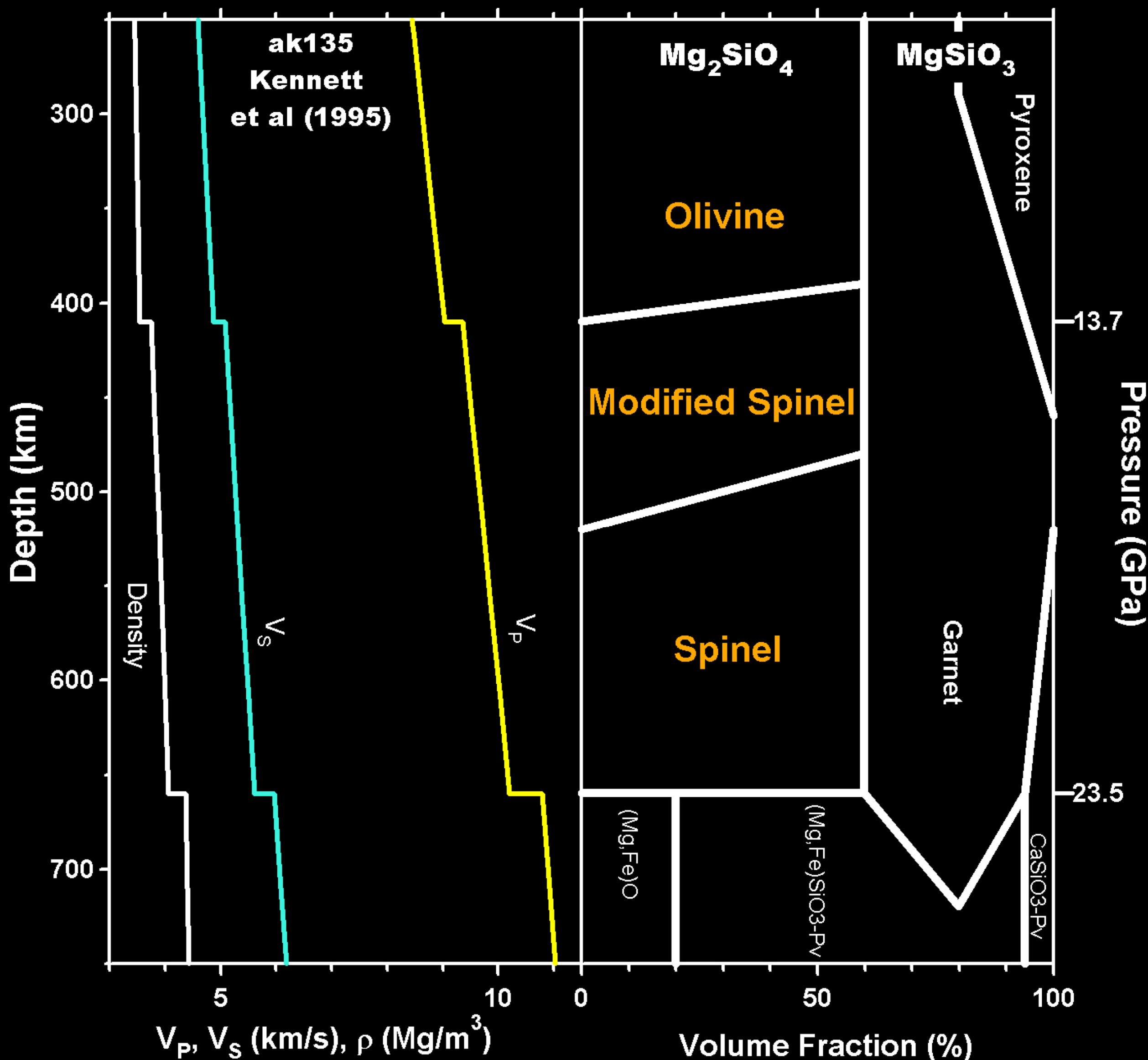
Weidner and Wang (1999)
Phase transformations - implications for mantle structure

The Transition Zone



Complex Interactions among Minerals in the Transition Zone

- Mg-Si-O
- Mg-Fe-Si-O
- Mg-Fe-Ca-Al-Si-O (this study)

Pyrolite

Table 1. Composition of pyrolite model from *McDonough and Sun* [1995]. The last column indicates the cumulative cation percent including all cations that are more abundant.

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Please see:

Weidner, D. J., and Y. Wang. "Phase transformations: Implications for mantle structure. In Earth's deep interior: mineral physics and tomography from the atomic to the global scale." *Geophysical Monograph* 117 (2000): 215-235.

