Lecture 11 Large Layered Intrusions

Friday, February 25, 2005

Chapter 12: Layered Mafic Intrusions

Table 12-1. Some Principal Layered Mafic Intrusions

Name	Age	Location	Area (km^2)
Bushveld	Precambrian	S. Africa	66,000
Dufek	Jurassic	Antarctica	50,000
Duluth	Precambrian	Minnesota, USA	4,700
Stillwater	Precambrian	Montana, USA	4,400
Muskox	Precambrian	NW Terr. Canada	3,500
Great Dike	Precambrian	Zimbabwe	3,300
Kiglapait	Precambrian	Labrador	560
Skaergård	Eocene	East Greenland	100

Large or particularly well-studied LMIs exposed in continents (many in flood basalt provinces)

The form of a typical LMI

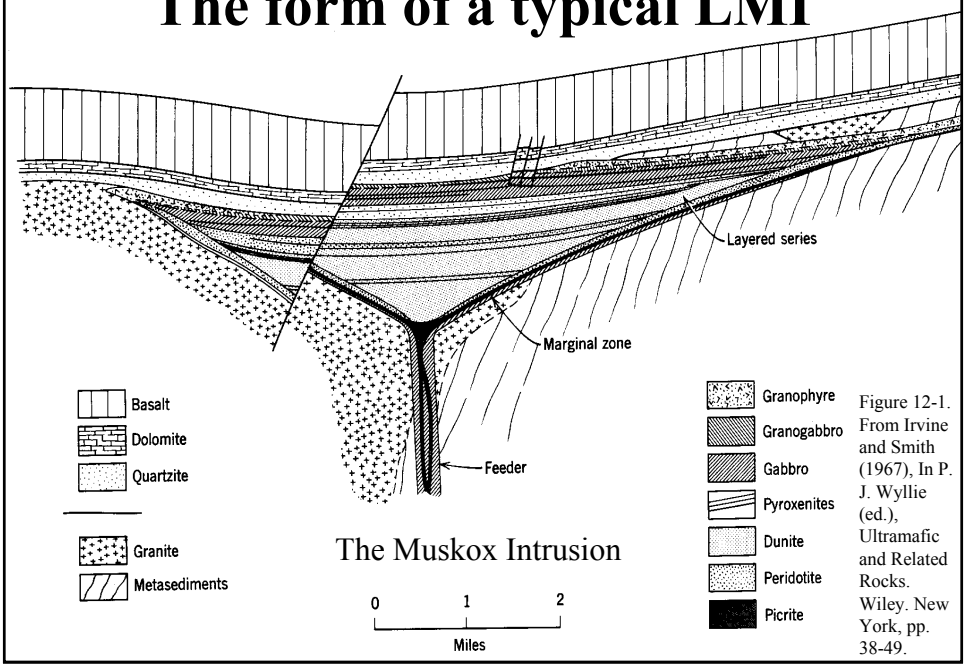


Figure 12-1. From Irvine and Smith (1967), In P. J. Wyllie (ed.), Ultramafic and Related Rocks. Wiley. New York, pp. 38-49.

Layering

layer: any sheet-like cumulate unit distinguished by its compositional and/or textural features

- uniform mineralogically and texturally homogeneous

Uniform Layering

Figure 12-3b. Uniform chromite layers alternate with plagioclase-rich layers, Bushveld Complex, S. Africa. From McBirney and Noyes (1979) J. Petrol., 20, 487-554.

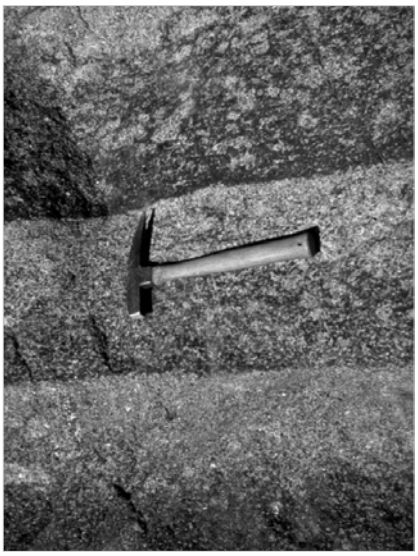
Layering

layer: any sheet-like cumulate unit distinguished by its compositional and/or textural features

- uniform mineralogically and texturally homogeneous
- non-uniform vary either along or across the layering
  - graded = gradual variation in either
    - mineralogy
    - grain size - quite rare in gabbroic LMIs

Graded Layers

Figure 12-2. Modal and size graded layers. From McBirney and Noyes (1979) J. Petrol., 20, 487-554.



