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Classification, genesis and evolution of ferruginous surface grains

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Studies of ferruginous surface grains (FSGs) have shed considerable light on the origin of both these enigmatic grains and on regolith evolution. This paper describes a user-friendly classification scheme, and the genesis and evolution of FSGs.

The classification system has four levels. The first is based on initial observations necessary to recognise the class of regolith material to which FSGs belong, namely lags. The second separates FSGs from other lag components, such as rock fragments and resistant mineral grains, and hence requires more detailed observation of the sampled material. The third level of classification requires petrographic and mineragraphic examination—the main textural types are homogeneous, lithorelic, pseudomorphic, vesicular, sandy, and oolitic. The fourth level of classification identifies modifying microfabrics, namely concentric, cutanic, compound, mottled, and syneresis fabrics.

FSGs are formed in three main environments: the weathering profile (mottled zone and saprolite); surfical environments (soils and sediments); and subaqueous environments (lakes and rivers). They form by four main processes: ferruginisation of a protolith (mainly in the weathering profile, but also in subaerial and subaqueous sediments); concretion in a solid medium (surficial materials and the weathering profile); accretion in subaqueous environments, (lakes and rivers); and fragmentation of existing ferruginous material.

Diagenesis of FSGs causes both textural and mineralogical changes. Dehydration, mineralogical unmixing, dissolution, and precipitation all alter the original fabric. Replacement, dehydration, and recrystallisation change the mineralogy. Hydration of hematite to goethite also occurs in humid climates. Ions of interest to exploration geochemists may be lost during syneresis and unmixing.

Application of this classification system requires integration of microfabric studies with geomorphological mapping, regolith stratigraphy, mineralogy, and geochemical data.

Introduction

Ferruginous surface grains (FSGs), commonly known as 'pisolites', 'ironstone gravel', 'buckshot gravel' or similar terms, are important components of lag over much of Australia. Lag sampling is widely used in exploration of deeply weathered environments. A summary of the use of lags is given by Carver et al. (1987), whose work demonstrated that lag is a very useful and sensitive medium for gold and base metal geochemical exploration in deeply weathered terrains over wide areas, despite difficulties in sample collection, higher processing costs, and noisy data. FSGs and lags provide clues to hidden ore bodies in at least two ways: through anomalous element distribution inherited from their protoliths; and through trapping of remobilised indicator elements by iron and manganese oxides and oxyhydroxides constituting the FSGs. Until comparatively recently, little had been published on the character, genesis, and evolution of FSGs, apart from the pioneering studies of Anand et al. (1989) and Nahon (1991). More recent studies (Alipour et al. 1994; Kotsonis et al. 1994; Clarke 1994; Robertson 1994; Tilley et al. 1994) were presented at the 1994 Australian Regolith Conference at Broken Hill (Pain et al. 1994). Data in these studies complement those in this paper.

Our research has concentrated on the fabric, mineralogy, and association of FSGs from different geomorphic and geologic settings (Fig. 1). These data are synthesised into a proposed classification system, which is useable by the explorationist, and which can be related to the genesis and evolution of these grains in the regolith. Use of the classification system will enable better interpretation of geochemical data from lag samples.

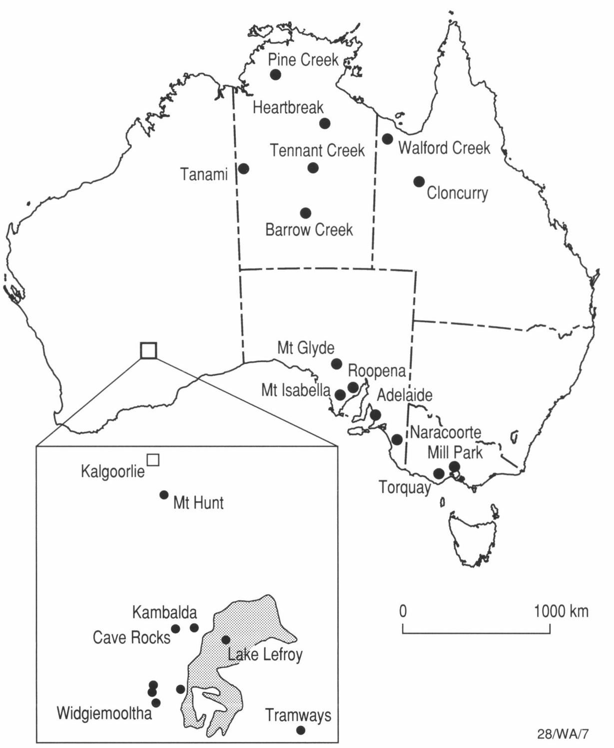

Figure 1. FSG sample localities.

Study methods

Samples of FSGs were collected from various localities in Western Australia, South Australia, Victoria, Queensland, and the Northern Territory (Table 1).

Polished thin sections were prepared of all samples, which were examined with a Leitz Orthoplan-pol microscope under both reflected and transmitted light. Oil immersion proved most useful at higher magnification, particularly for observing clays in transmitted light. Distribution of trace elements in some FSGs was mapped with a Cameca SX-50 microprobe at Melbourne University. In some cases, 3-D surface features of FSGs were examined with the JEOL JSM-35 SEM, also at Melbourne University and WMC's JEOL JSM-T200 in Kalgoorlie, to compare results with those obtained from visible light studies.

Problems of FSG classification

Classification of FSGs is difficult, as the grains tend to be superficially very similar. Hence, there is a tendency for many explorationists to call any reddish brown to black surficial grain (0.5 mm–5 cm) a 'pisolite', irrespective of its composition, surface fabric, internal structure, whether the grain is loose on the surface, buried in soil, reworked into a gutter or rill, or cemented into a ferricrete.

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Table 1. Setting of FSGs sampled in this study.

