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# Loess and fragipans: Development of polygonal-crack-network structures in fragipan horizons in loess ground

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ABSTRACT

One of the defining features of the fragipan horizon is the presence of a blocky polygonal network structure. In loess soils, this network structure can be explained by contraction forces (due to drying) operating after hydrocollapse due to loading and wetting, as in the Bryant hypothesis for fragipan formation. Three stages are identified in the formation of a fragipan horizon in loess ground. There is a deposition phase in which the aeolian deposition of loess material produces certain ground properties. A collapse stage allows the soil structure to deform under the influence of loading and wetting. This collapsed material develops internal tensile forces as drying contraction proceeds and these cause the development of a characteristic crack network. The crack network can be modelled using a very simple Monte Carlo approach and the two dimensional structure produced gives a good representation of fragipan cracking. The collapse-contraction process for fragipan formation offers explanations for the strength and hardness of fragipans, the constant depth to fragipan horizons, the slaking in water (predominance of short range contact bonds) and the mineralogical similarities throughout the system. The fragipan horizon impedes drainage, and this becomes increasingly important as land use becomes more widespread.



## 1. Introduction

A fragipan is a diagnostic soil horizon (USDA Soil Taxonomy, 2010, p.7). It is a dense horizon with limited permeability and it tends to develop in loess soils. The fragipan is a much discussed phenomenon (see reviews by Grossman and Carlisle, 1969; Smalley and Davin, 1982; Smeck and Ciolkosz, 1989; Witty and Knox, 1989; Bockheim and Hartemink, 2013). Many defining characteristics have been listed including: the high density relative to other parts of the soil system, the disaggregation reaction when plunged into water, the fairly consistent depth from surface to top of fragipan, the mineralogical similarity to the adjacent soil horizons, the formation where the ratio of rainfall to evapotranspiration is quite high.

Witty and Knox (1989) listed 16 points which are required to be considered in the definition of fragipan. Point 10 is the most relevant to this discussion:

It (fragipan horizon) has few or many bleached, roughly vertical planes that are faces of coarse or very coarse polyhedrons or prisms.

We discuss the formation of these polyhedrons or prisms, the whole large-scale structural network (see Fig. 1 for sketch impression, from Van Vliet and Langohr, 1981). Some other Witty and Knox points have relevance to the current discussion:

4. Compared to the horizons above it, the bulk density is high.
7. When a dry fragment is placed in water, it slakes or fractures.
11. Most commonly, it has an abrupt or clear upper boundary at a depth of 33–100 cm below the original surface. (At about 70 cm in Fig. 1).

The purpose of this paper is to discuss the development of the macro-structure within the fragipan layer, the network of characteristic polygonal units. In Keys to Soil Taxonomy (USDA, 2010, p.7), some requirements are listed for the definition of fragipan horizons. Requirement no.3 demands that the fragipan layer has a very coarse prismatic, columnar, or blocky structure of any grade, has weak structure of any size, or is massive. This is the large-scale structure discussed, and it is hoped that providing a realistic and

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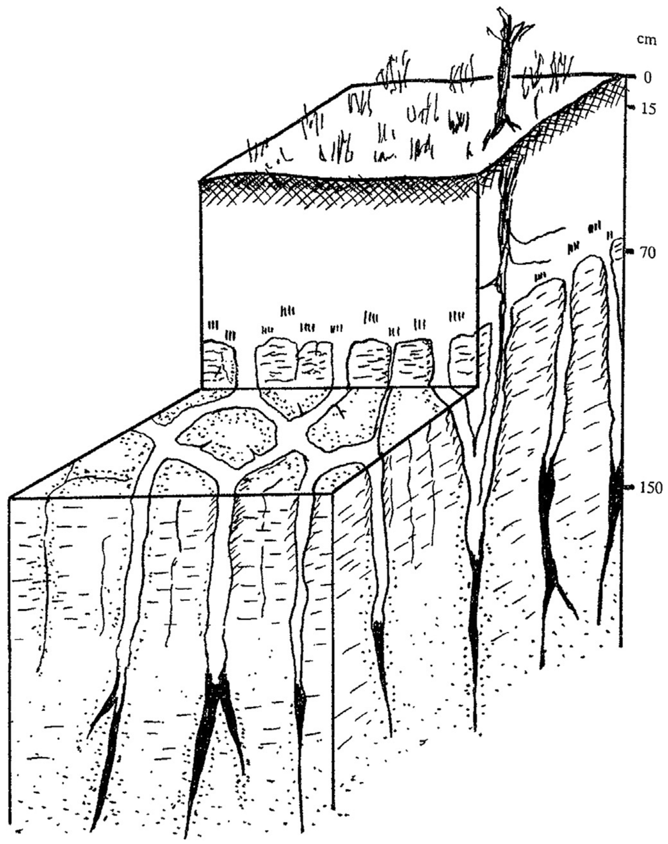


**Fig. 1.** The fragipan in position, after Van Vliet and Langohr (1981). See Smalley and Davin (1982 p.80) for discussion. A version of this figure appears on the cover of Smalley and Davin (1982).