Olivine and Plagioclase

Orthopyroxene and Plagioclase

Layering (or stratification)

Addresses the structure and fabric of sequences of multiple layers

1) Modal Layering: characterized by variation in the relative proportions of constituent minerals

Layering (or stratification)

2) Phase layering: the appearance or disappearance of minerals in the crystallization sequence developed in modal layers
   - Phase layering *transgresses* modal layering

3) Cryptic Layering (not obvious to the eye)
   - Systematic variation in the chemical composition of certain minerals with stratigraphic height in a layered sequence

The regularity of layering

- Rhythmic: layers systematically repeat
  - Macrorhythmic: several meters thick
  - Microrhythmic: only a few cm thick
- Intermittent: less regular patterns
  - A common type consists of rhythmic graded layers punctuated by occasional uniform layers

Rythmic and Intermittent Layering

Figure 12-3a. Vertically tilted cm-scale rhythmic layering of plagioclase and pyroxene in the Stillwater Complex, Montana.

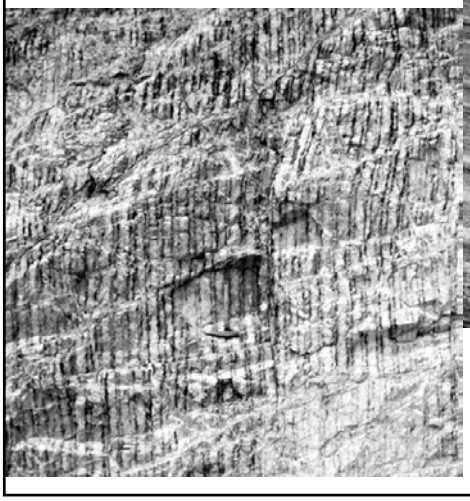


Figure 12-4. Intermittent layering showing graded layers separated by non-graded gabbroic layers. Skaergård Intrusion, E. Greenland. From McBirney (1993) Igneous Petrology (2nd ed.), Jones and Bartlett. Boston.

The Bushveld Complex, South Africa

The biggest:
300-400 km x 9 km

The Red Granite intruded 50-100 Ma afterwards

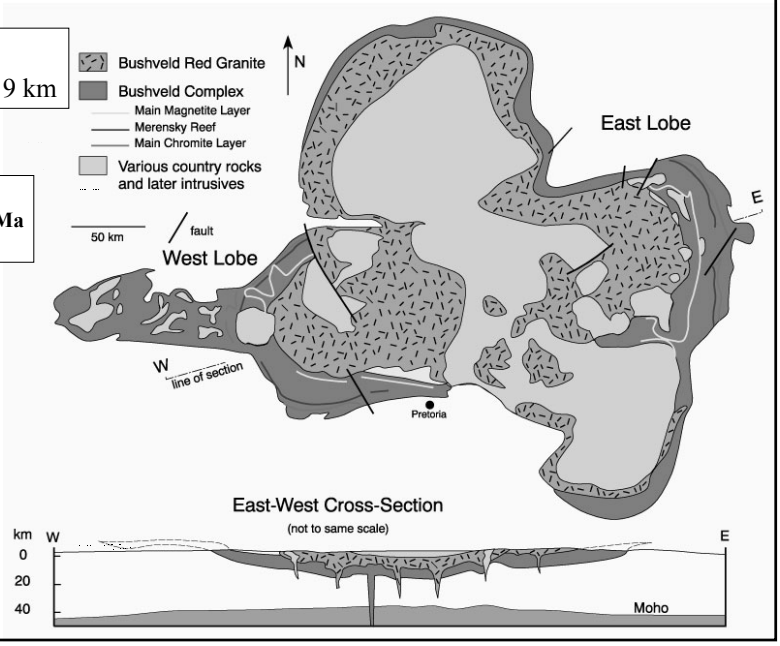


Figure 12-5. Simplified geologic Map and cross section of the Bushveld complex. After Willemse (1964), Wager and Brown (1968), and Irvine *et al*. (1983).