Locality	*Climate*	*Substrate*	*FSG host*	*Host lithology*	*Age of host*
Widgiemooltha	semi-arid	---------	ferricreted sediments	sands, silts	Cainozoic
Cave Rocks	semi-arid	Archaean	ferricreted residual sediment	gravels, sands	Meso-Cainozoic
Tramways	semi-arid	Archaean	ferricreted residual sediment	gravels-silts	Cainozoic
Kambalda	semi-arid	Archaean	ferricreted residual sediment	gravels, sands	Cainozoic
Lake Lefroy	semi-arid	---------	sediment	sands, silts	Miocene
Mt Hunt	semi-arid	Archaean	ferricreted residual sediment	gravels-silts	Meso-Cainozoic
Tennant Ck	arid	Proterozoic	residual	soils	Quaternary
Pine Ck	monsoon tropical	Proterozoic	residual	soils	Quaternary
Barrow Ck	arid	Proterozoic	residual	soils	Quaternary
Heartbreak	monsoon tropical	---------	sediments	soils	Cainozoic
Roopena	mediterranean	Proterozoic	residual	soils	Quaternary
Mt Isabella	mediterranean	Proterozoic	residual	soils	Quaternary
Mt Glyde	arid	Proterozoic	residual	soils	Quaternary
Adelaide	mediterranean	Adelaidean	residual	soils	Cainozoic
Naracoorte	temperate	---------	sediments	sands	Quaternary
Mill Park	temperate		sediments	sands, gravels	Quaternary
Torquay	temperate		sediments	sediments	Eocene
Cloncurry	semi-arid		sediments	silts, sands	Cainozoic
Walford Ck	monsoon tropical		residual sediments	sands, gravels	Quaternary

The terms 'pisolite' and 'pisolith' also present problems. According to Bates & Jackson (1980), a pisolith is "One of the small, rounded or ellipsoidal accretionary bodies in a sedimentary rock, resembling a pea in size and shape, and constituting one of the grains making up a *pisolite*. It is often formed of calcium carbonate, and some are thought to have formed by a biochemical algal-encrustation process. A pisolith is larger and less regular than an *oolith*, although it has the same concentric and radial internal structure. The term is sometimes used to refer to the rock made up of pisoliths. Syn: *pisolite*."

The key features of pisoliths in this definition are: accretionary origin, rounded shape, particular size (0.5–1 cm), and a radial and concentric internal structure. In respect to size, sedimentary petrologists (Peryt 1983) commonly classify pisoliths as coated grains >2 mm in diameter with no upper size limit; however, 10 cm appears to be the absolute maximum in practice. Sedimentary coated grains <2 mm are termed ooids.

Ferruginous grains, loosely called 'pisolites' by exploration and other geoscientists, often fail to meet some or all of the criteria outlined above. Many are clearly detrital rather than accretionary; rounding is sometimes poorly developed and some are highly angular; they may be smaller than 2 mm and a concentric internal fabric is not present in all. A radial fabric was not observed in any of the ferruginous 'pisoliths' examined during this study, nor was one reported in any of the literature reviewed. Radial fabrics appear confined to coated grains of other compositions (Peryt 1983).

To avoid these difficulties, the term FSG (ferruginous surface grain) is suggested as a more accurate, non-genetic term to describe these grains. 'Surface' includes all near-surface materials (e.g. soils, sediments, residual material) as well as those exposed on the regolith–atmosphere interface. The term 'FSG' avoids the size (>2 mm), textural (rounded), fabric (concentric), and genetic (accretionary) implications of the term 'pisolite'.

FSGs can be classified by many criteria. Existing classifications by CSIRO (Anand et al. 1989) and by us (see below) are based primarily on fabric. Other parameters not used to date, but which may be useful in some circumstances, include size, shape, colour, mineralogy, density, and magnetic properties.

Existing classifications

The most comprehensive previous attempt to systematically classify FSGs is that of Anand et al. (1989). Their work was based on extensive studies of weathering profiles and products in the Darling Ranges, east of Perth, and parts of the Eastern Goldfields region of Western Australia.

Anand et al. (1989) divided FSGs (pisoliths in their terminology) into four basic types. These were **homogeneous** (no internal fabric), **lithorelics** (grains with relic rock fabrics and at least partial preservation of primary mineralogy), **pseudomorphic** (purely secondary minerals, but some preservation of primary fabrics, and **concentric** (with multiple rinds indicating concretion or accretion).

Each of the four basic types could be modified by any of three additional terms. These were **cutanic** (thin outer layer or layers present, but not enough to impart a true concentric fabric), **compound** (several originally separate grains that have been cemented together), and **syneresis** (vuggy and fissured internal fabrics indicating dewatering of clay and oxyhydroxides). A FSG might, therefore, be classified as cutanic, compound and homogeneous, indicating that several homogeneous grains had been cemented together by cutan growths.

Size terms were also included in the classification of Anand et al. (1989). **Ooliths** are lateritic grains <2 mm in size; **pisoliths** and **nodules** are lateritic grains 2–64 mm in size. Nodules are more irregular or angular in shape than pisoliths, a term restricted to the more rounded grains. Pisoliths were noted as rarely exceeding 20 mm in diameter.

Of all these diverse grain types, only cutanic, concentric and some compound (if containing concentric or cutanic grains, or cemented by cutanic and/or concentric growths) grains can be considered as being pisolitic in any usage of the term, consistent with the definition of pisolite quoted earlier.

Although useful in many ways and an important starting point, this classification fails to completely represent the diversity of FSG types and the complexity of their genesis. It does not include what is among the most common type of FSG encountered—fragments of ferricreted sediment. For this reason we have found it necessary to introduce a new classification to reflect this diversity and complexity. This will place the whole FSG terminology into a classification system which will assist in understanding and interpreting FSG geochemistry and regolith evolution.

Proposed classification

The proposed classification scheme consists of four hierarchical levels (Fig. 2), determined by the degree of sophistication needed by the observer to discriminate between them. This allows classification of the grains at whatever level is appropriate.

