True-False - Print the letter T or F in the blank to indicate if each of the following statements is true or false. Illegible answers are wrong. (1 point each)

6   T   1. Cataclasis refers to mechanical crushing and grinding, with no recrystallization. Rocks exhibiting this behavior have undergone brittle deformation.

0   T   2. At very low metamorphic grade, reaction rates are slow.

0   F   3. The Franciscan belt lies nearer the former subduction zone than the Sierra belt. The Sierra belt is richer in alkaline elements than the Franciscan belt.

2   F   4. The original facies classification was based primarily on metamorphosed felsic rocks.

3   T   5. There is little difference in mafic rock facies that develop at low, medium, or even high pressure.

0   T   6. The presence of garnet in a facies indicates it formed at medium to high pressures.

0   T   7. Eclogites associated with xenoliths in kimberlites or basalts belong to the high-temperature group.

4   F   8. Carbon dioxide solubility is very high in silicate melts.

0   F   9. For most paths, $P_{\text{max}}$ and $T_{\text{max}}$ occur at the same time.

0   T   10. Cordierite has a large molar volume, which indicates it is stable at low pressures.

2   T   11. In a Buchan sequence, oligoclase appears before hornblende.

3   F   12. Metamorphic grade is most closely related to $P_{\text{max}}$.

0   T   13. If equilibrium is maintained, there is a correlation between the An content of plagioclase and the temperature at which metamorphism occurred.

Exam Total ______/208 ______% Grade ____________
14. Ca-bearing minerals, like laumontite, prehnite, and pumpellyite are stable in water-rich, carbonate-free fluids.

15. When andalusite is present, the pressure at the time of formation exceeded 0.4 Gpa.

16. Prograde metamorphic reactions are exothermic.

17. New minerals will growth during deformation, parallel to $\sigma_1$.

18. The Franciscan trajectory has a large increase in pressure with a relatively small increase in temperature.

19. Granofels have a finer grain size than hornfels.

20. Barrow found a much greater change in the pelitic rocks he studied, compared to the sandstones.

21. Barrovian zones were developed in an area of rather narrow compositional range. In regions with different compositions, the use of additional or replacement index minerals may be appropriate.

22. During compression, if $\sigma_2 \approx \sigma_3$, then folding is likely to occur.

23. If electrolytes or other dissolved fluids (CO$_2$) are present in the water, the position of the critical point is depressed to lower temperatures and pressures. It is raised.

24. An index mineral is never present in zones higher than its own.

25. The high P/T series is characteristic of below normal geotherms.

26. Pure shear results in foliation perpendicular to the short axis of deformation.

27. Metamorphic recrystallization often leads to an increase in grain size.

28. Rock materials formed under high-strain conditions may be either cohesive or non-cohesive.

29. Ordinary prograde metamorphic reactions are common in high-temperature mafic igneous rocks.

30. The alkali feldspars form a complete solid-solution series at room-temperature. Sanidine, orthoclase, and microcline have different structures. They also have the same chemistry so, for two reasons, they cannot be a solid-solution series.

31. A biotite-hornblende granite contains more biotite than hornblende.

32. The chemistry of the Atlantic, Pacific and Indian Ocean ridges is remarkably consistent.
Multiple-Choice - Choose the best response to each statement or question. Print the letter corresponding to your choice in the blank. (1 point each)

0   A  1. Load pressure is another name for:
   A. Lithostatic pressure
   B. Hydrostatic pressure
   C. Tectonic pressure
   D. Impact pressure

1   B  2. Which of the following is the most effective mineralizer?
   A. Water
   B. Fluoride ion
   C. Carbon dioxide
   D. Sulfur dioxide

2   B  3. Where might the geothermal gradient be lower than average?
   A. Near zones of crustal thickening or crustal extension
   B. In a subducting plate
   C. Near an igneous intrusion
   D. Above a hot spot

2   B  4. Which British petrologist made one of the first systematic studies of metamorphic rock types, their variation, and the mineral assemblages generated in an episode of progressive metamorphism?
   A. George Barrow
   B. Pentii Eskola
   C. Viktor Goldschmidt
   D. Peter Wyllie

1   B  5. Who first formulated the idea of metamorphic facies?
   A. C.E. Tilley
   B. Pentii Eskola
   C. George Barrow
   D. Alfred Harker