Marginal Zone: the lowest unit, is a chill zone about 150 m thick

Fine-grained norites from the margin correspond to a high-alumina tholeiitic basalt

[NORITE = Hypersthene + Plagioclase (Gabbro)]

Stratigraphy

Basal Series

Thin uniform dunite cumulates alternating with orthopyroxenite and harzburgite layers

The top defined as the Main Chromite Layer

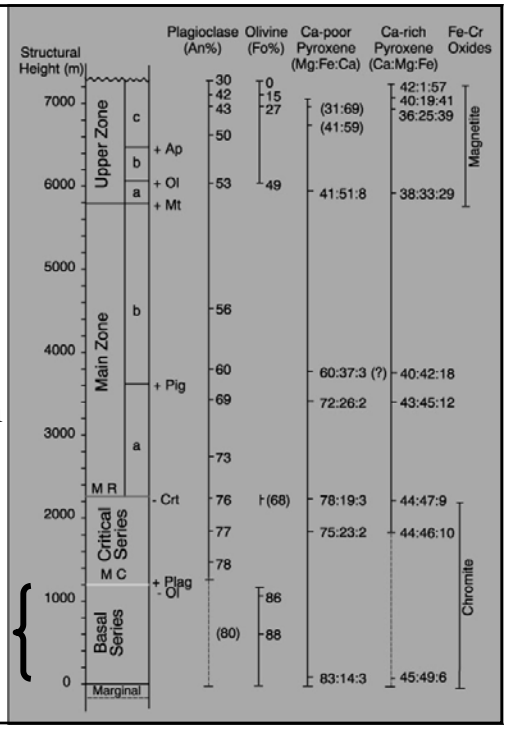


Figure 12-6. Stratigraphic sequence of layering in the Eastern Lobe of the Bushveld Complex. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. San Francisco.

Critical Series

Plagioclase forms as a cumulate phase (phase layering)

Norite, orthopyroxenite, and anorthosite layers etc

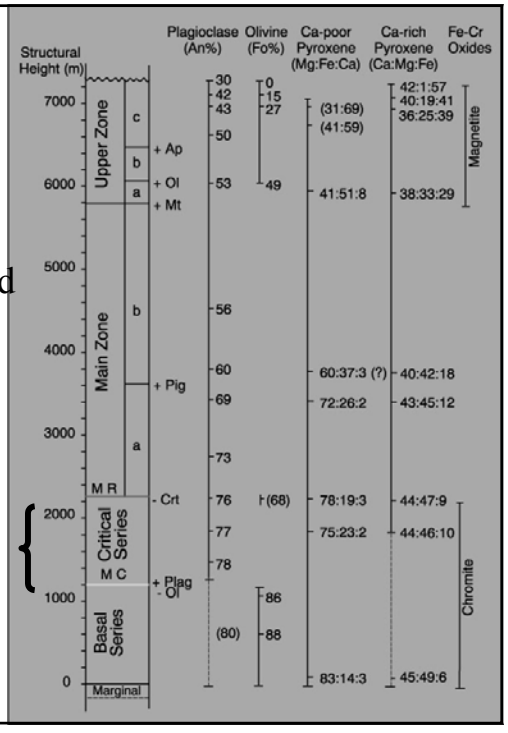


Figure 12-6. Stratigraphic sequence of layering in the Eastern Lobe of the Bushveld Complex. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. San Francisco.

The Merensky Reef

~ 150 m thick sequence of rhythmic units with cumulus plagioclase, orthopyroxene, olivine, and chromite

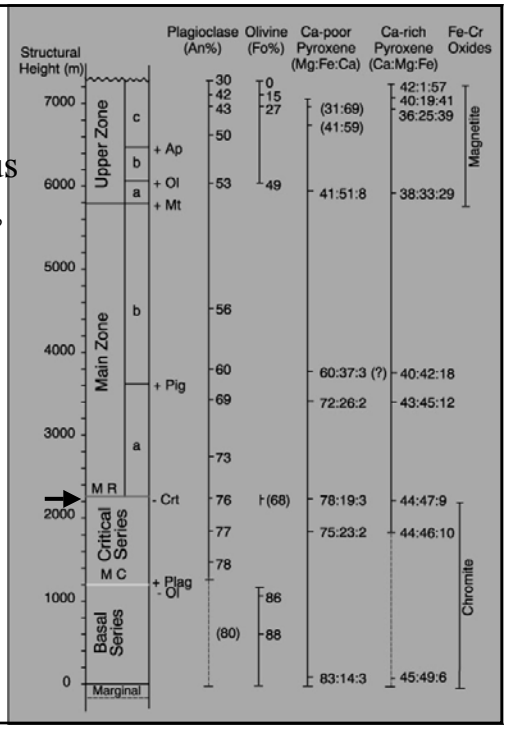


Figure 12-6. Stratigraphic sequence of layering in the Eastern Lobe of the Bushveld Complex. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. San Francisco.