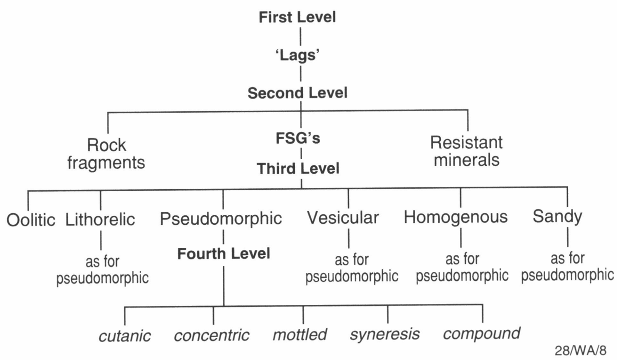


Figure 2. Proposed 4-level classification system.

First level

The first-level classification in the proposed scheme is that of lags. This can be made by cursory inspection with the naked eye. It is thus applied to field samples before they are sorted into different components.

Second level

FSGs are a subset of the second level of lag materials. This classification requires careful inspection of lags, possibly with the aid of a hand lens or binocular microscope. FSGs may dominate some samples and be absent in others. Other components are resistant minerals (quartz, feldspars, heavy minerals, etc.) and rock fragments. The relative abundance of each of these types of lag will vary according to the nature of the regolith at each sample location. The composition will also vary, depending on the abundance of each type of lag. It is thus important to suddivide the lag, where possible, into FSGs, resistant minerals, and rock fragments, rather than use an all-inclusive term such as lag. Discussion of these other components in surfical lags is beyond the scope of this paper. Fragments of bedrock-derived sedimentary ironstone and gossans may be confused with FSGs formed in the regolith unless careful external inspection or internal textural examination is undertaken. Rock fragments and heavy mineral separates are legitimate sample media in their own right (e.g. for diamond exploration), but also beyond the scope of this study.

Third level

The third level of classification in this scheme requires examination of internal fabrics. As FSGs are composed largely of opaque or semi-opaque minerals, use of a mineragraphic reflecting light microscope to study polished thin sections is essential. Polished slabs of larger grains can be studied with a binocular microscope. Polarised, transmitted light is useful for identifying transparent minerals in thin section and oil immersion techniques for transmitted light have proved to be very helpful, at higher magnifications, for studying fine-grained replacements of clays.

The four basic classes (homogeneous, concentric, lithorelic and pseudomorphic) defined by the CSIRO (Anand et al. 1989) are relevant, but with modifications. **Homogeneous** FSGs have no protolith relics or pseudomorphic protolith fabrics, and contain less than 10% detrital grains. They may exhibit other fabrics, however. The term **concentric** is changed from being a basic fabric (third level) to being a modifier (fourth level). Three new modifiers must be added. These are vesicular, sandy, and oolitic FSGs. **Vesicular** FSGs consist of fragments of vesicular ferricrete. **Sandy** FSGs contain >10% detrital sand and may be either matrix or grain supported, the matrix consisting of a ferruginised cement or soil plasma. **Oolitic** FSGs consist of smooth, mostly continuous, concentric laminae in contrast to the more irregular, discontinuous laminae of concentric FSGs. This differs from the use of the term by Anand et al. (1989), who applied 'oolitic' to any coated regolith grain smaller than 2 mm in diameter. In the present classification, 'oolitic' FSGs are those which formed in agitated, subaqueous, sedimentary environments, in contrast with the pedogenic environments of cutanic and concentric FSGs. Unlike cutanic or concentric FSGs, oolitic FSGs are thus *accretionary* in origin rather than *concretionary*. Typical examples of these fabrics are illustrated in Figure 3.

Fourth Level

The fourth level consists of the modifers concentric, cutanic, compound, mottled, and syneresis. Each of these terms modifies the third-level fabrics. **Cutanic** fabrics are formed by irregular and sometimes discontinuous overgrowths on the exterior of the FSG (Fig. 4). **Concentric** FSGs are formed by multiple layers of such overgrowths forming a concentric. **Compound** fabrics occur in aggregate grains and, where there is a significant proportion of detrital quartz, may be difficult to differentiate from sandy FSGs. **Mottled** fabrics arise from reordering of metastable oxide and hydroxide phases. **Syneresis** fabrics are cracks formed by clay and oxyhydroxide dewatering. Typical examples might be concentric sandy FSGs, or syneresis vesicular FSGs. Oolitic FSGs are the exceptions in that they do not require modifiers.

Application

Application of the classification with relevant mineralogical descriptors to individual grains results in composite names being applied to individual grains. Three examples of extended description and naming are given in Table 2.

Studies of populations of FSGs reveals that almost all contain a mixture of types. The classification of FSGs from all study areas is shown in shown in Table 3. Predominant mineralogy, prevalence of cutans (and thus applicability of the term 'pisolith'), and abundance of various FSG types are shown. The variability shown in FSGs from different areas reveals that sampling FSGs during geochemical exploration is unwarranted unless the following factors are determined—which fraction (rock fragments, resistant minerals, FSGs) of the lag is carrying the geochemical anomalies, and what is the nature and history of that fraction? With all fractions, and not just FSGs, polished thin section studies are necessary to characterise their nature and to place them in a local geomorphological and regolith stratigraphic context.

Origin and evolution of FSGs

Four factors are needed for reconstructing the origin and evolution of FSGs. These are: the environment of formation; the process of formation; post-formation transport; and mineralogical evolution. Environment of formation and post-formation transport are shown in Figure 5; the textural evolution of representatives of the main FSG types is shown in Figure 6. The process of formation and mineralogical evolution are illustrated by Figure 7.

Environment of formation

FSGs can form in a wide range of weathering and sedimentary environments. The three most important are *in situ* weathering profile, surficial environment, and subaqueous environment.