0   B  6. The Barrovian type of metamorphic trajectory is characteristic of which baric series?
   A. High P/T
   B. Medium P/T
   C. Low P/T
   D. May be any of the above
7. Phyllonites are foliated cohesive rocks rich in what mineral?
A. Plagioclase
B. Mica
C. Pyroxene
D. Olivine

8. A cohesive high-strain rock that has undergone significant recrystallization is known as what?
A. Phyllonite
B. Microbreccia
C. Blastomylonite
D. Cataclasite

9. The starting material from which a reaction or recrystallization begins is called what?
A. Granofels
B. Isograd
C. Protolith
D. Spillite

10. Under extreme conditions, frictional heating will produce partial melting, creating glass. Rocks with glassy seams are called what?
A. Fault gouge
B. Hornfels
C. Pseodotachylyte
D. Shatter cones

11. Under high pressure conditions, the mafic minerals exhibit far greater changes than felsic minerals. Since mafic minerals are common in this environment, conspicuous changes are seen. Blueschist is one example. Precambrian blueschists are rare. How can we interpret this?
A. There was no subduction before the Cambrian
B. Geothermal gradients were higher, and the P/T ratio would have been lower
C. Early metamorphism has been overprinted by later events, and is no longer recognizable
D. Either, or both, B and C

12. Granulite facies rocks are depleted in LIL elements, as well as other incompatible elements. What causes this?
A. Incompatible elements are removed by a departing fluid phase, as the result of dehydration reactions
B. Incompatible elements are preferentially incorporated into early melts
C. The bulk composition of the protolith is different for the granulite facies rocks than for the amphibolite facies rocks
D. Either A or B
13. The beginning of the hornblende hornfels facies is characterized by:
A. The conversion of actinolite → hornblende
B. The loss of albite by the albite → oligoclase conversion
C. The formation of pyralspite garnet
D. The formation of chlorite

14. The Franciscan assemblage in California shows the assemblage Jadeite + albite, which is typical of what type of protolith?
A. Mafic
B. Pelilitic
C. Psammitic
D. Ultramafic

15. Why are divergent boundaries more likely to be found in oceans than on a continent?
A. Oceans cover 70% of the earth’s surface, so the statistical chance of a rift forming in the ocean is greater
B. Ocean crust is thinner than continental crust, and therefore easier to split
C. Continental rifts may split a continent, creating an ocean, and thus converting themselves to an oceanic rift
D. All of the above

16. The minerals mullite, tridymite or cristobalite, and pigeonite are found in a contact metamorphic rock. To what facies does this rock belong?
A. Albite-epidote hornfels
B. Hornblende hornfels
C. Pyroxene hornfels
D. Sanidinite

17. Metasomatism is brought about by:
A. Chemically active fluids
B. Directed pressure
C. Heat
D. Melting

18. A xenolith in a peridotite pipe has a measured density of 3.38 g/cm³, and contains omphacite. The xenolith is:
A. Basalt
B. Blueschist
C. Eclogite
D. Amphibolite
19. In a chemical classification of igneous rocks, a rock with 54 wt % silica would be:
   A. Felsic  
   B. Intermediate  
   C. Mafic  
   D. Ultramafic

20. Three trimorphs of this group, very important in metamorphic petrology, are kyanite, andalusite, and sillimanite.
   A. Al₂SiO₅  
   B. Clay  
   C. Epidote  
   D. Serpentine

21. In the system diopside-anorthite, a binary eutectic is present. As conditions change from a dry case with pressure equal to 1 gigapascal to one where $P_{tot} = P_f = 1$ GPa, what happens to the position of the eutectic?
   A. It decreases in temperature, and shifts toward the diopside end member  
   B. It decreases in temperature, and shifts toward the anorthite end member  
   C. It increases in temperature, and shifts toward the diopside end member  
   D. It increases in temperature, and shifts toward the anorthite end member

22. In the Hawaiian Island sequence of basaltic eruptions, alkaline basalt is seen in all of the following stages except:
   A. Post-erosional  
   B. Post-shield  
   C. Pre-shield  
   D. Shield-building

23. The lack of HREE depletion excludes which of the following as a source for MORB?
   A. Garnet lherzolite  
   B. Plagioclase lherzolite  
   C. Spinel lherzolite  
   D. None of the above