Main Zone

The thickest zone and contains thick monotonous sequences of hypersthene gabbro, norite, and anorthosite

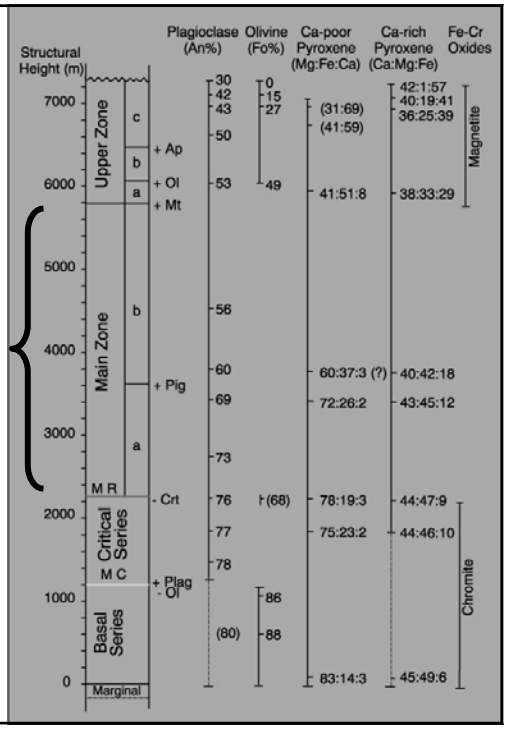
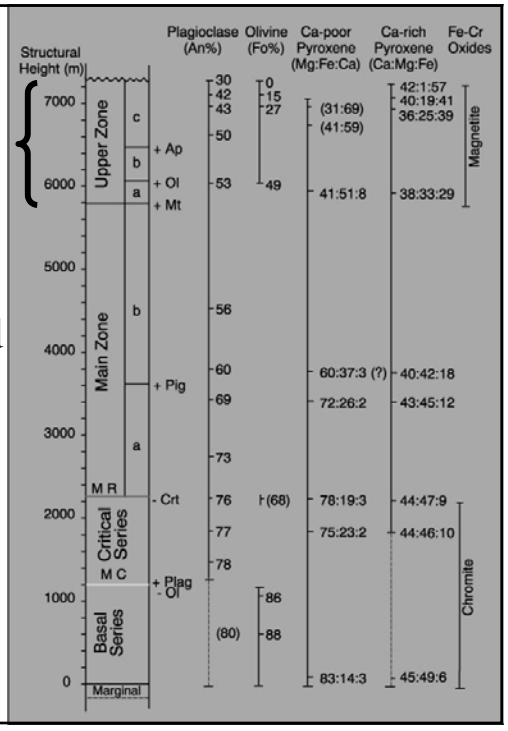


Figure 12-6. Stratigraphic sequence of layering in the Eastern Lobe of the Bushveld Complex. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. San Francisco.

Upper Zone

- Appearance of cumulus magnetite (Fe-rich)
- Well layered: anorthosite, gabbro, and ferrodiorite
- Numerous felsic rock types = late differentiates



Also note:

- Cryptic layering: systematic change in mineral compositions
- Reappearance of Fe-rich olivine in the Upper Zone

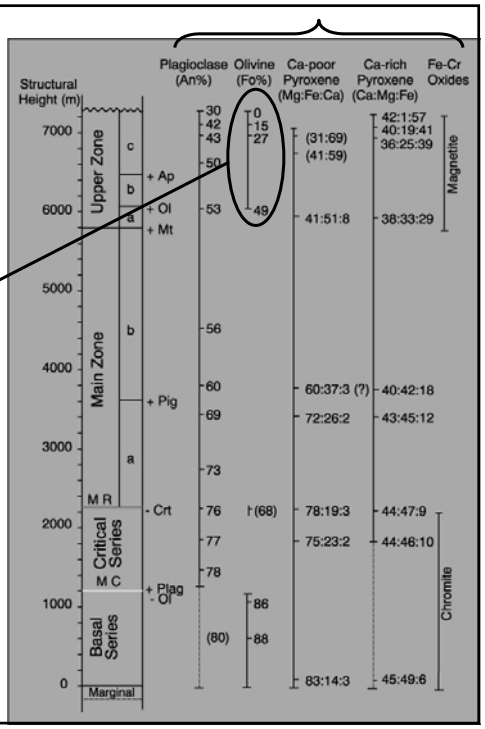


Figure 12-6. Stratigraphic sequence of layering in the Eastern Lobe of the Bushveld Complex. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. San Francisco.