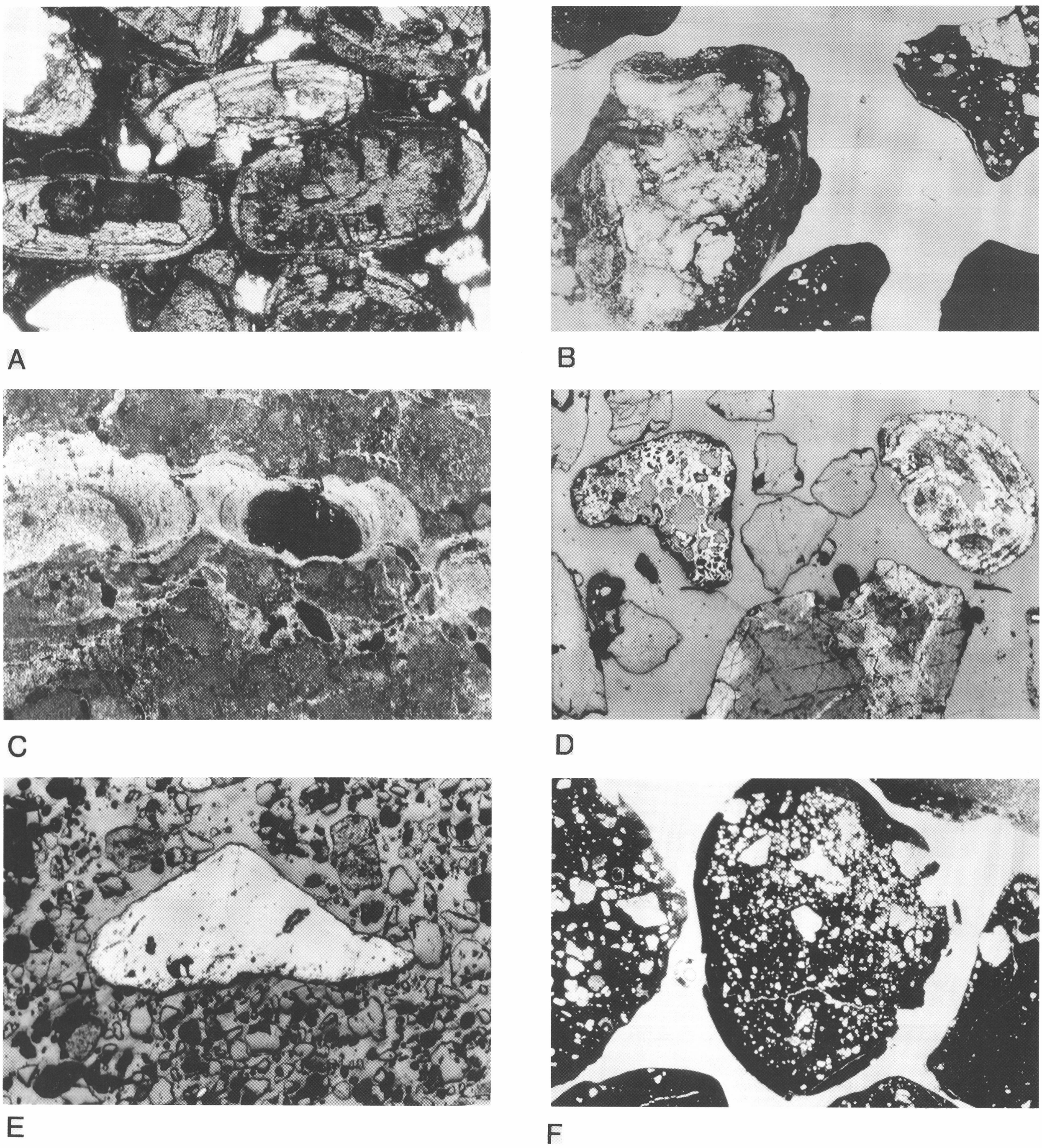
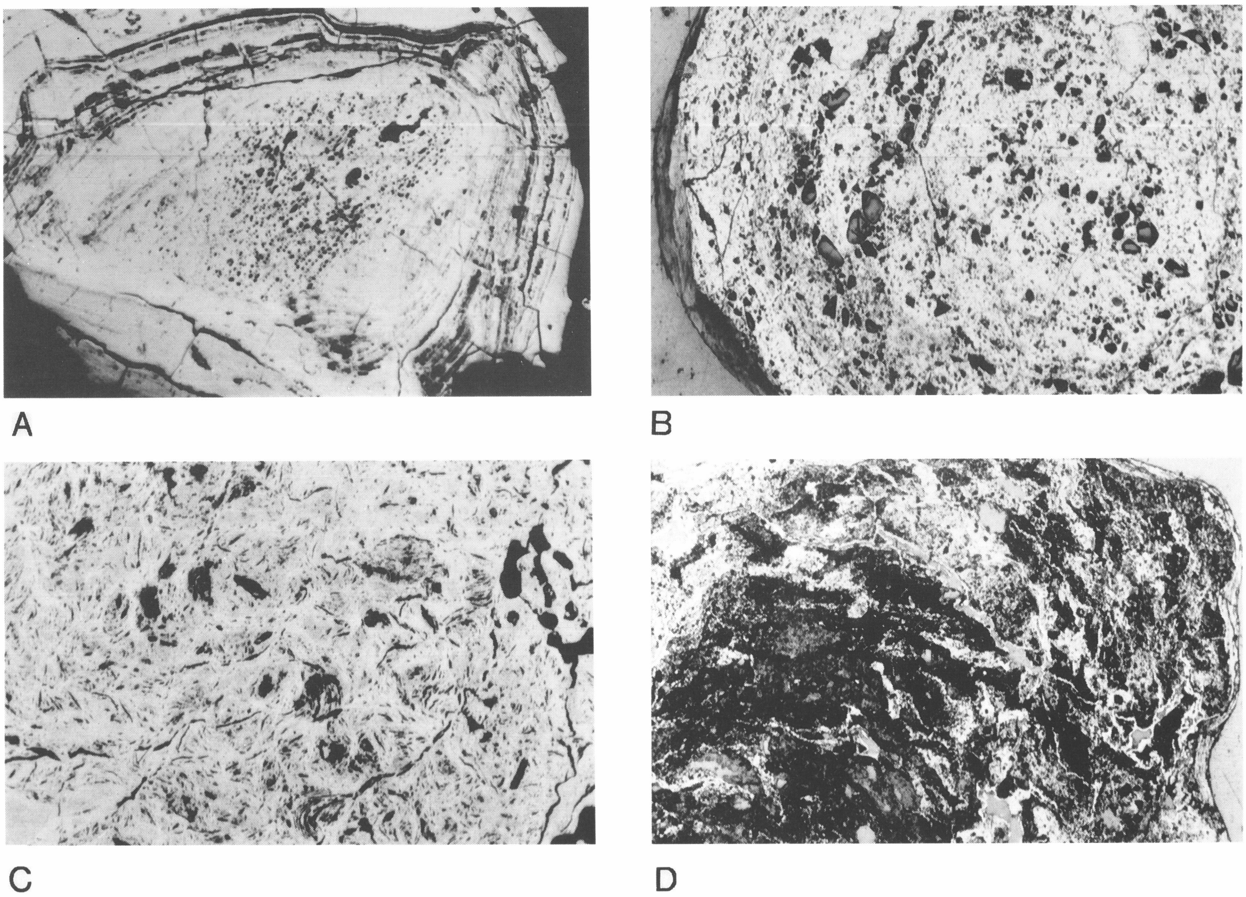