24. MORB’s do not show a Eu anomaly. Which of the following layers would likely produce a Eu anomaly if it were the source of MORB.
   A. Garnet lherzolite  
   B. Plagioclase lherzolite  
   C. Spinel lherzolite  
   D. None of the above

George Santayana said, “Those who do not remember the past are condemned to repeat it.” The corollary to that is that those who do not learn from mistakes on midterms are condemned to miss the question again on the final.
25. The dominant rock type associated with volcanic activity within plates, rather than at interacting plate margins, is:
   A. Basalt
   B. Granite
   C. Granodorite
   D. Tonalite

26. Wollastonite, rhodonite, and pectolite all form chains of tetrahedra in which silicate group?
   A. Chlorite
   B. Feldspathoid
   C. Pyroxenoid
   D. Zeolite

**Matching** - Match the definitive assemblage listed in column I with the correct facies from column II. Answers may be used once or not at all. (1 point each)

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Laumontite, wairakite, analcime</td>
<td>A. Amphibolite</td>
</tr>
<tr>
<td>2. Orthopyroxene + clinopyroxene + plagioclase ± garnet ± hornblende</td>
<td>B. Blueschist</td>
</tr>
<tr>
<td>3. Pyrope garnet + omphacitic pyroxene ± kyanite</td>
<td>C. Eclogite</td>
</tr>
<tr>
<td>4. Hornblende + plagioclase (An17-50) ± garnet</td>
<td>D. Granulite</td>
</tr>
<tr>
<td>5. Chlorite + albite + epidote (or zoisite) + quartz ± actinolite</td>
<td>E. Greenschist</td>
</tr>
<tr>
<td>6. Chlorite + albite + epidote (or zoisite) + quartz ± actinolite</td>
<td>F. Prehnite-Pumpellyite</td>
</tr>
<tr>
<td>7. Chlorite + albite + epidote (or zoisite) + quartz ± actinolite</td>
<td>G. Zeolite</td>
</tr>
</tbody>
</table>
Fill-Ins - Write in the word or words which best completes each statement or answers each question. (1 point per blank)

3. Hydrous pelitic and quartzo-feldspathic rocks do not reach granulite grade. Why?
   The melting point of minerals in these rocks is below the temperature necessary to form granulite facies rocks. The rocks start to melt under conditions found in the amphibolite facies, to form migmatites.

0. Metamorphism produced by decreasing temperature and pressure is called RETROGRADE ______ metamorphism.

1. In metamorphic assemblages, the symbol ± is short for what phrase?
   WITH OR WITHOUT ____________________________

1. As grade increases, the color of hornblende changes from green to brown. Why?
   DUE TO INCREASING TI CONTENT IN THE HORNBLENDE ____________________________

1.5. IUGS stands for THE INTERNATIONAL UNION OF GEOLOGICAL SCIENCES _______.

2. C.E. Tilley coined a term that is used to describe the line which marks the beginning of a Barrovian zone on a map. The term is ISOGRAD ________________.

2. A metamorphic rock will typically be buried, metamorphosed, possibly with orogenic forces acting on it, then brought to the surface through uplift and erosion. The path that it follows is called a P-T-t ______ path.

9. A basalt that has been hydrated to form greenstone, and then progressively metamorphosed to higher temperatures, may reach the granulite facies with a chemistry dominated by plagioclase and pyroxene, like the protolith. However, it will differ from the protolith in one important respect, which is:
   THE TEXTURE OF SUCH METABASALTS IS GNEISSIC, COMPLETELY UNLIKE THE PARENT ROCK.
9. Granulites are thought to form in regions of crustal thickening. Why?

**AREAS OF CRUSTAL THICKENING HAVE VERY HIGH GEOTHERMS, WHICH ALLOWS GRANULTIES TO REACH THE 700-1000°C RANGE THEY REQUIRE TO FORM.**

10. A rock composed of mostly equant crystals will most likely show what type of texture?

**MASSIVE**

11. Preferred orientation of prismatic or tabular minerals due to flow is known as **FOLIATION**.

12. If plates move slowly, the individual eruptions over a hot spot coalesce to produce an **ASEISMIC RIDGE**.

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**Discussion Questions** - Answer all of the following questions completely but concisely. Points as indicated. Diagrams (labeled) may be used to supplement your written answers, where appropriate.