Physical Properties of Minerals

Table 2. Comparison of acoustic velocities for different phases and compositions in relation to $MgSiO_3$ in the orthopyroxene structure (enstatite).

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Physical Properties of Minerals

- ~4% variation in Fe results in ~1% variation in physical properties.
- Replacing 25% of the (Mg,Si) in Gt with Al results in 1% increase in acoustic velocity.
- However, adding Al stabilizes Gt instead of Il.

410 Discontinuity

- Olivine → Wadsleyite
- Pyroxene → Garnet
- Not an isolated system!

410 Discontinuity

- Phase relations and element partitioning

- With Fe: Ol → Ol+Wd → Wd
- High T and low Fe → Deeper and narrower discontinuity
- Gradual transition from Px to Gt
- Gt takes Fe from Ol or Wd, whereas Px gives Fe to Ol or Wd.

→ Depth and thickness of 410 may be sensitive to degree of the Px→Gt transition

410 Discontinuity

- Phase relations and element partitioning

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Figure 1. Ca content in diopsidic pyroxene as a function of pressure and temperature. Two dotted lines are fit to Fe-bearing data at 1473 K (upper dotted line) and 1873 K (lower dotted line).

Figure 2. Al content in garnet as a function of pressure and temperature. Two dotted lines are fit to the Fe-bearing data at 1473 K (upper) and 1873 K (lower), respectively.

Figure 3. Ca content in garnet. Again, two dotted lines are fit to Fe-bearing data at 1473 K (upper) and 1873 K (lower), respectively.

Fe lowers Ca in Px.

Al decreases in Gt with P, due to formation of Mj

410 Discontinuity

- Effect of temperature

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Figure 4. Volume fractions of stable phases in pyrolite (Table 1) as a function of mantle temperature. A: along a 1473 K isotherm; B: along a geotherm with a gradient of 0.7 K/km and a foot temperature of 1473 K. Also included is the latent heat effect due to the olivine-wadsleyite transition; C: similar to B but with a foot temperature of 1673 K.

A – isothermal (1473 K)

B – uniform gradient of 0.7 K/km

C – temperature gradient of 0.7 K/km with a T increase from Ol→Wd transition.

Latent heat of Ol→Wd transition increases T by 40 K.

410 Discontinuity

- Effect of Al

Al effect is greater than T-effect for Gt stability.

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Figure 5. Volume fractions of stable phases with varying Al contents as shown (ratio of all other cations remains constant). For the low Al (1 cation %) model, pyroxenes dominate the non-olivine component. Note that in this plot the higher pressure field for pyroxenes is not shown, which should include wadsleyite/ringwoodite plus stishovite. Note gradual increase in garnet as Al content increases.

Figure 6. Density (upper), Vs (middle), and Vp (lower) of pyrolite with various Al contents. All models follow a geotherm whose zero pressure temperature is 1473 K. Higher Al models have high density and velocities because garnets have higher shear and bulk moduli than pyroxenes.

410 Discontinuity

- Effect of T

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Figure 7. Width of the olivine-wadsleyite two phase region at the 410 km discontinuity for pyrolite as a function of thermal models. (1) - constant mantle temperature; (2) - temperature gradient 0.7 K/km, no latent heat; (3) - latent heat 85 K for olivine-wadsleyite transition, no temperature gradient; (4) - combined effects of latent heat and temperature gradient.

410 width increases with T

(1) Constant T

(2) 0.7 K/km gradient

(3) Latent heat (Largest effect)

(4) Latent heat + 0.7 K/km gradient

A. T directly affects depth and width of the Ol→Wd transition.
B. T affects the Px→Gt transition and changes Fe partitioning.

410 Discontinuity
- Effect of Composition

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Figure 8. Width of the olivine-wadsleyite two phase region at the 410 **km** discontinuity for pyrolite as a function of small variations in Al and Fe. (A) - Al_2O_3 = 5%, FeO = 5.7% ; (B) - Al_2O_3 = 1%, FeO = 5.7%; (C) - Al_2O_3 = 5%, FeO = 6.5%.

A→B: increase in Fe

A→C: decrease in Al (Gt)

Less Fe is taken from Ol

410 Discontinuity

- Effect of Composition

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Figure 9. Depth of the 410 km discontinuity (defined by the mid-point of the olivine – wadsleyite transformation) as a function of mantle composition. All models are based on pyrolite with slight variations in Al and Fe. (A) - Al_2O_3 =5%, FeO = 5.7% ; (B) - Al_2O_3 = 1%, FeO = 5.7%; (C) - Al_2O_3 = 5%, FeO = 6.5%.