Figure 3. Main FSG fabrics. ***A.*** **Oolitic goethitic FSGs from Tertiary of Lake Lefroy; Transmitted light; width of photo 14 mm.** ***B.*** **Lithorelic goethitic FSG (left-hand side) from Tanami desert. Transmitted light; width of photo 14 mm.** ***C.*** **Clay infills replaced by goethite, forming pseudomorphic goethitic FSG from Tennant Creek. Reflected and transmitted light; width of photo 0.7 mm.** ***D.*** **Vesicular hematitic FSG (upper left), Widgiemooltha. Reflected light; width of photo 3 mm. E. Homogeneous hematitic FSG, Widgiemooltha. Width of photo 3 mm.** ***F.*** **Sandy goethitic FSGs (some with cutans), Tanami desert. Transmitted light; width of photo 14 mm.**

Iron precipitation in the lower part of the **weathering profile** consists mainly of concretionary replacement of metastable minerals and the infilling of joints, fractures, and voids. Lithorelic and pseudomorphic FSGs are formed by erosion of the upper parts of the regolith and redistribution of the fragmented material. The upper part of the weathering profile (mottled zone or laterite proper) is the main zone of formation for pseudomorphic, relict and some concentric fabrics through growth of nodules and mottles. Ferruginisation may also occur in the uppermost part of the weathering profile. This results in homogeneous and matrix-supported sandy FSGs, where a soil plasma has been replaced by goethite (and/or hematite). Modification by syneresis is also widespread in this environment. Erosion of the weathering profile will produce detrital FSGs with a wide range of fabrics.

Surficial environments, specifically soils, sand sheets, alluvial, colluvial, and aeolian deposits, and bogs, are where most, though not all, sandy, homogeneous, and vesicular FSGs are formed. Cutanic, compound, and concentric modifying fabrics can also be attributed to these environments. The chief process is chemical precipitation of iron oxides and oxyhydroxides, which displace, replace and/or cement the original



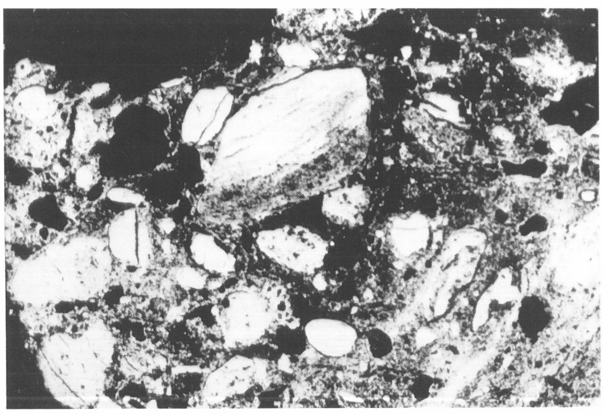


Figure 4. FSG modifying fabrics. A. Cutan on hematitic FSG from Tramways. Reflected light; width of photo 3 mm. B. Concentric hematitic FSG, Tanami desert. Reflected light; width of photo 3 mm. C. Mottled fabric in hematitic FSG from Tramways. Reflected light; width of photo 0.7 mm. D. Syneresis cracks in pseudomorphic hematitic FSG from Tanami desert. Reflected light; width of photo 0.7 mm. E. Compound FSG of homogeneous hematitic FSGs, Tramways. Reflected light; width of photo 3 mm.

soil and sedimentary material. Faecal pellets may be present. Erosion of weathered profiles or ferricretes, followed by cementation to generate detrital FSGs with diverse fabrics also takes place here.

Subaqueous environments, chiefly rivers and lakes, are the only environments where oolitic FSGs, as defined in this paper, can form. Marine oolitic FSGs and the manganese-rich equivalents (such as those at Groote Eylandt, see Bolton et al. 1988) are not likely to be confused with FSGs of other origins because of the presence of marine fossils in either the oolitic sediments or associated lithologies. Lacustrine or fluvial oolitic ironstones may be more easily confused with FSG-rich deposits formed by other processes because subaqueous indicator fossils may be scarce. Fossil wood, freshwater gastropods, and freshwater algae may be present, however. Oolitic FSGs are present in Lake Lefroy near Kambalda, in the Tertiary of Victoria, at Walford Creek, and in the Pilbara, where they form the Robe River Pisolite (Zimmerman et al. 1973; van Houten 1992). They may be mixed with FSGs of other origins, particularly in fluvial settings. Oolitic FSGs are often attributed to erosion and re-deposition of a 'laterite' (cf. Hall & Kneeshaw 1990). Internal fabrics (smooth and continuous, rather than irregular, discontinuous laminae), grain nuclei (fossils or detrital sand grains), and isopachous (smooth, even coatings) cements reveal their subaqueous origins. Homogeneous pellets are commonly associated with oolitic FSGs; these may be faecal in origin.