1. A student studies the fluid inclusions in a rock. They form a planar array. Will careful analysis of the fluid allow the student to determine the composition of the original fluid associated with metamorphism? Why? (2 points)

   **PROBABLY NOT. PLANAR ARRAYS ARE USUALLY FORMED BY POST-METAMORPHIC FLUIDS SEEPING INTO THE ROCK ALONG CRACKS.**

2. Below a certain depth, around 10 km, the pressure at the point of mineral contact, \( P_{\text{lith}} \), will be very much greater than the pressure exerted by the intergranular fluids on the minerals. One of two things may happen to reduce this imbalance. What are they? (2 points)

   **1. THE MINERAL GRAINS DEFORM, AND COMPRESS THE PORE SPACE UNTIL \( P_{\text{fluid}} = P_{\text{lith}} \).**

   **2. PRESSURE SOLUTION OCCURS. MINERALS AT THE STRESSED CONTACTS BETWEEN GRAINS HAVE A HIGHER FREE ENERGY THAN ADJACENT GRAINS NOT IN CONTACT. THEY MAY DISSOLVE AND BE REPRECIPITATED IN THE PORE SPACE. THIS LOWERS THE OVERALL FREE ENERGY OF THE SYSTEM, AND ALSO ALLOWS THE GRAINS TO MOVE CLOSER TOGETHER, AS WELL AS FILLING THE PORE SPACES. THIS CONTINUES UNTIL \( P_{\text{fluid}} = P_{\text{lith}} \).**
3. Ocean-floor metamorphism involves considerable chemical replacement. What elements are principally involved? What is the source of the new ions? (2 points)

THE MAJOR REPLACEMENT IS OF CA AND SI BY MG AND NA. SODIUM AND MAGNESIUM COME FROM SEA-WATER, WHICH INFILTRATES ROCK NEAR THE MAGMA-WALL ROCK BOUNDARY.

4. What is the difference between fault gouge and fault breccia? (2 points)

FAULT BRECCIA IS BROKEN, CRUSHED ROCK FILLING IN ALONG THE FAULT. GOUGE IS A CLAYEY ALTERATION OF THE BRECCIA, PRODUCED BY GROUNDWATER PERCOLATING DOWN THE FAULT ZONE.

5. What important contribution did Viktor Goldschmidt make to the study of equilibrium mineral assemblages? (3 points)

GOLDSCHMIDT STUDIED A SERIES OF CONTACT METAMORPHOSED HORNFELSES WHOSE PROTOLITHS INCLUDED PELITIC, CALCAREOUS, AND PSSAMITIC ROCKS. THIS PROVIDED A CONSIDERABLE VARIATION IN PARENT ROCK COMPOSITION, BUT GOLDSCHMIDT FOUND SIMPLE MINERAL ASSEMBLAGES OF SIX OR FEWER MAJOR MINERALS IN THE INNER ZONE OF AUREOLES AROUND GRANITIC INTRUSIONS AROUND THE OSLO AREA OF SOUTHERN NORWAY. HE NOTED THAT THE EQUILIBRIUM MINERAL ASSEMBLAGE WAS RELATED TO THE BULK COMPOSITION, AT A PARTICULAR METAMORPHIC GRADE, AND THAT PAIRS OF MINERALS WERE CONSISTENTLY SEEN TOGETHER, SUCH AS ANORTHITE-HYPERSTHENE OR DIOPSIDE-ANDALUSITE.

6. What two minerals are considered characteristic of impact metamorphism? What other material is often found in impact zones? (3 points)

COESITE AND/OR STISHOVITE, HIGH-PRESSURE POLYMORPHS OF SILICA, ARE THE CHARACTERISTIC MINERALS. AMORPHOUS GLASS, PRODUCED BY IMPACT MELTING, IS OFTEN PRESENT.
7. Prograde and retrograde reactions differ in several ways. Describe each process, explaining the differences. Which is typically the faster process? Why? (4 points)

**Prograde Reactions** are endothermic. The heat supplied causes them to progress rapidly. They often involve dehydration or decarbonation, or both. This helps to maintain equilibrium.

**Retrograde Reactions** are exothermic. However, this assumes the fluids (water or carbon dioxide) are available for rehydration or recarbonation reactions. In most cases, the fluids are driven off during prograde reactions, and are not available. Thus, prograde reactions are often fast, whereas retrograde reactions are slow due to lack of fluids.