A→B: decrease in Al (Gt)

Less Fe is taken from Ol

A→C: increase in Fe

410 Discontinuity

- Lateral variations in T

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Figure 10. Change in acoustic velocities and density due to a 100K decrease in temperature for two mantle geotherms. Changes include the contributions of phase transformations and changes in properties of the different phases.

T-insensitive depth would decrease with Al ↓ or T ↑.

410 Discontinuity

- Lateral variations in Al

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Figure 11. Changes in acoustic velocities and density due to a 2% decrease in the Al content for two mantle geotherms.

520 Discontinuity

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Figure 12. Volume fractions of major phases in the pyrolite model as a function of depth across the transition zone.

520 Discontinuity

- Formation of Ca-pv
- Wd → Rw: 21 km thick
- But with Rw more enriched in Fe with Gt, the thickness becomes 12 km.

660 Discontinuity

- Post-spinel, post-garnet, post-ilmenite
- Rw (54 vol%), Gt (39 vol%), Ca-pv (7 vol%) in pyrolite
- Weinder considers Fe-free system for 660.

660 Discontinuity

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Figure 14. Phase diagram in the system $MgSiO_3$ - $Mg_3Al_2Si_3O_{12}$ at 1773K [after *Irifune, et al.*, 1996]. The dashed curve is a tentative phase boundary between single-phase perovskite and the two-phase region of perovskite + corundum at 2073K.

- If all Al in Pyrolite goes in Pv → 6.3 mol% Al2O3
- > 12 mol% Al2O3, pure Al2O3 appears

660 Discontinuity

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Figure 13. Phase diagram of the CMAS system (CaO, MgO, Al_2O_3, SiO_2) from *Weidner and Wang* [1998] as modified after *Gasparik* [1996a, b]. Abbreviations are Gt-garnet, Sp-spinel or ringwoodite phase, CaPv- $CaSiO_3$ perovskite phase, Pv-$MgSiO_3$ perovskite phase, Mw-magnesiowustite, St-stishovite, Il-$MgSiO_3$ in the ilmenite phase. Solid lines indicate the phase boundaries of the olivine normative and the pyroxene normative systems. The numbers on the lightest lines indicate the pyrope content of the garnet in equilibrium with the other phases. Dashed lines indicate possible geotherms with labels that indicate the temperature at 660 km depth. The region between the two heavy lines indicates the possible garnet composition for pyrolite.

- Along 2100 K,

Rw+Gt(Py50) → Gt(Py25)+Mw → Gt+Pv+Mw → Pv+Mw

- Along 1900 K

Rw+Gt(Py50) → Pv+Mw+Gt(25<Py<50) → Pv+Mw

- Along 1700 K

Rw+Gt(Py50) → Rw+Pv+Gt → Gt+Pv+Mw → Pv+Mw

660 Discontinuity

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Figure 15. Calculated volume per cent of garnet and ringwoodite as a function of depth along the three geotherms for a pyrolite-like composition [from *Weidner and Wang*, 1998]. A) is for a system with 5 cation % Al and B) represents the results for 3% Al. Calculations are based on the phase diagrams described in the text.

Figure 16. Calculated density and acoustic velocities for different geotherms for a pyrolite-like composition [from *Weidner and Wang*, 1998]. A) indicates these properties for a model with 5% Al and B) indicates the results for 3% Al. The properties were calculated using the parameters of *Weidner and Wang* [1998] and the phase diagrams described in the text. Temperature refers to the temperature at 660 km depth with an adiabatic gradient. The values for PREM are included for reference.

660 Discontinuity

- Lateral variations

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Figure 18. Change in acoustic velocities and density due to the change in mineralogy resulting from a 100K decrease in temperature. A) is for an adiabatic geotherm that is 1700K at 660 km depth, B) referenced to 1900K at 660 km depth, and C) referenced to 2100K at 660 km depth. Temperature dependence of acoustic velocities of each phase are not included in this diagram.

- Δ T = -100 K
- No consideration of T effect on the physical properties

Conclusions

- Changes in phase relations by minor elements (Fe, Al, Ca)
- Phase relations + physical property measurements yields interesting possibilities:
  - T-insensitive depth near 410
  - Rw or Gt-dominated 660 depending on T and Al
  - Gt→Il transition above 660 in cold mantle.

Uncertainties

- Relative positions of the phase boundaries
- Effect of minor elements for the physical properties of minerals

660 Discontinuity

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- Rw→Mg-Pv + Mw + Gt, then Gt contains Py50
- Rw→Gt + Mw + Gt, then Gt contains Py25
- If Gt with Py50 transforms to Pv, Corundum will be formed.