Processes of formation

The processes that form FSGs are as diverse as the environments in which they form. The most important are ferruginisation, concretion, accretion, and fragmentation. Cementation of FSGs into larger aggregates is important locally.

Ferruginisation of pre-existing mineral phases (Herbillon & Nahon 1988; Beauvais & Colin 1993) is generally recognised to be important in the formation of mottled zones of 'laterites' (Ollier & Galloway 1990). The ferruginisation of *in situ* mineral matter in a weathering profile results in lithorelic and pseudomorphic FSGs, depending on whether the ferruginisation is respectively partial or complete. Bourman (1993b) attributed vesicular and massive ferricrete to ferruginisation of fine-grained and possibly organic-rich soils. Fragmentation of such ferricretes, ferruginous mottled zones, and ferruginous duricrust leads to the formation of homogeneous and vesicular FSGs.

Accretion in fully subaqueous environments is responsible for ooid formation (Siehl & Thein 1989). Ooids grow in periodically agitated environments, by addition of more or less smooth and even, concentric laminae to the outer surface. The smooth laminae distinguish accretionary FSGs from concretionary FSGs. The ooids may have a nucleus of detrital quartz or a fossil.

Ferruginised material tends to be harder than the surrounding non-ferruginised surficial material or weathered profile. Erosion of weathering profiles and surficial soils tends not only to **fragment** ferruginous material, but also to concentrate the fragments through winnowing. The resulting lag may comprise a mixture of FSGs of diverse origins and ages. The lag may remain unconsolidated or become cemented to form a ferricrete. Bourman (1993a) attributed many ferricretes to cementation and ferruginisation of surfical FSG deposits.

Biogenic–detrital processes result in the formation of small (0.1–2 mm) FSGs as faecal pellets. Invertebrates ingest fine-grained soil or sediment and then excrete the non-digestible residue as small, homogeneous pellets. If the ingested material is iron-rich, then so will the pellets, but they are as liable to later ferruginisation as any other material. Faecal pellets are common in most surficial environments, and are directly analogous to the pellets found in many marine sediments (Tucker & Wright 1990).

Table 2. Examples of FSG description and classification.

Description	*Name*
FSG comprising goethite-cemented sandy ferricrete with an outer cutan	Cutanic, sandy goethitic FSG
Homogeneous FSG of hematitic composition with internal mottles and syneresis cracks	Syneresis, mottled, homogeneous hematitic 'FSG'
FSG with multiple nuclei of homogeneous, sandy, and lithorelict grains cemented by multiple, concentric cutans	FSG with multiple nuclei of homogeneous, sandy, and lithorelict grains cemented by multiple, concentric cutans

Diagenesis

Comparison of FSGs from different areas and of different ages indicates that diagenetic alteration of FSGs is widespread. Diagenetic alteration results in both textural and mineralogical changes.

Fabrics evolve through a number of processes (Nahon 1991). For example, dehydration of clays and iron oxyhydroxides can lead to syneresis cracks and cavities. Unmixing of metastable gels and minerals, because of changing environmental conditions or simply time, can result in mottled fabrics, consisting of irregular networks of one iron oxide phase, such as hematite, separating irregular islands of another phase, such as lepidocrocite. FSGs can grow through concretion or accretion of additional material, forming cutanic and concentric fabrics. Furthermore, changes in water chemistry will lead to dissolution of previously stable mineral species, leaving voids or pseudomorphs. Alternating periods of FSG growth and dissolution form micro-unconformities within individual grains. This is most evident in cutanic, concentric, and compound FSGs. Typical evolutionary trends consist of the gross FSG fabric (third-level terms) being modified by the imposition of fourth-level fabrics. This may be followed by one or more stages of fragmentation and transport, with intervening periods of further secondary fabric modification through syneresis, unmixing, cutanic development, and cementation.

Mineralogical evolution is characterised by ferruginisation,

Table 3. Characteristics of FSGs sampled in this study.

Sample locality	*Mineralogy*	*Cutan status*	*FSG type*					
			lithorelic	*pseudomorphic*	*homogeneous*	*vesicular*	*sandy*	*oolitic*
Widgiemooltha	hematite	present, relict		present	abundant	common	present	
Cave Rocks	hematite	very common, relict	common	present	present	present	present	
Tramways	hematite	abundant, relict		very common	very common			
Kambalda	hematite	present, relict		common	present	common	common	
Lake Lefroy	goethite, hematite	present						abundant
Mt Hunt	hematite	present, relict			abundant			
Tennant Ck	hematite, goethite	very common, relict, active	present	present	very common	very common		
Barrow Ck	hematite, goethite	common, relict					abundant	
Pine Ck	goethite	present, active	present	present	present			
Heartbreak	goethite	present, relict		rare	common		present	
Roopena	goethite, hematite	absent	rare		rare		abundant	
Mt Isabella	hematite	present, relict		common	common		common	
Mt Glyde	hematite	absent					abundant	
Adelaide	goethite	absent	common	common	common		common	
Naracoorte	goethite	present, active					abundant	
Mill Park	goethite, hematite	absent					abundant	
Torquay	goethite	present						abundant
Cloncurry	goethite	present, relict					abundant	
Walford Ck	goethite	absent	very common	rare	present		very common	

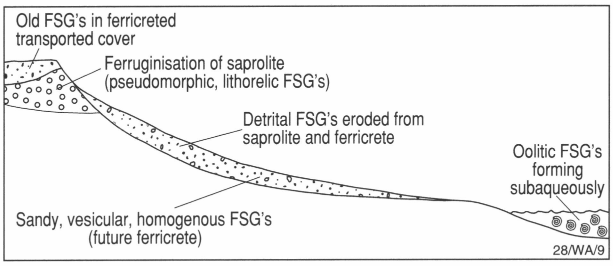


Figure 5. FSG-forming environments.