8. OIA rocks are depleted in both Ni and Cr relative to OIT and MORB. What does this indicate? (2 points)

This indicates the OIA's have experienced fractional crystallization of olivine prior to eruption.
Short-Answer Questions - Write a complete, concise answer to one of the following two questions. Please answer on the following page, and write the number of the question you are answering in the blank provided. (5 points)

1. Barrow defined a series of six metamorphic zones based on the presence of index minerals for his Scottish Highlands site. Name three of the six zones, and describe the rocks characteristically associated with each zone. For extra credit, describe the minerals which might be associated with each zone.

   Chlorite zone - Slates or phyllites
   Minerals: Chlorite, muscovite, quartz, albite

   Biotite zone - Phyllites, schists
   Minerals: Biotite, chlorite, muscovite, quartz, albite

   Garnet zone: Garniferous schists
   Minerals: Red almandine garnet, biotite, chlorite, muscovite, quartz, albite or oligoclase

   Staurolite zone: Schists
   Minerals: Staurolite, biotite, muscovite, quartz, garnet and plagioclase

   Kyanite zone - Schists
   Minerals: Kyanite, biotite, muscovite, quartz, and plagioclase, ±garnet, ±staurolite.

   Sillimanite zone - Schists and gneisses
   Minerals: Sillimanite, biotite, muscovite, quartz, plagioclase, and garnet, ±staurolite, ±kyanite.
2. Miyashiro developed the idea of paired metamorphic belts to describe the Ryoke-Abukuma belt and the Sanbagawa belt on the islands of Shikoku and Honshu in Japan. Similar belts have been recognized in many other places in the world. Describe the general tectonic setting of the belts, and the relationship of each belt to the tectonic setting. Then describe the type of metamorphism seen in each belt. Which two belts in the Western United States are equivalent the Ryoke-Abukama and Sanbagawa belts?

Paired metamorphic belts are associated with ocean-continent subduction zones. The Sanbagawa belt lies closer to the subduction zone. It shows much higher pressures than the Ryoke belt. Alkaline rocks are common and glaucophane develops in the alkaline rocks, giving way to hornblende at higher grade. Glaucophane is an important indicator mineral, denoting high-pressure low temperature conditions. The bluish color of the glaucophane is used in naming the rocks blueschists. It is a typical high P/T belt. The Abukuma or Ryoke belt, which lies to the NW, farthest away from the subduction zone, is a Buchan type low P/T belt. Rocks are meta-pelitic sediments ranging up to sillimanite zone. Granitic plutons are common. These rocks represent high-temperature, low-pressure conditions. The North American belts are the Franciscan and Sierra.

<table>
<thead>
<tr>
<th>Question #</th>
<th>Times Answered</th>
<th>Points missed</th>
<th>Average Missed</th>
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<tr>
<td>1</td>
<td>8</td>
<td>6.5</td>
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<td>2</td>
<td>4</td>
<td>7</td>
<td>1.8</td>
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</tbody>
</table>

Have a great summer and enjoy SFC if you are going on it. It’s been fun!
Final Exam Grades (out of 88)

86.5
82.5 - 2  A
76.0
75.0 -2  MEDIAN = 74.7
74.0 B  MEAN = 73.6 (83.7%)
72.5 B-
68.5 C+
65.5 C
64.0 C-
61.5 D+

Previous Final Exam Results

Spring 2012  Mean = 73.6 (83.7%)
Spring 2011  Mean = 76.4 (86.8%)
Spring 2010  Mean = 79.5 (90.3%)
Spring 2008  Mean = 76.2 (86.6%)
Spring 2006  Mean = 81.3 (92.4%)
Fall 2001    Mean = 76.4 (86.8%)
Total Exam Results (Possible = 208)

200.0 A
185.5
185.0 B+
176.5
175.0
174.5 B
172.5 B-
162.5 C+
156.0 C
149.5 C-
135.5
131.0 D

MEDIAN = 173.5
MEAN = 167.0 (80.3%)

Exams Overall

Spring 2012 Mean = 80.3%, B-
Spring 2011 Mean = 83.0%, B
Spring 2010 Mean = 82.9%, B-
Spring 2008 Mean = 80.7%, B-
Spring 2006 Mean = 84.8%, B
Fall 2001 Mean = 81.9%, B-