Fractional crystallization follows
a – b – c –d
At d an Fe-olivine crystallizes together with tridymite

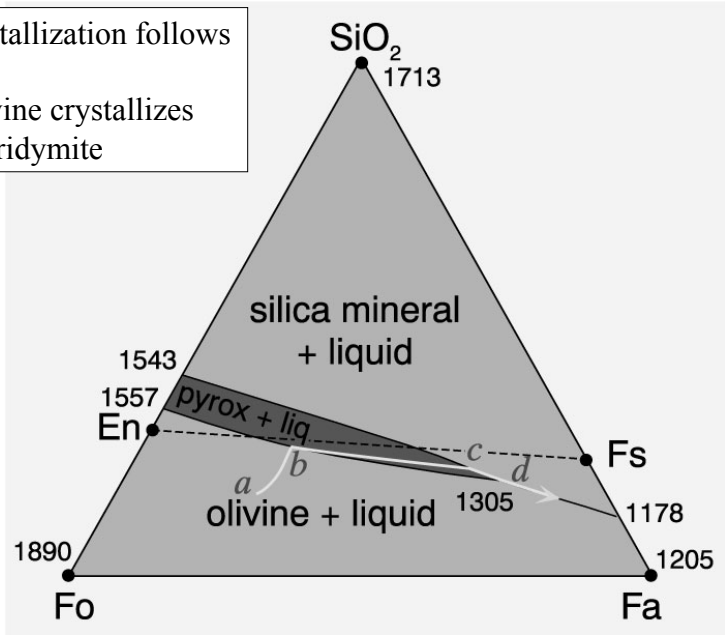


Figure 12-7. The Fo-Fa-SiO_2 portion of the FeO-MgO-SiO_2 system, after Bowen and Schairer (1935) *Amer. J. Sci.*, 29, 151-217.

The Stillwater Complex, Montana

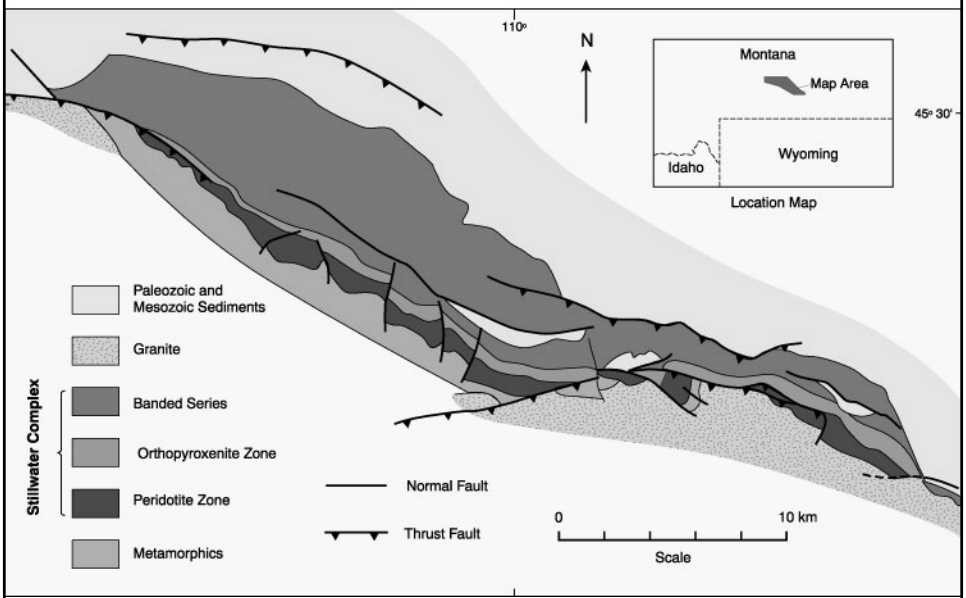


Figure 12-8. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. San Francisco.