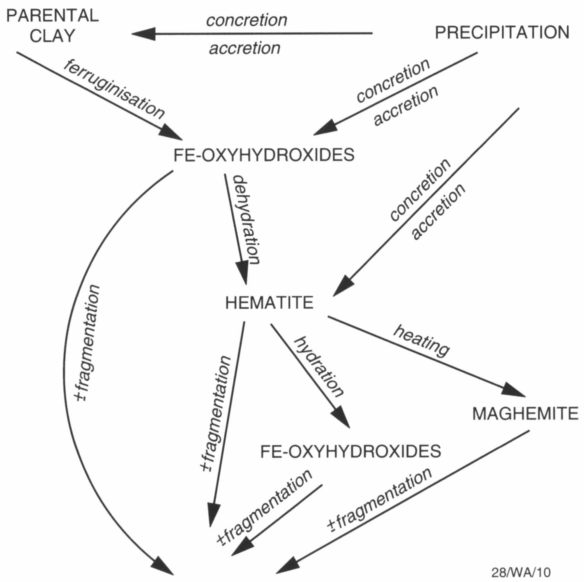


Figure 6. Textural evolution of FSGs (adapted from Nahon 1991).

dehydration, recrystallisation and re-hydration. Ferruginisation in the weathering profile occurs when clays replace metastable minerals in the protolith. These are progressively replaced by goethite, leading eventually to complete ferruginisation. Concretionary FSGs are at least partly formed by ferruginisation of precursor clays. In these cases, there appears to have been further direct precipitation of goethite. Goethitic FSGs are present in most samples examined, and have formed under a range of climatic conditions Schwertmann (1985).

Every gradation in replacement has been observed, from minor hematite associated with goethite to total hematite composition. Hematitisation occurs in two stages. Initial replacement of goethite by cryptocrystalline earthy hematite is followed by recrystallisation of the earthy hematite, which is still reddish under reflected light, to coarser crystalline hematite with a pale grey polish under reflected light. The conversion of goethite to hematite requires dehydration and crystal reorganisation. This may be by prolonged solar heating and drying or by the effect of bush fires. There is also evidence in some FSGs of the breakdown of hematite and its replacement by goethite. This process has been well documented by Beauvais & Colin (1993). Maghemite was present in some FSGs and has also been reported from ferricretes. With a much higher temperature needed for its formation than hematite, it has been postulated that the presence of maghemite may be due to baking of a few centimetres of the upper regolith by bushfires (Anand & Gilkes 1987 Bourman 1993b). Ordering processes during dehydration of iron hydroxides to form hematite and maghemite may result in loss of ions of interest to the exploration geochemist. This is because iron oxides have less accommodation spaces in their crystal lattice and less surface area in their crystallites compared with hydroxides.

Unmixing of metastable oxide and hydroxides leading to the formation of mottled fabrics may have a similar effect. The geochemically interesting ions are less likely to be accommodated in the new, more ordered structures, and are likely to have been lost to the surrounding environment.

Cementation can occur in surficial or subaqueous environments. In the vadose zone, cementation occurs through precipitation of iron minerals, clays, or carbonates from meniscus water films. Under subaqueous conditions, cementation occurs in water-filled pore spaces, resulting in isopachous and void-filling cements. Iron-poor substrates, such as clays, may be subsequently ferruginised. FSGs of diverse origins and fabrics may be cemented to rock fragments or residual grains. The resulting partly or wholly lithified material is then subject to fragmentation, erosion, and deposition, forming detrital compound FSGs. Subsequent re-cementation and further fragmentation will produce FSGs and ferricrete of polycyclic origin.

Anomalies in FSGs

FSGs may acquire metal anomalies in at least three different ways: by inheritance from anomalies in the protolith; by lateral solution transport and precipitation of elements on or in the FSGs; and by vertical solution transport and precipitation of elements.

Inheritance of protolith anomalies is the simplest and, from the explorationists' perspective, the ideal situation. For example, if the protolith is anomalous in gold, nickel, or copper, the FSGs should themselves be anomalous in these and associated elements. Whether the FSGs are themselves enriched or depleted in relation to the protolith will depend on their weathering history.

Two separate processes can form anomalies through lateral migration and precipitation. (1) Physical transport of geochemically anomalous FSGs can result in local concentrations and thus secondary geochemical anomalies composed of detrital FSGs. Depending on factors such as attrition, size of the source, dispersion, dilution, and hydrodynamic processes, the anomaly may be hundreds of metres or kilometres from the source. (2) Elements in solution can be transported over similar distances until their precipitation in geochemical traps, possibly by microbial activity. These are likely to be in topographic lows, ideal places for the formation of *in situ* ferricretes and FSGs, and accumulation of detrital FSGs.

Applications

Regolith studies

FSGs are produced by many different processes which result in superficially very similar end-products. Furthermore, fragmentation, together with vertical and horizontal transport, may result in mixing of FSGs of different ages, environments and processes of formation, and histories. Classification by their internal fabric is the only way to determine the origin of populations of FSGs. Fortunately FSGs are amenable to study through reflected light mineragraphy, supported by transmitted light studies, particularly if both are used in conjunction with oil immersion microscopy.

Exploration

A multidisciplinary approach is required to interpret geochemical anomalies. In this way the context and significance of each anomaly can be understood. It is important to consider at least three factors for each geochemical anomaly: geomorphology; composition of the regolith; and nature of the microfabric.