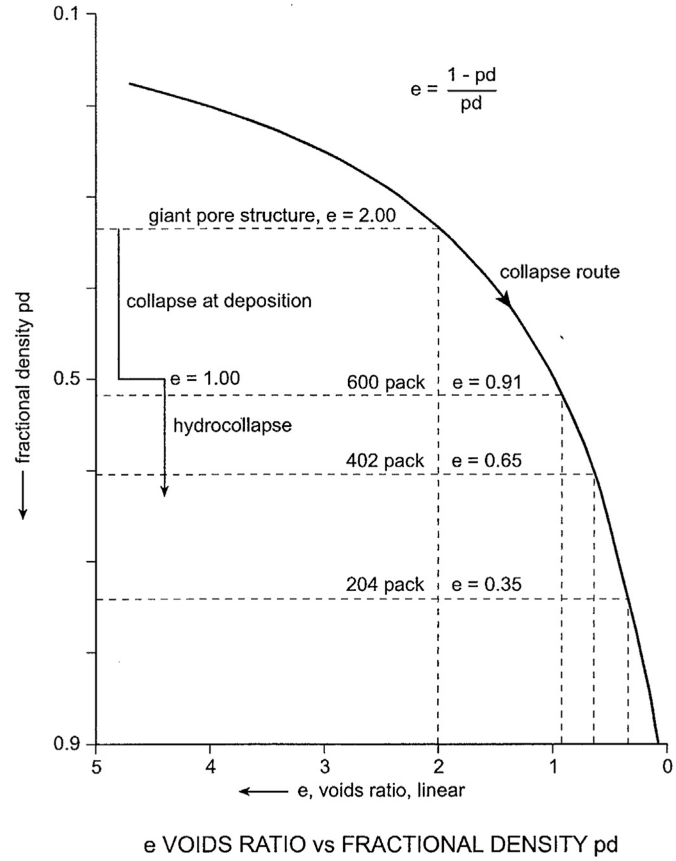


**Fig. 2.** The relationship between e voids ratio and PD packing density. Some regular packing densities are indicated, for 600, 402 and 204 packings (see Rogers et al 1994a for explanations). See Dijkstra et al., 1995 for discussions of packing transitions.

sensible explanation of this characteristic fragipan structure will be a positive contribution to the discussions on the mode of formation of the fragipan itself.

## 2. Densification

Consideration of changes in density will form an important part of this discussion so some critical density related terms need to be defined. Soil is a particulate system and in such a system relative packing density can be defined as the ratio of solids present in the system; the range is from all solid, PD = 1, to all empty, PD = 0. Voids ratio e, the relevant term used in soil mechanics, is defined as the ratio of space in the system to the solids in the system:

$$(e = [1 - PD]/PD).$$

A voids ratio of 1.0 is equivalent to PD = 0.5. The relationship of e to PD is shown in Fig. 2, which provides a convenient framework to demonstrate changes in the loess soil system as deposition is succeeded by collapse and then by contraction.

## 3. Deposition

The loess deposit is formed by aeolian deposition of largely silt sized material, much of which is quartz. The modal particle in a loess deposit might be considered to be a 30um quartz particle with a definite blade shape. Shape studies are not definitive or conclusive, but there are indications that certain shapes will be favoured. Rogers and Smalley (1993), using a very simple Monte Carlo method, calculated that the modal shape should be defined by a side ratio of 8:5:2. They called this a Zingg 3 m particle (see Smalley, 1966a for shape terminology) and it does have a remarkably pronounced blade shape (blade is simply defined as a > b > c). The blade shape is the least well-defined of the four straightforward particle shapes. In simple terms it might be called ‘flattish’. These particles, on aeolian deposition, have an open structure with a high porosity, a low packing density, a high voids ratio. It is a structure dominated by short range contacts, a relatively rigid structure.

In Fig. 2, the deposition process is given a speculative and imaginative presence. There is no evidence for the initial formation of a very open structure with a voids ratio of around 2, but it is believed that the initial deposition process would involve a modest amount of ‘tamping’ while the system settled to the eventually observed e value of around 1.0. This would be the classic initial loess, the Ur-Loess of Smalley and Krinsley (1981). From this position, the denser structures are developed.

In Fig. 2 some very ideal packings are indicated, with e values. Applying packing ideas to soil systems has never been very successful. The best attempt was probably by Morrow and Graves (1969), an attempt which was appreciated and discussed by Dijkstra et al. (1995). The 600 packing is the cubic packing and the 204 packing is the close rhombohedral packing. The transition from 600 to 204 is an interesting collapse manoeuvre, and Dijkstra et al. (1995) made some attempts to relate it to loess collapse.

Packing problems in general in geo-science settings have been discussed by Rogers et al. (1994a). In a loess deposit, there is a packing of particles and a set of interparticle bonds. The particles, in place, define the structure; the bonds control the post-depositional