contain additional minerals or elements as minor impurities, as can be seen in the table, and as a result, their calculated molecular weights will differ somewhat from the theoretical values. The final column in the table shows molecular weights calculated for each of the materials, based on the specific analysis shown (all the elements including the impurities). These specific molecular weights can be used, instead of the theoretical molecular weights given above, in the conversion of glaze recipes from weight percent to Seger molecular formulas. It should be kept in mind, however, that as the actual composition of the minerals varies with time and source, these calculated molecular weights will also change.

Feldspars We Use

The following table presents typical chemical analyses in weight percent, which will allow you to compare the compositions of different raw materials when it is desirable to make substitutions in clay body and glaze recipes.

Potash (Potassium) Feldspars

Name	SiO_2%	Al_2O_3%	K_2O%	Na_2O%	MgO%	CaO%	Li_2O%	TiO_2%	Fe_2O_3%	Calc. Mol. Wt.
Bell	68.2	17.9	10.1	3.1		0.4			0.1	607.69
Buckingham	66.3	18.4	11.8	2.7		0.4			0.1	566.44
Chesterfield	70.6	16.3	8.5	3.8		0.3			0.1	637.92
Clinchfield #202	68.3	17.6	10.9	2.6		0.2			0.1	616.44
Coles	69.0	16.9	10.8	2.7		0.5			0.1	597.00
Cornwall Stone	70.9	16.7	6.5	2.3		1.6		0.5	0.2	726.06
Custer	69.0	17.1	10.1	3.0		0.3			0.2	618.82
Del Monte	67.8	18.5	6.6	4.3		2.1			0.1	565.71
Eureka	69.8	17.1	9.4	3.5					0.01	638.85
Fukushima	65.4	19.2	9.8	4.6	0.2	0.3			0.1	526.34
G-200	66.5	18.6	10.8	3.0		0.8			0.1	560.19
Harshaw	65.4	19.6	12.1	2.2	0.3	0.4				558.82
Imperial	66.5	18.5	12.4	2.3		0.3				575.08
K-200	67.99	17.84	10.13	3.36		0.18			0.08	603.74
Keystone	64.8	19.9	12.2	2.5		0.2				575.92
Kingman	66.5	18.4	12.0	2.7		0.1			0.1	577.67
Kona A-3	71.6	16.3	7.8	3.7		0.4			0.1	667.52
Madoc	67.4	18.2	7.8	5.6		0.5			0.1	547.62
May	67.8	17.2	12.6	2.0		0.2			0.1	586.93
Oxford	70.6	17.3	8.1	3.3		0.4			0.1	686.70

Soda (Sodium) Feldspars

Name	SiO_2%	Al_2O_3%	K_2O%	Na_2O%	MgO%	CaO%	Li_2O%	TiO_2%	Fe_2O_3%	Calc. Mol. Wt.
C-6	67.5	19.0	5.4	6.8		0.9			0.1	543.93
Glaze Spar #54	67.1	21.2	1.5	9.1		1.1				548.41
Godfrey	71.7	16.5	4.6	5.3	0.9	1.0				570.18
Kona F-4	66.9	19.7	4.5	7.0		1.8				517.95
NC-4	68.5	18.9	4.1	6.9		1.4			0.1	557.18
Nepheline Syenite	56.5	24.2	9.1	8.1		0.1			0.1	404.80
Sil-O-Spar	77.6	13.5	2.9	4.9		1.1			0.1	781.96
Unispar 50	67.3	19.4	4.9	6.7		1.5			0.1	533.98

Lithium "Feldspars"

Name	SiO_2%	Al_2O_3%	K_2O%	Na_2O%	MgO%	CaO%	Li_2O%	TiO_2%	Fe_2O_3%	Calc. Mol. Wt.
Lepidolite	42.40	19.25	6.93	0.76			3.09		0.1	382.31
Lithospar	69.03	21.59	2.90	4.02		0.48	1.99			612.95
Petalite	77.13	17.50	0.26	0.25			4.32			655.86
Spodumene	64.50	26.00	0.10	0.30		0.10	7.60		0.1	376.28