Stratigraphy

- Basal Series
  - a thin (50-150 m) layer of norites and gabbros
- Ultramafic Series base = first appearance of copious olivine cumulates (phase layering)
  - Lower Peridotite Zone
    - 20 cycles (20-150 m thick) of macrorhythmic layering with a distinctive sequence of lithologies
    - The series begins with dunite (plus chromite), followed by harzburgite and then orthopyroxenite
  - Upper Orthopyroxenite Zone
    - is a single, thick (up to 1070 m), rather monotonous layer of cumulate orthopyroxenite

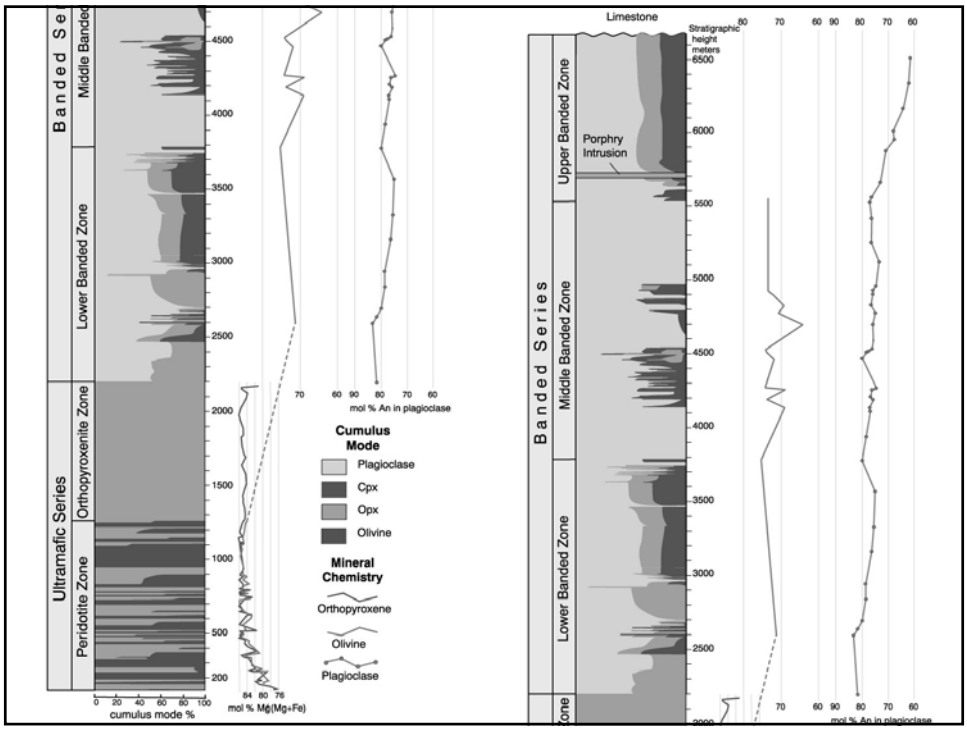
The crystallization sequence within each rhythmic unit (with rare exception) is:

- olivine + chromite →
- olivine + orthopyroxene →
- orthopyroxene →
- orthopyroxene + plagioclase →
- orthopyroxene + plagioclase + augite

Stratigraphy

The Banded Series

- Sudden cumulus plagioclase → significant change from ultramafic rock types (phase layering again)
- The most common lithologies are anorthosite, norite, gabbro, and troctolite (olivine-rich and pyroxene-poor gabbro)