The geomorphological context includes such factors as position in the landscape (interfluve, midslope, toeslope, valley floor) and whether it is part of the modern geomorphic regime or a relict feature. It is easy to determine that the landform is relict where is it is being actively eroded or exhumed, but

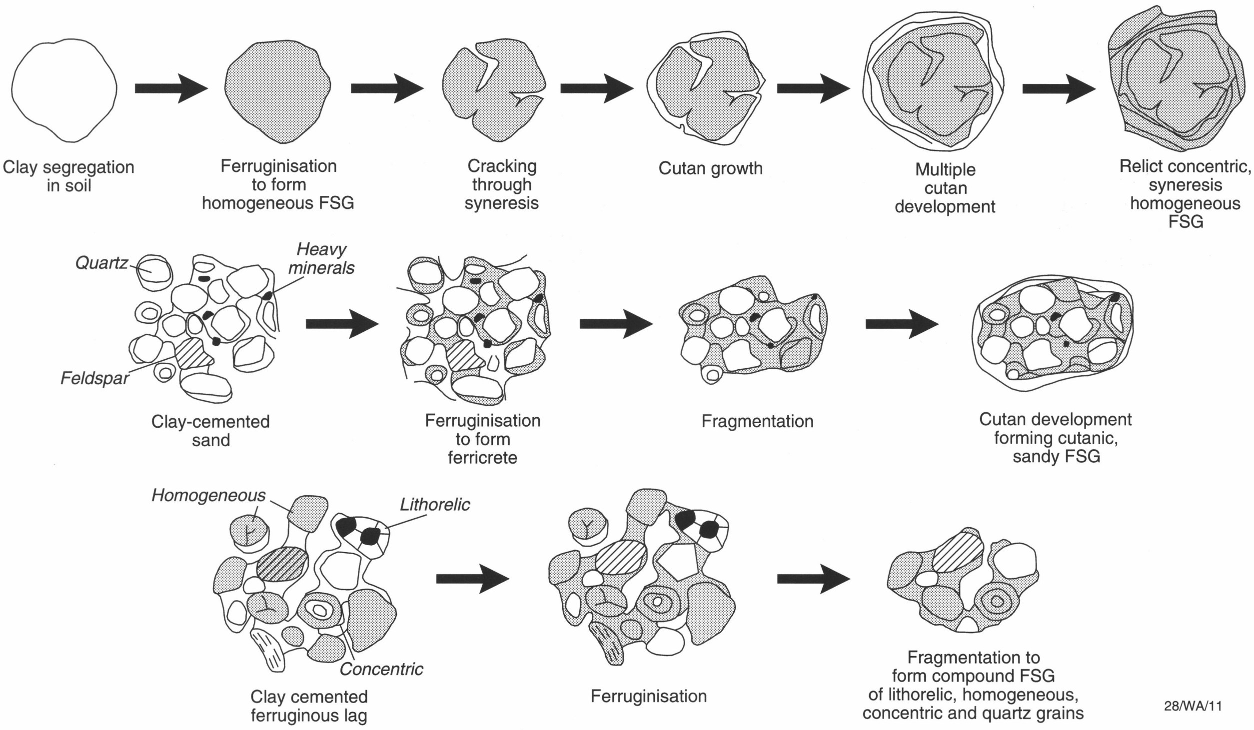


Figure 7. Mineralogical evolution of FSGs.

it is less easy where it is preserved intact but inactive. The possibility of topographic inversion must be born in mind in ancient Australian landscapes (Ollier 1991).

The composition and stratigraphy of regolith material which contains the FSG is of critical importance. Questions to be answered include (1) are the FSGs developed from *in situ* weathered material or transported material? (2) are the FSGs in transported material, have they grown *in situ*, or are they detrital? (3) what is the nature of the host material? and (4) is the host material relict or still forming?

Microfabric and mineralogical studies are not by themselves a substitute for understanding the geomorphological and regolith contexts of FSGs, but they can greatly increase our depth of understanding. Microfabric studies, in particular, can clarify the nature of the protolith, the mineralogical evolution of FSGs—whether they are monomict or polymict in origin, whether they are actively forming or relict grains—and the environment of formation.

Summary and conclusions

Conclusions from this study of FSGs from several widely dispersed localities in Australia are as follows.

- A four-level classification of FSGs is proposed, expanding on earlier schemes. The first level is that of superficial observation, which recognises only the class of regolith material to which FSGs belong, namely lags. The second separates FSGs from other lag components (rock fragments and resistant mineral grains). This level requires more detailed observation of the sampled material. Third-level classification is carried out through petrographic and mineragraphic examination of the FSGs. Categories are based on the major fabrics observed by transmitted and reflected light microscopy. The major fabrics are pseudomorphic, vesicular, sandy, and oolitic. The fourth classification level is based on textural modifiers, namely concentric, cutanic, compound, mottled, and syneresis fabrics.
- FSGs can be formed in three main environments: the weathering profile (saprolite, mottled zone); surficial materials (soils, sediments), and subaqueous environments (lakes, rivers).
- FSGs form through four main processes: ferruginisation of a protolith (mainly in the weathering profile); concretion in a solid medium (chiefly in surfical materials); accretion in subaqueous environments; and fragmentation of existing ferruginous material.
- Diagenesis of FSGs can result in original oxyhydroxides being replaced by hematite through dehydration. Heating may result in the formation of maghemite. Rehydration of hematite to form hydroxides can occur under humid conditions.
- Reordering of FSG mineralogy during diagenesis may result in loss from the FSG of elements of interest to the exploration geochemist. Mottled and syneresis fabrics together with oxide-dominated mineralogy are indicative of this process.
- Microfabric studies must be integrated with geochemical data, landform mapping, and interpretation of both regolith stratigraphy and composition. A multidisciplinary approach to FSGs has considerable benefits to both general regolith studies and interpretation of geochemical responses in soil lags.
- It should be possible to determine if lag sampling will be effective in a particular area by examining the characteristics of FSGs prior to carrying out an expensive lag sampling program.

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