Glossary of Common Ceramic Raw Materials

barium carbonate $BaCO_3$—alkaline earth—active high temperature flux, but also promotes matt glaze surface. Unsafe for low-fire functional glazes. Often used as an additive in clay bodies in very small percentages to render sulfates insoluble, reducing scumming.

bentonite Al_2O_3•$5SiO_2$•$7H_2O$—formed from decomposition of airborne volcanic ash. Suspension agent used in quantities no more than 3% of dry materials weight.

bone ash (calcium phosphate) $Ca_3(PO_4)_2$—high temperature flux—opacifier in low temperature glazes—translucence in high temperature glazes.

borax (sodium tetraborate) Na_2O•$2B_2O_3$•$10H_2O$—a major low temperature alkaline flux, available in granular or powdered form. Gives smooth finish, bright colors. Water soluble, so often used in fritted form.

chrome oxide Cr_2O_3—standard vivid green colorant—often softened with a little iron or manganese. Very refractory. With tin produces pink.

cobalt carbonate $CoCO_3$—standard blue colorant for slips and glazes—5% will give dark blue in glaze or slip. Will cause crawling if used raw for underglaze brushwork.

copper carbonate $CuCO_3$—a major glaze colorant to produce greens in low temperature and high temperature, copper reds in high temperature reduction, and greens and metallic effects in raku.

dolomite $MgCO_3$•$CaCO_3$—high temperature alkaline earth flux, promotes hard, durable surfaces and recrystallization/matting in glazes.

feldspar High temperature alkaline fluxes—insoluble aluminum silicates of potassium, sodium, calcium, and/or lithium—inexpensive flux for glaze.

frit Fluxes that have been melted to a glass, cooled, and ground in order to stabilize soluble and/or toxic components during handling of unfired material.

ilmenite An iron ore with significant titanium—most often used in granular form to produce dark specks in clay or glaze. Higher iron concentration than in rutile.

iron oxide, red (ferric oxide) Fe_2O_3—refractory red in oxidation, converts to black iron (flux) in reduction and/or high-fire. Low quantities in clear glaze produces celadon green—high quantities produce temmoku black or saturated iron red—powerful flux.

kaolin; china clay Al_2O_3•$2SiO_2$•$2H_2O$—very refractory white primary clay. Source of alumina in glazes.

lithium carbonate Li_2CO_3—powerful all temperature alkaline flux, especially with soda or potash feldspars. Promotes hardness and recrystallization in low temperature glazes.

magnesium carbonate $MgCO_3$—alkaline earth—high temperature flux, promotes mattness and opacity in low temperature glazes, smooth, hard, buttery surface in high temperature glazes—promotes purples/pinks with cobalt. Used to promote controlled crawl glaze effects.

manganese dioxide MnO_2—flexible colorant—with alkaline fluxes gives purple and red colors—by itself gives soft yellow-brown—with cobalt gives black. Used with iron to color basalt bodies. Concentrations of more than 5% may promote blistering.

nepheline syenite K_2O•$3Na_2O$•$4Al_2O_3$•$9SiO_2$—a common feldspathic flux, high in both soda and potash. Less silica than soda feldspars, and therefore more powerful. Increases firing range of low-fire and mid-range glazes.

rutile Source of titanium dioxide, contains iron, other trace minerals—gives tan color, promotes crystallization giving mottled multi color effects in some high temperature glazes, or in overglaze stain.

silica (silicon dioxide, flint, quartz) SiO_2—main glass-former—vitrification, fluidity, transparency/opacity controlled by adding fluxes and/or refractories.

spodumene Li_2O•Al_2O_3•$4SiO_2$—lithium feldspar—powerful high temp alkaline flux, promotes copper blues, good for thermal-shock bodies and matching glazes.

strontium carbonate $SrCO_3$—alkaline earth, high temperature flux, similar to barium, slightly more powerful—gives semi-matt surfaces. Nontoxic in balanced glaze.

talc $3MgO$•$4SiO_2$•H_2O—high temperature alkaline earth flux in glaze, promotes smooth buttery surfaces, partial opacity—similar composition to clay.