The Skaergård Intrusion E. Greenland

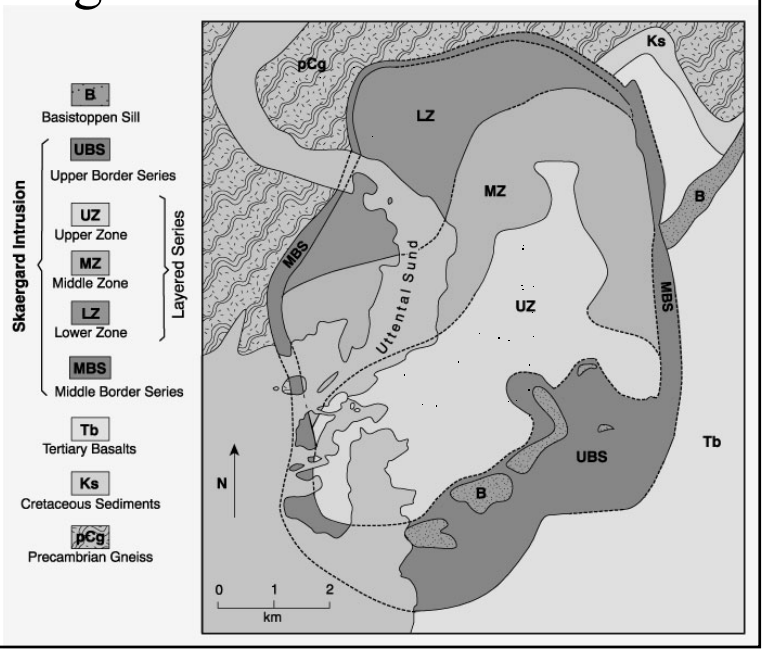
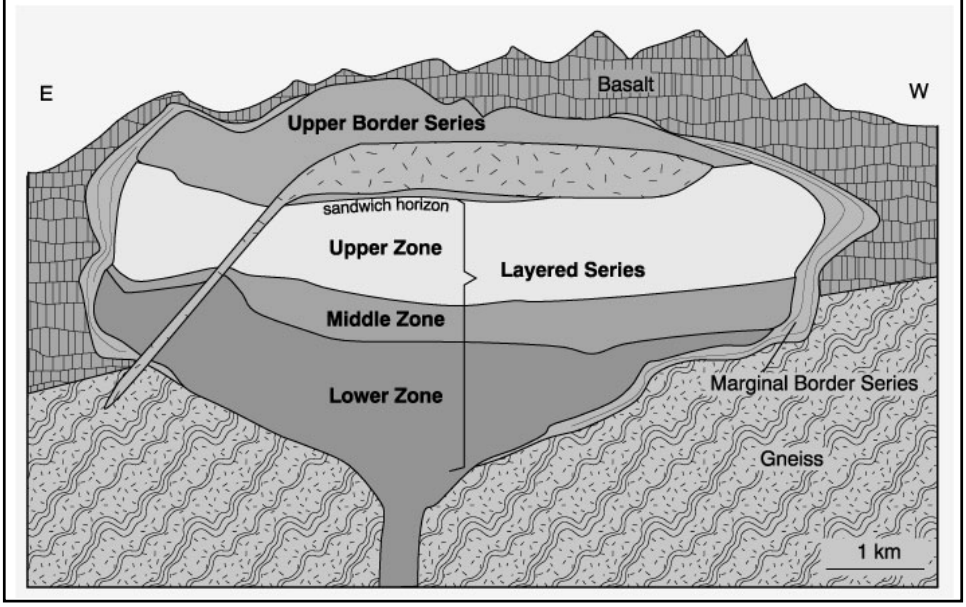


Figure 12-10. After Stewart and DePaolo (1990) Contrib. Mineral. Petrol., 104, 125-141.

Cross section looking down dip.

Figure 12-11. After After Hoover (1978) Carnegie Inst. Wash., Yearb., 77, 732-739.



- Magma intruded in a single surge (premier natural example of the crystallization of a mafic pluton in a single-stage process)
- Fine-grained chill margin

Stratigraphy

Skaergård subdivided into three major units:

- Layered Series (crystallized from floor up)
- Upper Border Series (crystallized from roof down)
- Marginal Border Series (crystallized at margins)

Upper Border Series and the Layered Series meet at the Sandwich Horizon (most differentiated liquids)

Layered Series: 2500 m thick but base is not exposed.

- Lower Zone: Cumulus olivine and plagioclase with poikilitic augite. Augite and then pigeonite become cumulus phases higher up
- Middle Zone: No more olivine. Phases are plagioclase, augite and pigeonite
- Upper Zone: Plagioclase, augite and return of Fe-olivine (no more pigeonite). Also interstitial quartz and K-feldspar

Upper Border Series: thinner, but mirrors the 2500 m Layered Series in many respects

- Cooled from the top down, so the top of the Upper Border Series crystallized first
  - The most Mg-rich olivines and Ca-rich plagioclases occur at the top, and grade to more Fe-rich and Na-rich compositions downward
  - Major element trends also reverse in the Upper Border Series as compared to the LBS

Sandwich Horizon, where the latest, most differentiated liquids crystallized

- Ferrogabbros with sodic plagioclase (An_{30}), plus Fe-rich olivine and Opx
- Granophyric segregations of quartz and feldspar
- F & G = immiscible liquids that evolve in the late stages of differentiation?