tin oxide SnO_2—most powerful opacifier, but expensive—inert dispersoid in glaze melt—5–7% produces opaque white in a clear glaze.

titanium dioxide TiO_2—matting/opacifying agent. Promotes crystal growth, visual texture in glazes.

whiting (calcium carbonate, limestone) $CaCO_3$—alkaline earth, contributing calcium oxide to glaze—powerful all temperature flux—major high temperature flux for glazes—gives strong durable glass.

wollastonite (calcium silicate) $CaSiO_3$—In some cases, it is used in place of whiting.

zinc oxide ZnO—high temperature flux that promotes brilliant glossy surfaces. Can encourage opacity, with titanium in low-alumina glaze can encourage macrocrystalline growth.

zirconium silicate $ZrSiO_4$—zircon opacifier—low-cost substitute for tin oxide—use double the recipe weight of tin. Includes Zircopax, Opax, Superpax, Ultrox.

Excerpted from *Clay: A Studio Handbook* by Vince Pitelka.

Primary Function of Common Ceramic Raw Materials

Material	Glaze Function	Substitute	Comment
Barium Carbonate	Flux	Strontium carbonate	
Bentonite	Suspension agent	Ball Clay	Do not exceed 3%
Bone Ash	Opacifier		
Borax	Flux, glassmaker	Boron frits	
Chrome Oxide	Colorant		Green
Cobalt Carbonate	Colorant	Cobalt oxide	Blue
Copper Carbonate	Colorant	Copper oxide	Greens, copper reds
Cornwall Stone	Flux, opacifier		
Custer Feldspar	Glaze core	Potash feldspar (G-200)	
Dolomite	Flux, opacifier	Whiting	Many brands
EPK Kaolin	Alumina, opacity	Kaolin	
Ferro Frit 3110	Glaze core, flux	Pemco P-IV05, Fusion F-75	Crystalline glazes
Ferro Frit 3124	Glaze core, flux	F-19, P-311, Hommel 90	Boron frit
Ferro Frit 3134	Glaze core, flux	F-12, P-54, Hommel 14	Boron frit
Ferro Frit 3195	Glaze core, flux	Hommel 90, Fusion F-2	Complete glaze
Ferro Frit 3269	Flux, glaze core	Pemco P-25	
Ferro Frit 3278	Flux, glaze core	Fusion F-60, Pemco P-830	
G-200 Feldspar	Glaze core	Potash feldspar (Custer)	
Green Nickel Oxide	Colorant	Black nickel oxide	Blues, tan, browns, greens, grays
Kentucky OM4 Ball Clay	Alumina, opacity	Ball Clay	
Kona F-4 Feldspar	Glaze core	Soda feldspar	
Lithium Carbonate	Flux		
Magnesium Carbonate	Flux, opacifier		Promotes crawling
Manganese Dioxide	Colorant		Purple, red, yellow-brown
Nepheline Syenite	Glaze core		
Red Iron Oxide	Colorant		Celadon green to brown
Rutile	Colorant	Ilmenite	
Silica	Glass former, glaze fit	Flint	Use 325 mesh
Spodumene	Lithium glaze core		
Strontium Carbonate	Flux	Barium carbonate	
Talc	Flux, opacifier		Many brands
Tin Oxide	Opacifier	Zircopax	
Titanium Dioxide	Opacifier		
Whiting	Flux, opacifier	Wollastonite, Dolomite	Many brands
Wollastonite	Flux, opacifier	Whiting, dolomite	
Wood Ash	Glaze core, flux, colorant	Whiting	Results vary by type
Zinc Oxide	Flux, opacifier		
Zircopax	Opacifier	Superpax, Ultrox	

Notes:
1. Substituting glaze ingredients may alter color, texture, opacity, viscosity, and/or sheen, as well as create pinholing, crazing, black spotting, and/or pitting. In most cases, additional adjustments to other ingredients need to occur when substituting.
2. Test and record your results.
3. Materials vary from supplier to supplier and batch to batch.

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