Stratigraphy, Modal, and Cryptic Layering

(cryptic determined for intercumulus phases)

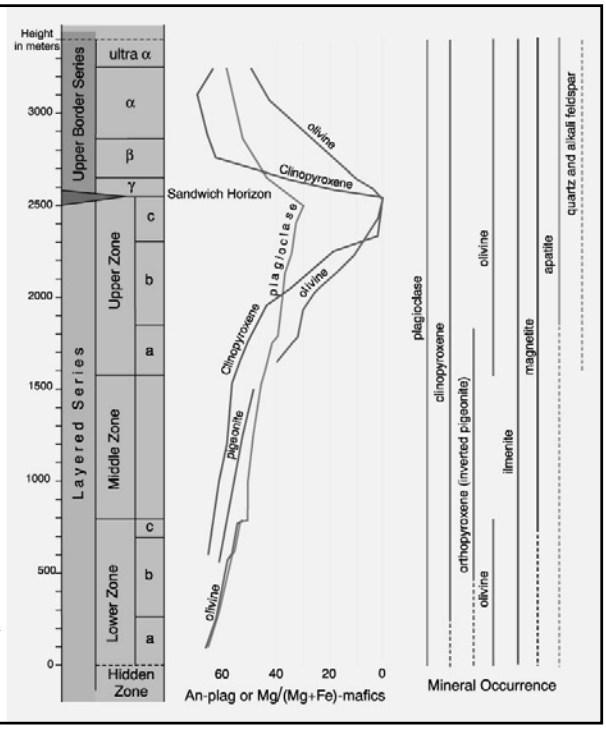
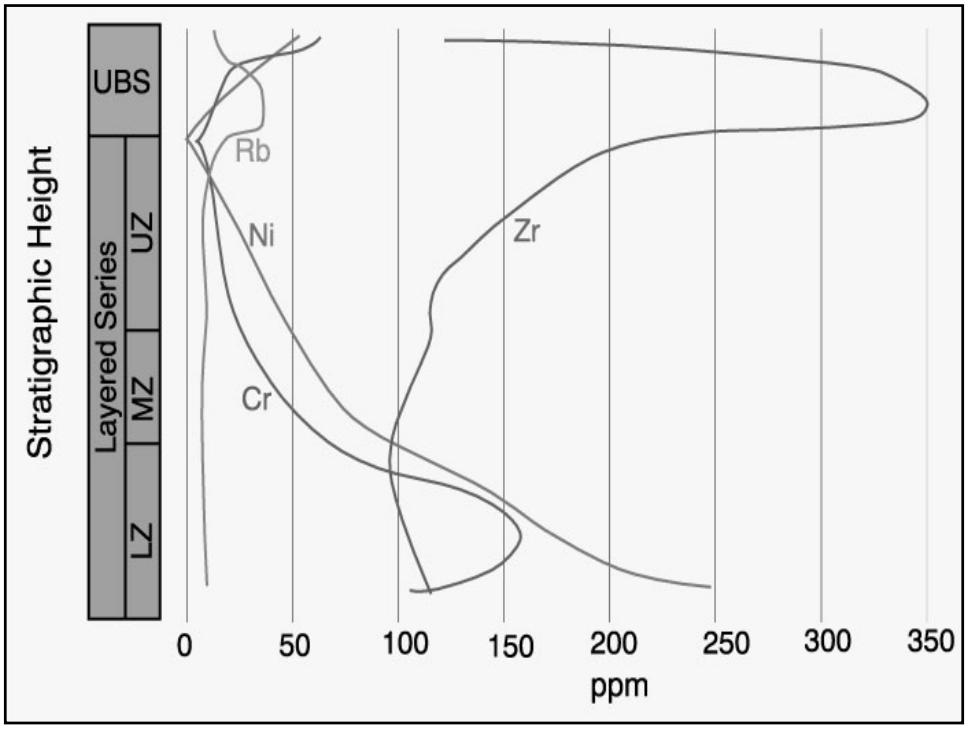


Figure 12-12. After Wager and Brown (1968) Layered Igneous Rocks. Freeman. and Naslund (1983) J. Petrol., 25, 185-212.



How can we explain the conspicuous development of rhythmic layering of often sharply-defined uniform or graded layers?

PROBLEMS!

1. Study of phase diagrams and lavas lead us to expect that with cooling crystallization of one mineral will be followed by additional minerals.
2. Layering appears to imply repeated injection of new magma or cyclical variation in physical properties
3. On the other hand overall progression in cryptic layering appears to imply involvement of the entire magma body